LECTURES ON INNOVATION IN BUILDING TECHNOLOGY

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LECTURES ON INNOVATION IN BUILDING TECHNOLOGY

LECTURE ARTICLES FOR STUDENTS OF ARCHITECTURE
DELFT 1992-2015 / NOTTINGHAM 2005-2011

Prof. Dr. Mick Eekhout
Full professor 1991-2015
Chair of Product Development TU Delft
Special Professor of Structural Design, Nottingham

LECTURES ON INNOVATION IN BUILDING TECHNOLOGY

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AUTHOR Mick Eekhout
LAYOUT Manuela Schilberg, Saphira Jon, Octatube, Delft
MASTER DESIGN Sirene Ontwerpers, Rotterdam

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PREFACE



Ian Ritchie [© Jocelyne van den Bossche]

The process of architecture is fundamentally concerned with the art of space, providing societies with technical, environmental and aesthetic solutions for various types of shelter for various human activities.

Traditionally, when it comes to realising a concept , the constraints of engineering safety, function, economy, and environmental responsibility require the input of individuals trained in various disciplines.

There is a wonderful confusion created among clients – and others – when a pan-disciplinary talent is encompassed within the expertise of an individual and in the execution of the work. Mick Eekhout is one such talent – a professional at ease within the fields of architecture, engineering, and industrial design.

However, when this talent is contained within a pan-disciplinary international company – the concept of the 'one stop shop' – then it is readily accepted.

Mick Eekhout came from architecture studies and practice, then moved on to industrial design and then focused on 3D space-frame structures, establishing his company Octatube Space Structures in 1982. He took the company internationally in 1997 and since then has designed , engineered and built structures in collaboration with some of the most prominent architects in the world.

In an era that has seen the power of the image and hyperbole swamp technical knowledge some individuals, like Mick, have continued to see and understand that beneath the waves the currency of research and know-how informs creativity, and have also understood the real pleasure that a sound technical foundation brings to the creation and development of the designer's ideas.

His research and projects exemplify a step-by-step improvement in product and performance, and he shares his discoveries generously while nurturing the next generation of designers.

Of these, those who have navigated 'flick of the cursor' egos because of their technical skills and imagination, and those also able to bring environmental and social awareness to what is realized, manifest a freshness of ideas and concept which is out of the ordinary.

When we mean to build,
We first survey the plot, then draw the model;
And when we see the figure of the house,
Then must we rate the cost of the erection;
Which if we find outweighs ability,
What do we then but draw anew the model
In fewer offices, or at last desist
To build at all? Much more, in this great work,
Which is almost to pluck a kingdom down
And set another up, should we survey
The plot of situation and the model,
Consent upon a sure foundation,
Question surveyors, know our own estate,
How able such a work to undergo,
To weigh against his opposite; or else
We fortify in paper and in figures,
Using the names of men instead of men:
Like one that draws the model of a house
Beyond his power to build it; who, half through,
Gives o'er and leaves his part-created cost
A naked subject to the weeping clouds
And waste for churlish winter's tyranny.

Shakespeare Henry II Pt 2, Lord Bardolph

Mick's career and work have evolved through research and development. These should be viewed as an investment – finance and energy invested to create knowledge. The innovation that results – based on this knowledge – delivers revenue.

Innovation is a good thing but not as an end in itself or without context – that is, in isolation. Innovation can create something completely new and, often, is seen as techno-centric. However, innovation can also be manifest in methods of teaching, leading, organising and delivering an architectural concept. In this context, for innovation to have a valuable and effective role in society, there have to be certain foundations for its success: a culture of market creation needs to exist that allows, supports and then exploits innovation.

At the moment, Europe does not create sufficient markets of this kind. Public procurement needs to recognise and support innovation. Public procurement is circa 16% of EU GDP and, currently, is driven by monetary rather than innovative concerns. Funds are spent on the "cheapest" solution rather than purchasing innovative products and processes that have the potential for long-term sustainability.

Innovation in a societal context requires flexibility of the mind, being less focused on the physical. Our information-based society has yet to develop a structure that reduces the need for physical mobility, yet clearly this is possible and desirable. Perhaps energy limitations , in tandem with information exchange technologies, will redefine the needs for such mobility.

Financial risk is an inevitable aspect of research and development; more entrepreneurs – business angels and venture capitalists – are vital if the results of research and development are to be realized. These people, with financial muscle, have learned to celebrate 'failures' as part of the learning process on the road to the creation of ' winners'. At the moment, the EU and our society in general are functioning on a "No Risk' or 'Zero Risk" ethos.

There is clearly a need for creative, innovative and pro-active legislation from government which recognises that through innovation we fabricate and frame our society's future.

Mick Eekhout's contribution to the advancement of lightweight structures, and the education of architects and engineers through his work over the past decades at TU Delft and Nottingham University, has been considerable. This collection of his lectures is a rich vein of information and thought and deserves to be read widely.

Ian Ritchie
London

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CONTENTS

PREFACE

INTRODUCTION XIII

REFERENCES XV

01 ARCHITECTURE & BUILDING TECHNOLOGY 1

02 TUBULAR STEEL STRUCTURES IN ARCHITECTURE 21

03 ON THE FUTURE OF SPATIAL STRUCTURES 45

04 'ZAPPI' OR RESEARCH IN THE STRUCTURAL USE OF GLASS 57

05 CARDBOARD DOME FROM IDEA TO CERTIFICATION 91

06 GRP SANDWICH ROOFS FOR THE RABIN CENTRE, TEL AVIV 107

07 SINGLE-LAYERED SPACE FRAME DOME FOR THE FRIESLAND BANK 141

08 MUNICIPAL FLORIADE PAVILION, HOOFDDORP 155

09 TENSEGRITY BRIDGE, PURMEREND 167

10 ALUMINIUM SPACE FRAME FOR DUTCH ALUMINIUM CENTRE 179

11 ALTERNATIVE DESIGN FOR GLASS ROOF FOR THE DG BANK, BERLIN 193

12 SPACE FRAME FOR FLORIADE PAVILION, HOOFDDORP 207

13 GLASS FAÇADES IN TOWN HALL OF ALPHEN AD RIJN 219

14 TRANSPARENT CUBICAL GLASS BUILDING IN MADRID 237

15 GLASS ROOF AND ZINC DOME IN BUCHAREST 251

16 DEVELOPMENT OF A SUPER SLIM FAÇADE FOR INHOLLAND 265

EPILOGUE 281

BIOGRAPHY 285

INTRODUCTION

This book is a survey of articles written in the recent years by Mick Eekhout and used in his lectures for the students in the Master of architecture program at the Architecture faculty of TU Delft and for students at the faculty of Architecture and the Built Environment of the University of Nottingham. The lectures and articles are based on a mixture of innovations in academia (Laboratory of Product Development, TU Delft) and industry (Octatube company, Delft).

The lectures elucidate on the relationship between architecture and building technology, on innovative design, development & research at the chair of Product Development at TU Delft and on innovative building technology employed in prominent projects as experienced in the 'Design & Build' practice of the author. The author holds a part-time position as full Professor of Product Development in Delft and was the 'Special Professor for Structural Design' in Nottingham. Standing with one foot in the industry and the other foot in academia, his target was to inspire students with the experiences from both worlds. To prepare students to be inventive in their future practice and successfully innovative by realising their dreams.

The basis of his activities is his design & build company Octatube Delft, established in Delft, but working worldwide. In scientific terms he regards the company as his experimental laboratory from which, over the last 30 years, he was able to develop an innovative technical vocabulary for lightweight structures and claddings for architecture.

Mixed into this bundle are articles (and lectures derived here from) on topics developed as a professor and working with students, like Tubular Structures in Architecture, like Maison d'Artiste, like the Concept House and like the Zappi and the Blob research.

To compensate for the lack of peer reviewed articles in international scientific magazines as a practice-oriented professor of Architecture he advocates the use of the experimental results of his design & build company which are documented and debated with students as a part of his scientific portfolio. Each innovative building part realised after an experimental

development process is described in a scientific manner and published. In the recent 20 years of his appointment more than 400 publications were created, 12 books published, and 8 more books are in preparation. By doing so this portfolio is added to the scientific state-of-the-art of the faculty of architecture.

For students this book is based on 16 articles written in the last decade on a number of technical items. These items are important for architecture students as they highlight the possibilities of innovative technical thinking. Technology as developed by an architect, who is interested in inventing and innovating the building technical vocabulary. The articles are a mix of developments at the TU Delft and at Octatube. As a professor, Mick Eekhout is interested in a debate on the quality of his innovations realised in projects all over the world, but also in encouraging the academic collaborators at his Chair and his research projects to stimulate innovation in the building industry by walking on ahead, to lead the way in developing and realising prototypes. As for example the Concept House Prototype, which opened in October 2012 as the first Dutch multi-storey industrially made and energy-positive apartment with an extreme low carbon footprint. This prototype launches a complete new development in the Netherlands of extremely sustainable apartments. It will be successful when – on the basis of this newly acquired knowledge – a pilot project can be realised of a Concept House Urban Villa of some 16 apartments in 2015. By then a whole series of research & development work has been done to elevate the level of know-how and insight in building sustainable housing. By then the students will have learned and enjoyed practical technical innovations, have been taught to undertake their own materialised innovations in the Product Development laboratory, nowadays called 'The Bucky Lab', and the industry has been inspired and its level of innovative technology has been improved.

The professor can retire.



REFERENCES

In the Netherlands a public debate on frequent scientific publications arose in 2014. Frequent publishing in different arena's leads to repetition of texts, improvement and deformation of texts. Since I finished the 12 books of Mick Eekhout (written or edited), parts of these books are repetitions for different purposes. In this book articles were translated from Dutch into English, scientific papers were copied, and other publications later were enlarged into books. This book was conceived to bundle a number of different subjects of lectures together for the use of students after my retirement. Im am aware that in my publications repetitions can be recognized, but they were written for different audiences. The Dutch term 'zelfplagiaat' or 'self-plagiarism' is regarded as a misleading word by the Royal Academy. They have proposed in the KNAW commission 'Correct Citations' (April 2014) to set rules. The rules have not been defined and in the meantime maximum transparency should be undertaken in citations. In the following publications the subjects are treated more extensively:

01: 'Architecture & Building Technology' was published in an overview of lectures by Mick Eekhout at Nottingham University 2004, internal publication.

02: 'Tubular Steel Structures in Architecture': Mick Eekhout, '*Tubular Structures in Architecture*', published Cidect, Geneva and TU Delft, 2011, ISBN 978-94-90675-01-1

03: 'On the Future of Spatial Structures': Mick Eekhout, '*On the Future of Spatial Structures*', published before in the international Journal of Space Structures nr 2, 2003, page 129-136

04: 'Zappi'or research in the structural use of glass' has been extended in the book: Mick Eekhout, '*Delft Glass Design Innovations*', Octatube Delft, 2015.

05: '*Cardboard dome form idea to certification*'; first published in Cardboard in Architecture, IOS Press, 2008, ISBN 978-1-58603-820-5 in the title: Mick Eekhout, 'The Cardboard Dome as an Example of an Engineers Approach', page 147-163.

06: GRP Sandwich Roofs for the Rabin Center, Tel Aviv; has been published before in Delft Science in Design 2, 2007, IOS Press, Amsterdam, ISBN 978-158603-739-0. This article was extended in the book: Mick Eekhout, Sieb Wichers, 'Lord of the Wings, the Making of Free Form Architecture', IOS press , Amsterdam, 2015, ISBN 9781614995494.

07. 'Single –layered Space Frame Dome for the Friesland bank': Original publication the 5th international Conference of space structures, Guildford, Surrey, 2002, Thomas Telford London 2002, ISBN 0727731734; Mick Eekhout, 'Single Layered Space Frame Dome on Top of the Friesland Bank in Leeuwarden, the Netherlands', page 1327 – 1336.

08. 'Municipal Floriade Pavilion, Hoofddorp', Top tech lectures TU Delft, 2010. Aluminium 2002, nr 6, Mick Eekhout, Gemeentelijk paviljoen op de Floriade, page 33 – 37.

09. 'Tensegrity Bridge, Purmerend', article written in the Dutch magazine Aluminium 2002, nr 7, Mick Eekhout, 'Een vlijmscherpe brug', pag 33 – 37.

10. 'Aluminum Space Frame for Dutch Aluminium Centre' is a translation of a publication in Aluminium, 2002, nr 5, Mick Eekhout, 'Productontwikkeling aan gelijmde ligger met geïndividualiseerde gietknopen voor het Aluminiumcentrum in Houten', pag 17-23; Research report Aluminium Centrum, Houten 1st part 1999, 50 pages.

11. 'Alternative Design for Glass Roof for the DG Bank, Berlin', is a translation of a lecture given for Bout students at the Berlin excursion 2002, and published in students magazine Rumoer Berlijn Extra, 2004 ISSN 1567-7699.

12. 'Space Frame for Floriade Pavilion Hoofddorp', article written for 3rd year students of the prototype laboratory at TU Delft.

13. 'Glass Façades in Town Hall of Alphen ad Rijn': translated from the reader TU Eindhoven, Stadhuis Alphen aan den Rijn, 2002, ISBN 90-6814-146-5, Mick Eekhout, Barbara van Gelder, Luis Weber, Tjibbe van der Werff, "Gevel', page 223 – 294.

14. 'Transparent Cubical Glass Building in Madrid' is described more extensively in Mick Eekhout, Delft Glass Design Innovations, Octatube Delft 2015.

15. 'Glass roof and Zinc Dome in Bucharest' has been partly described in Mick Eekhout, Delft Glass Design Innovations, Octatube Delft 2015.

16. 'Development of a Super-slim Façade for INHolland' in: Ulrich Knaack, Tillmann Klein, eds, 'Future envelope 2 , IOS Press 2010, ISBN 978-1-60750-026-1, Mick Eekhout, Peter van de Rotten, 'Development of a Super Slim Façade System for INHolland Polytechnic, Delft

01 ARCHITECTURE & BUILDING TECHNOLOGY

01.01 INTRODUCTION

The TU Delft lectures 'Innovation in Building Technology' are a part of the teachings for Master students of Architecture from the viewpoint of Building Technology. Innovation in building technology is translated as the building technical innovations that have been accomplished in architecture. It starts at the inventor side of technical design, and leaves the composer-side of architectural design for the architecture teachings. Because of the frequent 'wall of fear' between architecture and building technology, even a building technology professor of high ranks as myself is not allowed to teach about architecture, by mandate of the professors of architecture; whatever professionals may think about this artificial division. Hence the separate approach. I will try to elucidate my point of view.

1.01 NEW, RENEWED, INNOVATED OR IMITATED TECHNOLOGIES

Although the scientists in the field of product development are mesmerized by the designing and developing of completely new products and by the drastic renewing of existing products, as they prefer this over renewing only one small aspect, there is a positive awareness of the relativity of the notion 'newness'. We must be realistic about this. When do we speak of a 'new' product after all? Does a cosmetic change or alteration of an aluminium façade system give it the right to the adjective 'new'? When a tilt/turn window, developed and customary in Germany, is added to a system of Dutch window frames and windows – usually only twist no turn, should we then speak of a new product on the Dutch market? Or must a product involve a totally new concept before it can be classified as a new product? The notion 'innovation' plays an important part in this. Innovation literally means 'renewing'. Naturally, this does not define whether it must be complete or partial new demand, or a complete or partial new answer to that demand. Innovation is a marketing term rather than a technical one, and it is usually misused. If an existing solution

would be the most appropriate answer, it is not the engineer's task to pose as a designer, at best as an applicant for a solution that others already found and executed before him. The real engineer designing work always has to do with 'original & ingenious', on the basis of the education. Innovation is a magic word, which implies that, with the renewal of one single product characteristic, more characteristics have been renewed. Or, when more than one characteristic has been renewed and improved, that this is true for the entire product. The marketing pretension of the word 'innovation' is of no use to a completely new product, because that product cannot be compared with a product that existed beforehand. We should call products which are completely new but maintain an existing function 'new' products, while new products for a new function should, in fact, be named 'super new' products. These completely double-new products can be distinguished in an absolute sense (for the general population) and a relative sense (to us as professionals in the building industry, which may mean nothing to others!).

As a product designer and component architect, raised in the architectonical trend of functionalism, the author tends to use the following basic criteria as a starting point to measure the degree of originality and ingenuity, of innovation or newness:

- Function;
- Technique;
- Aesthetics;
- Economy.

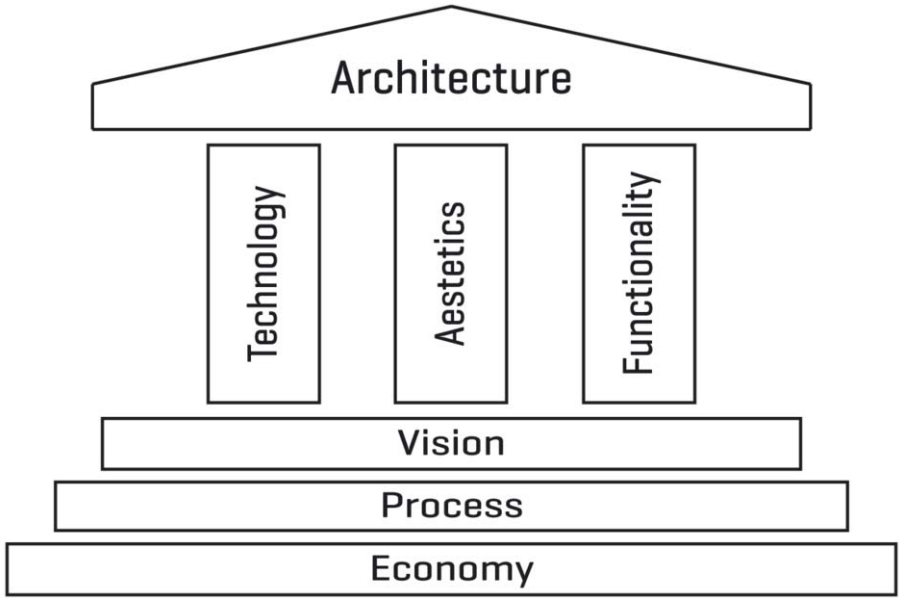

FIG. 01 Temple scheme of functional architecture

An artist will choose a different order, so will a contractor or a principal, but to a functional architect this order fits. Roman architect and author Vitruvius wrote, some 2000 years ago, of *"Firmitas, Utilitas, Venustas"* (Durability, Usefulness and Beauty), but efficiency and economy are consciously present as underlying considerations in his 'De Architecturas' or the Ten Books as well [Ref. 01.01]. In this respect, not much changed in two millenniums. When a new product scores as 'new' on both the aspects technique and aesthetics, we consider this a new product. We usually design products for existing functions. Therefore we focus on new products, which will have to replace existing products. That is why function is rarely a criterion for newness. Next to that, economy is derived from technique and aesthetics (as well as from selling, applications and more such items) and therefore economy as such does not play a part in the newness assessment. In all sincerity, we could sum up four categories of products with a decreasing degree of newness:

- super-new;
- new;
- renewed;
- imitation.

A further refinement would be to apply a grading to:

- one characteristic;
- more characteristics;
- most characteristics;
- all characteristics.

Completely new products are real triggers in their newness and uniqueness. They should have to offer solutions for new problems which, until now, were not an issue. For instance a new, lightweight and unbreakable glass-like building material which is load-bearing, strong and rigid and chemically resistant (the new and yet undiscovered unbreakable transparent construction material 'Zappi'. Or a single-layered roofing that can be spread evenly on roofs in a liquid form, attaches to everything, even to damp surfaces, is not bothered by vapour tensions, is waterproof and obtainable in several colours. Or a laminated fully tempered cold bent glass roof without metal frames or posts with proper solar transmission capacities, maintaining high light transmission. Any fantasy: you name it! And everything that comes close to these fantastic ideas. Very often a fundamental examination is needed for these new products, which really does not leave one stone upon the other.

However, lengthy development work with much examination effort, demanding a vast financial investment proves to be hardly possible in the building practice in general and is certainly not common. But new products do have a renewing effect on our thought processes and on the product assortments of the building sector. Replacing existing products with renewed products, which show slow improvements in important points. Only in one or some aspects. For instance, aluminium window frames with single or double cold bridge barriers. Glass panels with a high thermal insulation value and an invisible coating, transmitting hardly any solar energy, but still fully transparent.

Imitation products will only be new or innovative to a certain company person or company, but they are not new on the market. There are companies that want to get their share of the market with a 'me too' attitude, usually after they have made a copy of another company's product, typically with a more daring attitude. Each and every company has legion products which are inspired by a continuous following of the market process, what the demands are and also what is supplied by the competition in the branch. Followers are never exceptionally original but, by jumping on the back of a riding bicycle, they avoid the initial expenses and especially the initial risks. Therefore they can be less expensive. That is often the reason for this attitude. To be successful there is a big parcel to be positively filled with ingredients: the 'product mixture'. Imitation products with a carefully assembled product mixture can, in principle, score higher than new products, sadly enough. It is therefore not illogical to assume that relations between marketing people and designers are often strained. This can go very far; exemplified by a Dutch member of the English Pilkington glass concern speaking at a TU symposium, saying that renewing came into being by "Logical thinking, clever stealing and creatively pushing on". He put himself on paper twice in the proceedings of that symposium. Of course, after this incident a correspondence followed between the author and this speaker.

Next to our own vision as product developers on super new, new, renewed or imitation products, the opinions of the producing company and the consuming project architects count as well. If the architect considers a product with only one significant improved characteristic to be 'completely renewed', the producer will hurry to join in. On a mainly conservative product market, such as for instance the German market, this will even be an advantage, in order not to drown in the swamp of 'Systemzulassungen' and 'Zulassungen im Einzelfall', system permits and special permits for building these product systems. Thus it might be better to consider only detail improvement and partial innovations, or even cosmetic alterations, to keep the authorities from becoming frightened off. So, the notions 'innovative' and 'new' are often a give and take. 'Imitation' will naturally only be applied to the competition, rather than to ourselves! They others follow us; we, of course, are more original! An actual insight in the above-mentioned could be obtained by analysing, for example, one hundred recommended new or innovative products and seeing their actual degree of newness during a visit at any building exhibition in the world.

My hypothesis would be that 'new' will be limited to a small percentage, maybe renewed applies to ten percent, and the rest will be imitation. It will be interesting to work that out further and philosophise on its consequences for the future development of the building industry as a whole. But even more interesting is, of course, to drastically jack up the number of 'new' products and with that make our influence as building product developers felt by the quality in the building practice in a positive way.

AN ENGINEER IMAGINES: PETER RICE [REF. 01.02]

"Invention, innovation and creativity are three of the great buzz words of today. To be creative or innovative, especially, implies a God-given talent, possessed by the few who the rest of us admire. From the outside it seems impossible to achieve these qualities,

as though somehow the gifted appear to have some mystical status, a status that cannot be claimed, only conferred. How can we become innovative or creative? As I have argued already the creative talent is essentially artistic and is essentially associated with architects, designers and artists. For the engineers or other practitioners in science or fact-based information, the aim is to innovate. Is it so different? I think not.

It is a myth that there is something special about the innovative engineer. Probably every solution put forward by an engineer has some unusual element, some feature that could be called innovative, but is not recognized because it is buried in an otherwise conventional solution. And if we examine the nature of these otherwise innovative or inventive elements, we will find that it is just the result of the engineer being intelligent or sensible about the way some detail has always been, and so reassessing the problem from another point of view.

This kind of innovation arises a hundred times a day on building sites throughout the world. It is taken for granted. But it is nonetheless an important part of everyday work of engineers everywhere. Every solution involves some original thought, some special contribution which we would classify as innovation. This need not be spectacular, it is enough to be new or original".



FIG. 02 Dutch Architecture Institute (NAi) Rotterdam, Jo Coenen

1.02 ARCHITECTS: DON'T IMITATE, INNOVATE!

An even more interesting consideration is how new products would be received in the market by professional consumers. We assume that those consumers are project architects and contractors (usually one of the two has the authority of deciding the application of a building product). Some people will immediately use a renewal as soon as it is introduced to the market. Sometimes for opportunistic reasons, where the danger that the first application will remain the only one is always present. The 'first on the block effect' is an American illustration of this: the first tenant on the block buying a pink Cadillac will create a sensation; the second only imitates the first. To get the second and third buyer on the same block to go that far is far more difficult than it is for the first buyer. Project architects can look forward to new products because a function will improve or a composition will become more beautiful. In 1995, Dutch architect Jo Coenen was in absolute exaltation about the frameless Quattro glazing system of the entrance hall of the Netherlands Architecture Institute at Rotterdam, because it offered a new and unique manner to express the transparency between inside and outside. Some high tech architects (the author has particularly experienced this with Foster Associates and Richard Rogers Partnership, but it is no different with other London offices) fortunately are so dedicated to practice directed research and development in the field of building components, that they continuously take the initiative for product development in the field of their building components as an integral part of their office approach. They employ technical architects and component architects in their offices who, in turn, try to challenge the industry and pull it forward. Others will want to wait and see, until the product has proved its value on the market. Especially architects who rather choose from a building catalogue of products with proven qualities will not be rushing to be the first to integrate the new product into their building.



FIG. 03 Space frame borderstation, Benthem Crouwel

Dutch architects Benthem and Crouwel (among other things house-architects of Schiphol Airport) have made it known repeatedly that they want to belong to this category: using an innovative application of an existing proven product, rather than an experimental application of new products. Contractors will normally wait for the practical proof of reliable quality behaviour, so they will never want to build the firstling. Others again, architects and contractors alike, will never start something new. In analogy of known terms from the consumer market we could distinguish five categories of consuming product appliers for our industrial building market, based on the point in time on which they apply a new product. As possible product appliers we see: project architects and contractors. Non-appliers are not included in the list.

PIONEERS

Project architects are looked upon as pioneers, they themselves take initiative to develop new components, usually as part of their own projects, but because of the sincerity and thoroughness with which they do this, they will often be a few steps ahead of producers in developing. Often a producer, respectively a product designer, can rapidly answer their wishes by introducing a new component product, drastically improving an existing product or introducing a method of manufacturing; or realising renewed products thought up by these pioneers, or together with these pioneers. The pioneers are often ahead of the producers and therefore producers and their product designers have to do their utmost to take over the initiative and again enter a dialogue with the pioneers. Danish architect Jørn Utzon was such a pioneer when he designed the Sydney Opera House in 1956, with its famous concrete shell roofs at a time when nobody knew how such shell structures could be realized. The young Peter Rice had his hands full with this problem for years.

Many British high-tech architects can be considered as pioneers, for instance Richard Rogers, who developed a new type of translucent glass for the Lloyds building in London. Norman Foster, who developed a reflection mirror for the Hong Kong and Shanghai Bank in Hong Kong, automated and using the sun to pull the outside light into the internal atrium. Renzo Piano, who developed new scale components for light distributors above the roof of the Menil Museum in Texas, is a pioneer. Although Piano went further with this in the spirit of Louis Kahn and others, his shell roofs have their very own place in the building product development due to their prefabrication assembly. In recent times, Dutch architect Jan Brouwer has advanced the Dutch glass fibre reinforced polyester industry with his GRP façade components. He is a pioneer. It is only too bad that he did not leave a proper oeuvre behind when he retired as a professor of building technology. We shared many good adventures. Dutch architect Peter Gerssen applied the first 'structural glazing' façade to the office of the Zwolsche Algemeene in Nieuwegein in 1982. The Delft architects office Cepezed initiated new applications of metal sandwich panels in various projects in the Eighties.

EARLY APPLIERS

Early appliers are an innovative, spectacular and opinion-leading group of professionals whom the entire market is watching and whose opinion is highly respected. Once they consider a product good enough to be applied, other categories will follow more rapidly. Yet they are a group, which only accounts for a small percentage of the market, but which quickly tends to apply an innovation. Compared to the late appliers they will be younger, technically more daring and typically do not dwell on the most small-minded or squeezed-out projects. They have a good reputation, which they like to keep up. They have a broader look on the development of building technology, a worldly view on architecture and building technology. Often, they have already checked and compared data and facts through other sources. With their expertise, they tend to be able to differentiate an inspiring technical tale from a salesman tale sooner than most. Well grounded, but not gullible.



FIG. 04 Sydney Opera House, Jørn Utzon

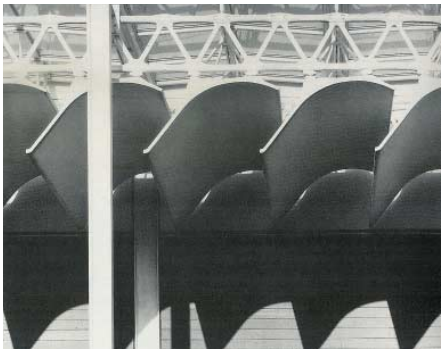

FIG. 05 Menhil Museum, Renzo Piano, detail roof

EARLY MAJORITY

This group accepts innovations just slightly sooner than the majority of the consuming architects. Convincing contacts are salesmen, advertisements and the early deciders. In contrast to the group of early appliers, this group will be much larger and surely worthwhile to pay attention to. They do not want to make the first experiments, but will read all about it and are positive on successful new developments.

LATE MAJORITY

This group really sits on the fence, rather sceptical when it comes to innovation. Usually they look at innovations from an economical viewpoint; partially because they are pushed in that direction by their principals ("Show us something new") because they do not want to run any risks. They often rely on the eloquence of their 'elders' or forerunners. Verbal advice falls onto more fertile ground with them than advertisements or salesman tales.

DAWDLERS

The last group of the market are the super-traditional dawdlers. They will be the last to take their chance with innovations or, if it concerns project architects, they will have innovations applied by contractors, which is usually bad business because in this case it is all about economical benefits, whoever maintains it (contractor or principal). By the time the dawdlers are ready to consider the new product, it is very possible that the pioneers are already busy with a once again improved version of that product. They are already behind when it comes to finally applying.

1.03 THE WALL OF FEAR BETWEEN ARCHITECTURE AND BUILDING TECHNOLOGY

The best architectural education is based on a continuous integration of architecture and building technology. In this Master program of the TU Delft you, the Master students, are taught first and extensively the architectural concept and the architectural composition; and separately, or more often afterwards and too late you are told to deal with the materialization phase, sometimes requiring to make only one or two details. It is from my background and my professional experiences (that is why I elaborated on it) that I feel I have to warn you on the thin varnish that most of the current architecture graduates carry regarding building technology. In my opinion, if you want to become mature architects, you will have to dive deep into building technology. Dive deep enough to be able to compose adequate buildings. Never be ill advised by all kind of salesmen around you. If you are not trained technically, the danger is that you will belong to the generation of graduates who do not know enough about technology to be able to become good architects.
Even famous Professor Carel Weeber, ex-architect, agreed to my opinion in his farewell speech in June 2003. The program of the Master of Science in Architecture does not give the opportunity of technical development of the student. In my eyes we are educating a lost generation of architects. It is up to yourself to study more deeply and more extensively on building technology, in order to avoid belonging to the lost generation. Prominent architectural offices (like PRO, The Hague) in the Netherlands have not selected Delft graduates for years as they cannot engineer properly; that is to say they cannot materialize the designs of the senior architect. Other offices (like Bureau Bouwkunde, Rotterdam) try out candidates for one year; to select only one out of ten being proper Delft building engineers after that period. Our graduates certainly are excellent in conceptual design, but that is only 10% of any office time consumption. The other 90% of time is usually devoted to information traffic and materialization. In this Master program of Architecture the designated time for building technology is so limited that there are only three alternatives:

- To learn it the hard and expensive way: in practice;
- To learn it parallel to the official Master program by reading or selecting the free study space in your program to building technology;
- To learn it by making a combined graduation program AB or BA or A + B, which will take you only one semester longer than the theoretical duration of 2 Master years. (If you do not find work immediately after graduation, why not add the Masters of Building Technology to your diploma, to enhance your chances on the market?)

Sorry to say that the students who follow this line of study will become the back seaters in the architectural practices of tomorrow. The front row will be filled by the very few amongst you who can bluff their way in and out of the rooms of their clients and get away with that. The rest of you will have to face a professional life with a long learning curve in practice, before you can consider yourself mature architects. In my opinion the professional architect should be able to cope with the entire building process on his/her own. For larger and more complex processes the architect has to co-operate with co-designers and advisors. After all, most of the architects have one-person operated offices. These sole professionals need to know about all aspects of the architectural professional practice. Otherwise they will be beaten up on all sides by their project partners in the building process.

1.04 COMPOSING & INVENTING: ARCHITECTURE & BUILDING TECHNOLOGY

I had the fortunate background of a father who started as a carpenter and became a general contractor. During my student times I designed houses and small buildings that were built immediately. I learned the practice of building technology from childhood onwards and I started my architectural practice 2 years after graduation. Only 5 years after graduation the consciousness came to be able to design good buildings. I could engineer my designs and could make specifications and budget estimates and supervise the construction phase properly. All thanks to a fortunate background and a balanced engineering education. In my student times the structural and constructional parts of the teachings were quite impressive and in harmony with the architectural teachings. The best balance is 50% architecture and 50% building technology. Alas, the current new Master of Architecture program focuses more on architectural concept and composition than on materialization and technology. In the last 2 years I have tried to change the technology content of this Master of Architecture program, which was set up by the professors of architecture in the years, but in vain.

It is time for you, students, to create a revolution for your own good. That is: the best would be to study Architecture and Building Technology in an integrated manner. If not, sit still and suffer. I like my statements to be clear and ready for debate at all times. The reality is

that debates are usually evaded or smothered in small rooms in this house. At the end of my high school (St. Stanislas in Delft) I wanted to study languages. I liked to write, still do. I filled the entire school magazine 'Pythia' with writings under many pseudonyms: articles, interviews, theatre critics and poems. But my teacher in Dutch language persuaded me to make use of one of my other skills that apparently had struck him: creativity and design. My father always doubted the virtues of architects, being the guys who made life difficult. But after one visit in the office of architect Van Manen in Voorschoten, I took a chance. From day one my study was a magnificent time. When the student revolution of May 1969 came I took the opportunity to make my own program and went abroad. My study was technically oriented architecture. Actually I was determined to try to capture the newest techniques and technologies. This is, I realize, still the case today. I grew up in the time of the student revolution of 1969 and took all possible liberty to study anywhere possible. When the mountain does not go to Mohammed, Mohammed should go to the mountain. I worked in the Stuttgart Institute for Lightweight Structures of Prof. Dr. Frei Otto in the times of the Munich Olympia Roofs. And worked for a short time at Renzo Piano's office in Genova. A short time may be, but a lifelong motivation and ambition towards the same goal. I, for one, have done a double graduation in Architecture, studying a complex building under Prof. Carel Weeber, and in Building Technology, designing and developing a space frame system (which later caused the start of my Octatube company) under Prof. Jaap Oosterhoff. I graduated with first class honours (cum laude) in 1973 after 5 years of study. In 1989, 16 years later, I received my doctor's degree with the dissertation "Architecture in Space Structures", an overview of my design oeuvre up to that moment, again with first class honours (cum laude).



FIG. 06 Olympia Roof in Munich, Frei Otto

I am the son of a building contractor who employed 40 people. Three of my brothers are contractors continuing my father's company. So I was raised in the machine workshop of my father and I still smell the air of freshly sawn red cedar. I cleaned more building sites than I want to remember. I was lucky enough to design most of the projects my father built as a contractor since my third year in Delft. This was more rewarding than you working at Ikea! Although I am officially registered as an architect in the Dutch 'Architectenregister' as I design one building each year, I am probably the only Delft university professor who owns a contractor's certificate, necessary to lead my 'design & build' company Octatube.



FIG. 07 Prinsenhof, Delft, 1997



FIG. 08 Synagogue, Den Haag, 2004

Two years after my graduation I opened up my own architect's practice, which I had for 8 years with max 8 people. I have done my share of houses and smaller projects until I realized that to be an architect-inventor attracted me more that being an architect-composer. I closed the architect's office officially in 1983 after opening my current design & build company, not to have any confusion with my current clients who are project-architects. Fig. 65 displays interior views of the Glass Museum Hall of the Prinsenhof Museum in Delft (1997) and the extension of the synagogue in The Hague (2004), both of them designed by me as an architect and built as a specialist contractor thereafter. Fig. 9 displays one of my largest villas in Bilthoven in modernist style, realized around 1980. In the last 20 years I have essentially been busy as a designer with a combination of skills: architectural, structural and industrial design. On top of that I am also a specialist-contractor taking many risks and responsibilities from my endless experimentations and an entrepreneur with a design & build company of 50 to 60 people, working world wide. But in doing what I do the oeuvre of amazing technical inventions and innovations is growing each year. Many of my adventures are written down in articles and books. See my cv at my website: www.mickeekhout.nl.

My foreign architect friends sometimes compare my work with a combination of the works of Peter Rice, Jean Prouvé and Gustave Eiffel, but in a Dutch way. It suits me fine. About 20% of my work is devoted to experimenting with new materials, with new technologies, with new structural schemes and putting these designs to work in real projects. 80% of my projects are duplicates of once experiments, multiplications and special systems. In repetition we earn the money that is lost or 'invested' in experimentation. In all of my projects I have to take the full legal product responsibility and in the majority of cases

we end up by taking over the design responsibility of the tendering engineers, advising the project architects. So I know what it means to design something and to take full responsibility, even if the technical composition is highly experimental and innovative. I know that each experimental project adds a sword of Damocles above my head, but up until now, not a single sword fell down, although some of them started swinging, hanging from one weak horse's hair only.

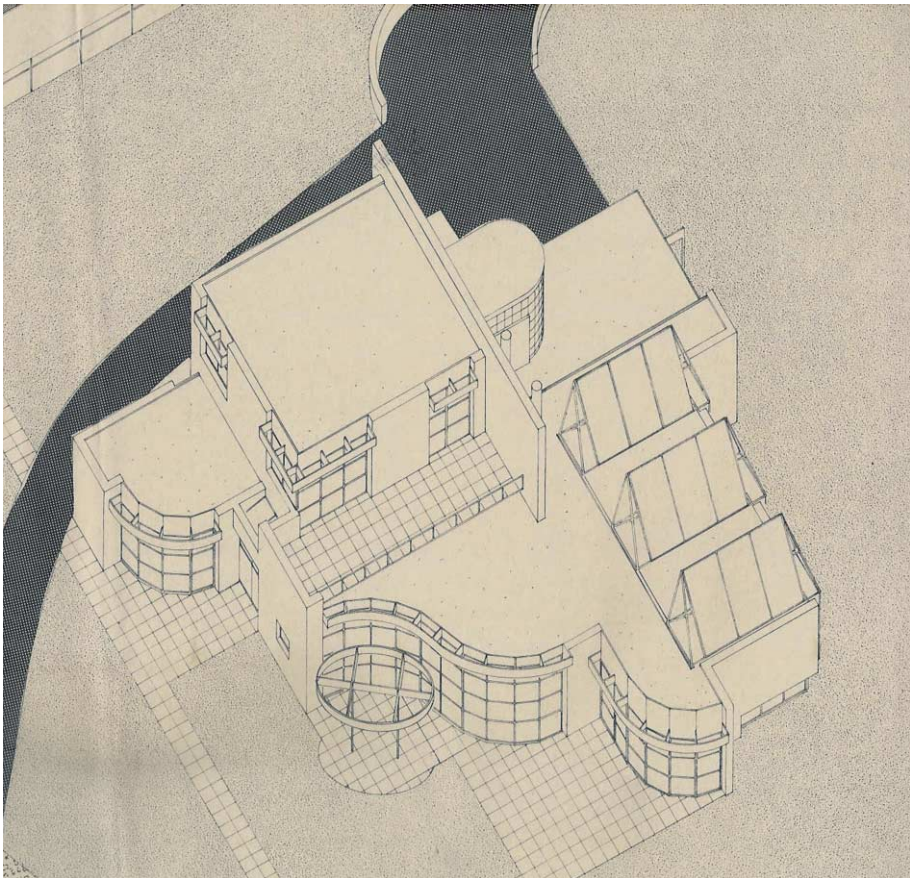

FIG. 09 Villa Bekkers, Bilthoven

In this faculty I hold the Chair of Product Development since 1992, mainly devoted to educate Building Technology Master students. But even more than teaching I am involved in developing the state-of-the-art technology by design, development and research. I call it: 'scientific design'. I stimulated 4 PhD students to their doctor's degree and have 6 PhD students by now, advocating scientific design as a dissertation subject.

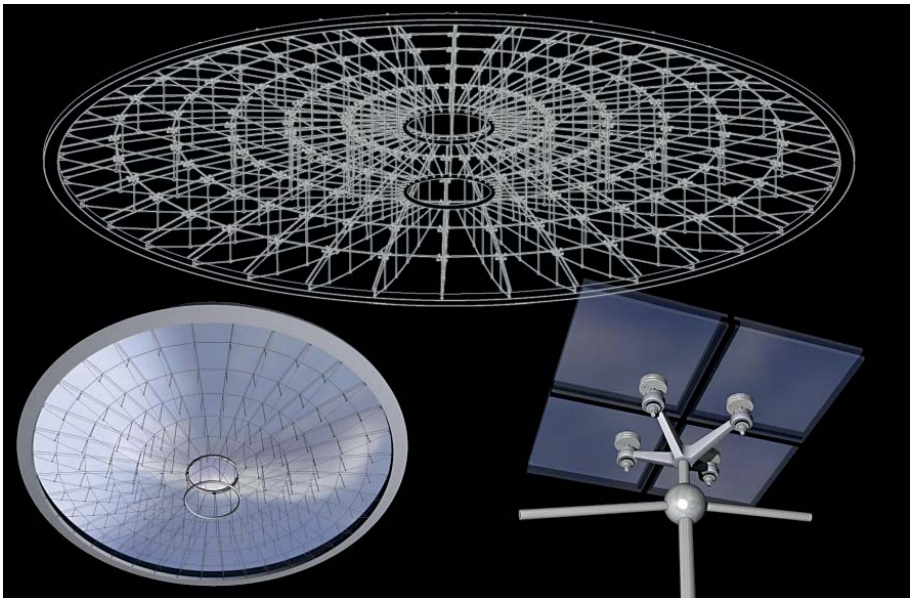

FIG. 10 Details of glass dome, Madrid, design proposal Octatube for architect, Kevin Roche

I was very lucky to be rewarded for my efforts towards design methodology, experimental designs, developments and research with my appointment in 2003 as a full member of the Royal Dutch Academy of Science, being the first architect to enter this Academy since 150 years. It is an appointment for life. So this is your teacher today, in case you did not open my curriculum vitae on the internet site of the faculty. An architect-inventor rather than an architect-composer.



FIG. 11 Atomium Brussels, André Waterkeyn

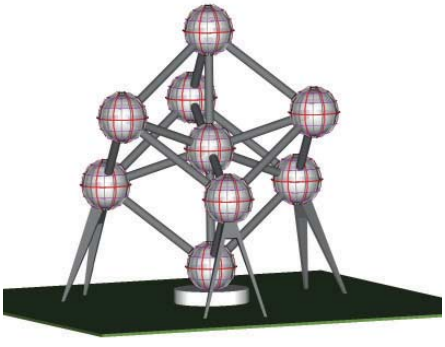

FIG. 12 Atomium redesign proposal by Octatube

1.05 THE ARCHITECT-INVENTOR

In 2005, there are over 10,000 registered architects in the Netherlands, in 3,000 offices. Some 50 of the bigger offices are able to design Architecture with a capital A. The other offices have to design and organize less impressive works which never will be published, but support society in a more modest way. Architectural students are following the international heroes, but end up in the first ten years or so of their professional career to be craftsmen who have to engineer the designs of the elder architects of the office. The assistance you may have to give to the project architect is similar to the position of Peter Rice in his co-operation with, for example, Renzo Piano. Peter Rice (1935-1992) was one of the best structural engineers at Ove Arup's office in the high days of high-tech architecture, in which he put a great deal of his innovative and original thinking power. He was an architecturally thinking designing engineer. He often worked together with architects of fame such as Renzo Piano, Richard Rogers and Norman Foster, right from the start of the design process. His position in the design process is a model for the co-operation between architecture and building technology.

Peter Rice wrote further in his book [Ref. 01.02] about his vision on the classical function of the engineer assisting the architect:

"I am an engineer. Often people will call me an 'architect engineer' as a compliment. It is meant to signify a quality of engineer who is more imaginative and design-orientated than a normal engineer. This is because in the minds of the public and of other professionals, the engineer is associated with unimaginative dull solutions. If people can find an engineer making original designs, designs which only an engineer can make, they feel they need to grant him or her tighter accolade, hence 'architect engineer'. It is not that I object at being called an 'architect engineer'. Occasionally it may even be appropriate, but mostly it is not because there is a fundamental difference between work and way of working of an engineer and that of the architect or designer.

To call an engineer an 'architect engineer' because he comes up with unusual or original solutions is essentially to misunderstand the role of the engineer in society. It is easiest to explain the difference between the engineer and others by comparing how each works and what they do. Designers just like famous car stylists like Paninfarina, or Giugiar, work essentially from within themselves. They respond to a design challenge by seeking to understand how they respond to the context and the essential elements of the problem: their response is essentially subjective. Different architects will respond differently to the same problem. Their solutions will reflect their style preference and their general belief in an appropriate response to a problem. Thus, if you ask an architect to respond to a particular design challenge, he will always give a solution based on the classical order, a solution which reflects his belief that the classical order is the only one satisfactory response which preserves an urban sense of scale and recognizes a link with the past which he interprets in his own way. Other architects would choose a different approach based on their subjective reactions as to what an appropriate architectural response

should be. Both the likely responses would be known beforehand and would probably have an important factor in the selection of the architect in the fist place. An architect's or a designer's response to any design challenge is subjective and is based on his feeling on the correct and appropriate response. He is employed to express his personal view of the correct solution.

An engineer and an architect would rarely find themselves tackling the same problem [...]. The engineer when faced with a design challenge will transform it into one which can be tackled objectively. As an example the engineer may seek to exchange the problem into exploration of how to exploit a particular material completely within the context of architecture. Thus the Lloyd's bank of London building became an exploration of the use and properties of concrete. And the engineer's contribution was to try and make the structure an essay on expression in the use of concrete. But it was the properties of concrete which motivated the search and the solution.

Similarly at the La Villette's 'Greenhouses' in Paris. The architect defined the architectural intention. The engineer transformed the simple architectural statement into an essay on the nature of transparency and of how to use the physical properties of glass to convey fully the concept of transparence. As an engineer I worked essentially with the glass. It was the properties of the material which motivated the development and the design. Thus, although we can say that there was originality and aesthetic choice in the way that the design developed, this way forward was directed by the need to express the properties of the glass in full.

I would distinguish the difference between the engineer and the architect by saying the architect's response is primarily creative, whereas the engineer's is essentiality inventive. The architect, like the artist is interested by his personal considerations whereas the engineer is essentially seeking to transform the problem into one where the essential properties of structure, material or some other impersonal element are expressed. This distinction between creation and invention is the key to understanding the difference between the engineer and the architect and how they can both work on the same project, but contribute in different ways. Indeed, it is important that engineers start to educate both people within the profession and the public at large on the essential contribution that the engineer makes on even the most mundane project." So far the quote of Peter Rice from his book 'An Engineer Imagines'. [Ref. 01.02]

I took the opinion of Peter Rice to back-up my own as to what should be a twin phenomenon, but sadly has led to a complete separation in the recent Bachelor/Master programs. We are working towards a greater share of Building Technology in the Masters of Architecture, but for the time being you will have to be awake and follow your own instinct on collecting building technological knowledge and insight, even if it means outside of the program. Architecture & building technology are always intertwined and should be regarded as twin phenomena, both in your studies as well as in practice.

In my Octatube office and factory I have created the fortunate opportunity of having a giant laboratory at hand, in which we can experiment with models, new materials, new connections, with new technical systems and technologies, where we build our mock-ups and tests, but where we can also produce one-off productions and the repetitive productions of once experimental quests that bring in the money needed to balance the losses caused by experimentations. I feel to be standing on the shoulders of Renzo Piano, one of my heroes who inspired me both as a daring professional and as a person.



FIG. 13 Peter Rice



FIG. 14 Interior Octatube factory

Renzo Piano is an architect with a great feeling for urban design, architecture and building technical design. He, too, was the son of a contractor. In the publication of each new project, he always surprises us with the new pallet of materials and techniques he has chosen and developed for this particular project. He regards building technology as a sort of twin brother who allows him to experiment new set-ups. He wrote on experimentation in his book 'The Renzo Piano Logbook' [ref. 01.03]: *"In ancient times, designing also entailed inventing machines that were needed to carry out the work. Antonio Manetti recounts that Brunelleschi studied the mechanism of the clock so that he could apply it into a system of great counterweights; this system was then used to raise the beams for the dome of the Florence cathedral. The means and the end were the fruit of a single experience, of one and the same process.*



FIG. 15 Mick Eekhout

The moment of testing is not the execution of a work that someone else has written down and directed – it is interpretation, performance; it is part of the creative process. When you work in a circular way the technical aspect returns to its place at the centre. It is given back its dignity. Experimentation serves to link together the idea and its material consequences. […]. Knowing how to do things not just with the head, but with the hands as well: this might seem a rather programmatic and ideological goal. It is not. It is a way of safeguarding creative freedom. If you intent to use a material, a construction technique or an architectural element in an unusual way, there is always a time when you hear yourself saying: "it can't be done", simply because no one has ever tried it before. But if you have actually tried, then you can keep going – and so you gain a degree of independence in design that you would not have otherwise".

When a designer really is determined to realize his dreams, he or she can take a different position than the usual one. One that connects, decision making and responsibility, knowing that in the game of roles he or she inevitably has to a take up more liability as well. But that makes the game rewarding. At last we can steer again!

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02 TUBULAR STEEL STRUCTURES IN ARCHITECTURE

This article is derived from the book: Mick Eekhout, 'Tubular structures in Architecture', Cidect, Geneva and TU Delft, 2011, ISBN 978-94-90675-01-1 [Ref. 02.01]

02.01 HISTORICAL DEVELOPMENTS

Today the technology of structural hollow sections has matured and become an integral design tool for the structural engineer and the architect. But it was only 150 years ago that the first rectangular hollow sections were considered for the Britannia Railway Bridge and the first elliptical hollow sections for the Saltash Railway Bridge. So the history of tubular structures began. The Firth of Forth Railway Bridge near Edinburgh, which displays an impressive use of the first circular hollow sections, followed these projects 40 years later, in 1889, the same year as the Eiffel Tower in Paris. The heroic enterprises of moving heavily laden trains over rivers and valleys without proper analytical tools still intrigues and captures the imagination. In many ways, these pioneers were heroes. The initial hollow sections from the last century were composed of plates and angles bolted or riveted together. With the technique of continuous roll forming and the introduction of steel welding processes in the 1920s, a continuous production of rolled welded tubes became economically more viable. Gradually circular, rectangular and squares hollow sections were introduced to the building industry. In the 1940s, open profiles still governed the steel construction industry but after that time an economic awareness together with a major development program with extensive research by tube makers, coordinated through CIDECT, (an organization linking together tube makers internationally in which Prof. Dr. Jaap Wardenier played an important role) pushed results towards a standard of design, engineering and fabrication of tubular structures that has achieved worldwide acceptance.



FIG. 16 Detail of the Pompidou Center in Paris.

02.02 FROM EARLY IRON TO TUBULAR STEEL STRUCTURES

In the Western world, the first structural use of iron dates back to the time when the ancient Greeks incorporated wrought iron beams as reinforcement for entablatures in certain temples. Iron was not used again until later in the medieval era, when iron components were occasionally used for spanning cathedral aisles. The first scientific investigations on iron tubes were carried out by Edmé Mariotte in 1660. He was charged with the design of water supply pipes for the palaces of Versailles and performed tension and bending tests to determine the strength of the material. However, the incorporation of iron for structural use was rarely attempted before the eighteenth century. Since a low rate of production and difficulty in shaping larger members ensured that iron remained a rare and expensive material, the most popular applications were found in the manufacture of armaments, where iron was used for gun and canon barrels. Smelting of iron depended upon charcoal which had a tendency to crush in the furnace and which limited the scale of operations. However, a major breakthrough in 1709 by Abraham Darby provided a more efficient and improved fuel for the smelting process. By converting coal into coke he enabled cheaper cast iron to be produced in bulk. As greater quantities became more economically available, it was cost effective to use cast iron for a broader range of components; and applications in building appeared. However, it was not until the 18th century at the start of the industrial revolution in the UK, that iron was generally accepted as a load bearing material in structures where it was used as columns.



FIG. 17 The iron bridge of Coalbrookdale still stands as one of the early and firm examples of structural cast iron.



FIG. 18 Design cross section of the Conway Railway Bridge at the Menai Strait designed by Stephenson & Fairbairn

These were a great deal more slender than those of stone or masonry used previously. The first cast iron columns are known to have been used as early as 1706 by Christopher Wren in the House of Commons, London. Many of the English cotton mill factories later that century were built using an internal structural frame of cast iron columns and beams, thereby improving the fire resistance of the building in comparison with the traditional timber frame structure. The columns used in this kind of structure were often hollow, mainly to save on casting material and weight. Another prime example of an early use of structural cast iron can be found in the iron bridge in Coalbrookdale built in 1779. In 1793, Henry Cort used a puddling furnace for melting iron ore where carbon was removed from the molten pig iron. The result was wrought iron, a material with improved tensile properties and greater ductility. By means of rolling techniques these innovations presented a greater opportunity to shape iron into plates, rods, rails and other open sections in a continuous production process instead of the former serial casting production. Hot forged rivets allowed fitters to join different section of wrought iron open sections together, so larger and more complicated iron structures could be realized. Apart from producing a more reliable structure, they performed excellently when absorbing vibrations from dynamic loading. With an explosive growth of industrial activities, the old building types and infrastructure no longer sufficed. New demands were placed on production and new factories with greater efficiency increased the use of iron in building railway stations and large span bridges. Progressive designers and structural engineers, although handicapped by the lack of experience and analytical tools, adopted iron enthusiastically. The use of iron as a structural material increased swiftly with the rapid progress of industrialization and scientific exploration. It was a determining factor in changing the course of 19th century architecture.

The new developments of this period were more clearly demonstrated by the engineering of structures than by pure architectural works. An example can be seen in greenhouses of that period constructed as filigree structures made from mechanically produced main structural and secondary glazing iron elements, with very thin glass infill panels. Structurally, this was not very experimental, but the impact of a fully transparent envelope, industrially produced, proved the antithesis of contemporary architecture. The development of smaller elements and components led to the use of wrought iron tubular elements in the Palm House at Kew Gardens, London; designed and constructed in 1848 by Decimus Burton and Richard Turner. Here, tubular elements connect all trusses by means of internal pre-stressed wrought iron rods, which give the trusses a greater stability. Glass envelopes stood as testimony to the changes in society due to the industrial revolution, but society still represented itself mainly in stone.

The Crystal Palace was the culmination of building technology from the 19th century, designed and built in 1850 by Joseph Paxton as an exhibition building for the first 'World Exhibition' at Hyde Park, London. The 145 metre wide and 563 metre long building was the prime example of the use of specially designed and mass-produced standardized building components. This building was erected in the very short time of nine months using the 'design & build' practice of the time. With the success of standardization in the project, industrial production in factories spread all over the UK and the ensuing efficiency of assembly and erection still seems unsurpassed. Although the excellent strength of the hollow beam had been recognized earlier, it took until the last quarter of the 19th century before more extensive scientific investigations on the strength of materials in relation to their cross sectional area were completed. Sir William Fairbairn was the first engineer to experiment with tubular iron beams of various cross-sections to construct a rigid rail bridge with a large span. With his work he assisted the chief engineer, Robert Stephenson, in the design of the Conway Bridge. The construction of this bridge seen in conjunction with the theoretical knowledge of the mathematician Hodgkinson was a great leap forward in the knowledge of the strength of engineering structures. Not only was the general stiffness, strength and stability of the tubular bridge established by model tests, but also the strength of the detailed iron plates and various types of riveted joints were similarly investigated. The science of structural design was improved in order to find the most economical means of construction, not because of a desire towards structural honesty, but simply because of growing economic competition. Many contracts were issued on a design & build basis, with contracts only awarded to the lowest bidder.

This situation comes back in an amended form in our current 'performance specifications', with the major difference that the architect as a consumer now still has a strong influence on the form of the components. Many experiments were carried out by manufacturers using different sections of rolled wrought iron in order to find the cheapest beam in relation to its strength-to-weight ratio. As a conclusion of these experiments structural components with a tubular cross section were developed. From the initial hollow rectangular cross section which consisted of angled sections riveted together, the rectangular cross section gradually evolved into the rolled circular structural tube.

Production developments by Henri Bessemer and by Siemens-Martin in the 19th century led to the large scale production of steel. Produced in liquid form it enabled larger components to be produced than those made from semi-molten wrought iron, and also offered improved properties. It led to the steady production of steel profiles with a good and guaranteed quality. The Firth of Forth Bridge in Edinburgh was constructed from rolled steel, whilst the Eiffel Tower was built at the same time in wrought iron, since it was assumed to be a temporary building. The production of steel represented a turning point in the construction industry and concluded the era of iron for structural purposes. The engineering problems which had to be resolved for rail expansion in the 19th century were great.

The Firth of Forth Bridge was one of the prime examples of the new use of steel and some of the bridge members were in the form of tubes. The bridge used cantilevering space trusses of wrought steel and tubular steel sections made from flat rolled plates, riveted together. The tubular forms of its major compression elements are acknowledged as very resistant to compressive load, in proportion to their size and weight. This bridge also symbolizes a transition from a purely functional and economical technology to one that is architecturally interesting. Some years later another development outside architecture would create a place in steel history. Striving to escape confinement from the law of gravity and in the enthusiastic atmosphere of early aeronautic experiments (1907), Alexander Graham Bell (1847-1922) developed in Canada a lightweight three dimensional tubular space truss for the purpose of creating a strong and lightweight wing for the airplane. Although the development proved to be too heavy for its initial purpose, the technology found success in an earthbound structure when used in the construction of a watchtower built from steel nodes and identical tubular bar elements. A look-out platform to watch the first airplanes was developed and built by a younger generation. The first steel space frame structure had been developed.



FIG. 19 The outlook tower by Alexander Graham Bell, (1907) as the first 3D industrialized space truss structure



FIG. 20 Details of the 1889 Eiffel Tower composed of wrought iron elements, at the time an old-fashioned material

Other designers were attempting to make use of tubes in lightweight structures; the avant-garde designs of a water tower by the Russian Vladimir Schuchow, his Adziochol light tower of 1911 and the glass roofs of the GUM warehouse in Moscow are examples still admired today. However, circular hollow section applications in columns, piping and scaffolding continued to dominate. From 1890 to 1920, all connections in steel were made by bolting or riveting. In the 1920s, the first fully electric welded truss was made, and from then on welding techniques were used extensively in the construction of steel structures. These new welding techniques made it possible to connect the total cross section of one tube to another by means of a butt welded joint with ease, providing a more direct and effective transfer of forces within the structure and achieving weight savings. Flat triangulated welded trusses were used for factories and other large span structures. However, during the same period reinforced concrete structures were beginning to replace steel structures because of their superior fire resistance. With the development of reinforced concrete for medium span structures in a prefabricated form, a part of the construction market for steel structures was lost.

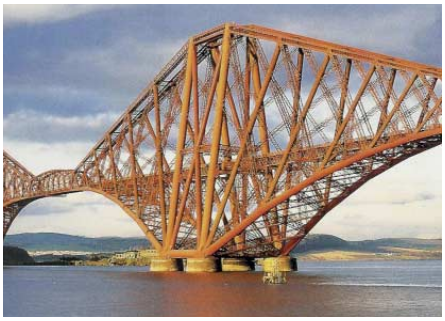

FIG. 21 The Firth of Forth Railway Bridge (1889)



FIG. 22 The MERO-nodal connection was the world's first commercially available space truss system

From the 1940s onward, tubular structures made use of longer rolled welded sections. The exception to this rule of welded butt jointing in tubular design are the space frame systems, consisting of many repetitive short prefabricated elements, bolted together to form a larger span. The first space frame system called 'Mero' was developed in 1942 in Germany by Max Mengeringhausen. This system was the first commercially successful space frame and is still in use worldwide. The system is free as the patent has run out. During and after World War II three dimensional tubular structures were used in large span structures. The intellectual projects and inventions of Konrad Wachsmann, combined with his inspiring teachings and writings, contributed to a refinement in the development of prefabricated tubular structures. He was a genuine apostle of post-war industrialism in America, advocating an industrial approach for mass production during the fifties and sixties. During this period, the difference between the European and American approaches to tubular structures stems from the different ratios of labour to material costs on the

two continents. The European structural designer sought for a greater cost saving on material because steel was a comparatively expensive material, and used more tubular structures than colleagues in America, who stayed with heavy open profiles. The American way had an obsession with identical elements and simplicity of building and was not focused on material savings. Behaving more like a European than an American designer, the anti-traditional American inventor Richard Buckminster Fuller tried to find economical solutions to a variety of structural problems with the application of geometrically dictated designs. In his search for a minimum use of material, much more intellectually driven than developments from the 19th century, he developed his highly intellectual single and double layered geodesic dome structures, followed by a series of tensegrity structures. Invented by his student Kenneth Snelson, these are considered to be the most academic of trussed structures, consisting exclusively of compression struts and tension rods, whereby the individual compression members are never in direct connection. Structure became art and the tensegrity the intellectual culmination of tubular structural design.

02.03 HISTORY OF TUBULAR STRUCTURES

Aside from circular hollow sections, square and rectangular hollow sections were developed in the sixties through the work of pragmatic engineers. Proving to cause less geometrical complications in the individual connections and having a surface that facilitates easier fixing of steel decking or wall and fascia cladding, they stood a better economical chance in the competition with open steel profiles. At this time the oil industry expanded enormously and stimulated research on tubular elements for the construction of drilling rigs and offshore platforms. The industry fully exploited the technical qualities of tubular structures, a prime reason being the ease of maintenance and effective protection from corrosion offered by the smooth surfaces of the large welded structures. Similarly, large steel nodal castings to accommodate the use of circular hollow sections were developed making the most efficient use of the material and having the least outside surface area. Later, similar castings stimulated the application of tubular structures in architecture.
By studying the structural principles of nature's flora and fauna, architects like Frei Otto investigated the possibilities of developments for the tensile type of lightweight structures. His early designs, pre-stressed or inflated, were composed of pre-stressed cable nets and cable reinforced membranes to create tensile zones, with circular tubes as compression masts and arches. The use of advanced technology is currently being used with success by architects who have designed some remarkable buildings, where the tubular structure forms an integral segment enhancing the visual expression of the building. In their designs they emphasize the structure of a building in its strength, grandeur and size. Their designs also reflect the image of a society dominated by a flexible functional use, once advocated by the Archigram group in the 1960s and by the requirements of industrialized production, but with each offering a personal and exciting interpretation.

1945 ATLAS AIRCRAFT HANGAR, KONRAD WACHSMANN, NEW YORK, USA

Post-war proposal consisting of a tubular space frame, supported by tubular truss columns, the structure had an impressive roof that cantilevered 50 m out over the airplanes. Designed at the end of the war, its development was immediately stopped after the peace agreement was signed. The hangar was conceived with self supporting transportable doors, which would form surrounding walls. The nodal points were complicated but ingenious interlocking end pieces fitting together in three dimensions to accommodate the angled members. This was the summit of industrialisation (universal nodes and high amounts of similar products) as designed by Konrad Wachsman.
He wrote his book 'Wendepunkt im Bauen' on the industrialisation of building products for construction and structures, in 1959 [Ref. 02.02].

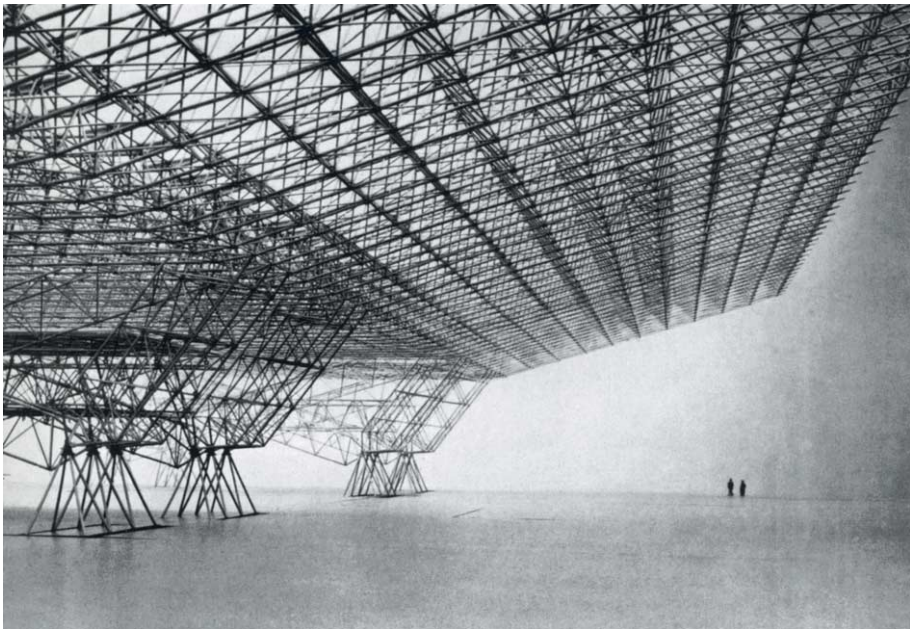

FIG. 23 Model of the Atlas Aircraft Hangar, Konrad Wachsmann, 1945

1964 VARIOUS PROJECTS, ARCHIGRAM, LONDON

Interchange City 1963, Under Water City 1964, Plug In City 1964, Walking City 1964 – rebellious conceptual designs for patterns of a future life. These compositions of technical components established freedom, mobility and flexibility as the reflection of an era. Archigram never had the opportunity to realize any of their schematic designs, but their ideas have been influential to generations of architects

1967 GEODESIC DOME, RICHARD BUCKMINSTER, FULLER, MONTREAL

In his life long quest to find geometric structural solutions for a variety of problems, one of the outcomes was a standardized dome system of nodes and tubular members, with infill sandwich or acrylic panels. His designs became the basis for many dome structures of our time. The dome has been welded, suffered from a great fire, but remained upright.

1969-72 OLYMPIC CABLE NET ROOFS, GÜNTHER BEHNISCH AND FREI OTTO, MUNICH

Cable net roof structures held up by circular hollow masts of different heights and diameters. This roof is a remarkable example of building engineering and experimentation in the field of cable net, membrane and tubular structures.

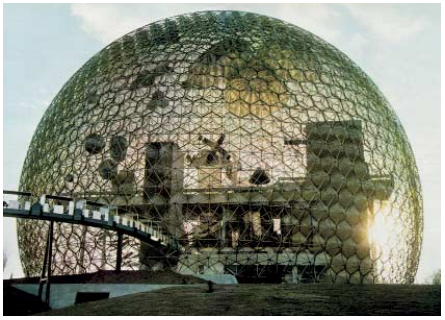

FIG. 24 The American pavilion in Montreal by Buckminster Fuller



FIG. 25 Cable net roofs at the Olympic Stadium in Munich

1970 FESTIVAL PLAZA EXPO 70, KENZO TANGE, OSAKA

A macro sized space frame (108 m x 291 m) on columns, composed of 10,5 m long tubular space frame components with a diameter of 600 mm and cast steel spheres of 1200 mm diameter with bolt connections. Four space-trussed columns with an inflatable air mattress roof supported the space frame.

1976 CENTRE POMPIDOU, RENZO PIANO AND RICHARD ROGERS, PARIS

The first major high-tech building located in an urban context had a major impact on the architectural world. It was constructed from a structural tubular steel skeleton cloaked with a glass envelope. Spun cast steel tube compression elements of 850 mm diameter, the 'gerberettes', were pin jointed to the columns with tension elements of 220 mm, solid round sections bolted to the ends of the gerberettes. The 3-metre deep main trusses had 45 metres between successive gerberettes. The stainless steel covering of the main trusses is a prime example of a functional and attractive material located on the outside of a building. The truss elements are jointed with smooth rounded cast joints and the vertical steel tubes are water filled for fire protection.



FIG. 26 Festival Plaza, Osaka

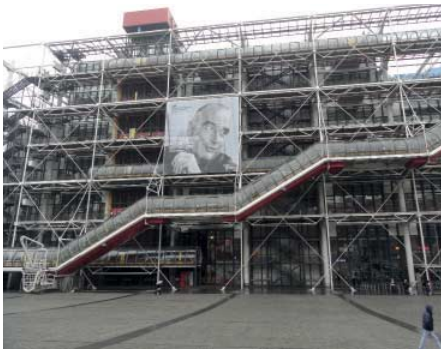

FIG. 27 Centre Pompidou, Piano & Rogers

1977 SAINSBURY CENTRE OF THE VISUAL ARTS, NORMAN FOSTER, EAST ANGLIA UNIVERSITY, NORWICH

The main structure is composed of 37 prefabricated fully welded trusses of tubular steel. Two cladding layers forming a uniform structural depth of 2,4 metres, creating a wall and roof zone to accommodate the various service functions, cover the building structure. The structure in its composition of triangular trusses is heavily over-designed for architectural reasons.

1979 STADIUM COVERING, MAGAS, SPLIT, CROATIA

These elegant roofs blending naturally with the design concept of the stadium and surrounding landscape are built up of two sickle shaped space frame curves with a span of 210 metres. Comprising 830 individual nodes and an even greater number of individual tubes from the Mero system, an early CAD program was used to produce the calculations and drawings for the structure. An early 'free form' canopy.



FIG. 28 Sainsbury Center of the Visual Arts, Norwich

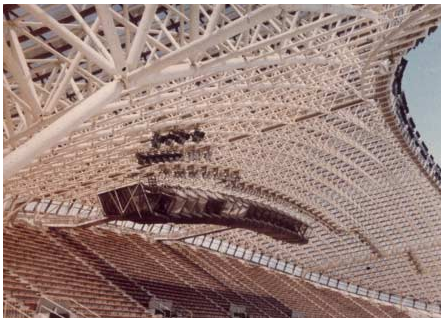

FIG. 29 Canopy roof of the Football stadium in Split

1980 CRYSTAL CATHEDRAL, PHILIP JOHNSON AND J. BURGEE, LOS ANGELES, USA

An irregular volume has been generated using three dimensional tubular space trusses combined with a reflective glass envelope to create an internal picture that produces a tangible and somewhat confusing impression. Probably the most extreme of all known space frame buildings.

1982 INMOS CENTRE, RICHARD ROGERS, GWENT, UK

The concept consists of a central circulation and service spine, 7,2 m wide and 1061 m long, functioning as an internal street. Conceived as a single storey steel structure composed from a kit of prefabricated parts, the tubular steel trusses are supported by tension rods from the spine towers, providing column free spaces for maximum flexibility. The structure is the message: we are flexible.

1984 SCHLUMBERGER LABORATORY, MICHAEL HOPKINS, CAMBRIDGE, UK

Two research wings are separated by a 24 m translucent fabric covered space, which accommodates the test station and winter garden. The superstructure is a steel frame with two different systems for enclosure; one for the large spans of the test station and winter garden, the other for the short spans of the research wings.

1986 HONG KONG AND SHANGHAI BANK, NORMAN FOSTER, HONG KONG

Although most of the internal tubular structure, with diameters up to 1200 mm, is covered with cladding panels the exposed structure, divided into five vertical zones, provides one of the most striking features of the building. Using a structural system derived from bridge construction, each zone is made up of a stack of lightweight steel and concrete floors that are suspended from exposed steel suspension trusses at double floor height intervals.

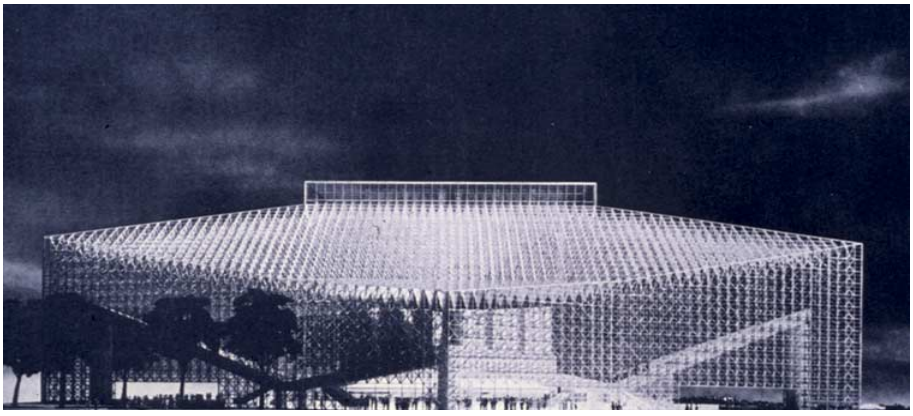

FIG. 30 Crystal Cathedral in Los Angeles



FIG. 31 Inmos Centre Gwent



FIG. 32 Schlumberger Laboratory in Cambridge



FIG. 33 Hong Kong and Shanghai Bank in Hong Kong

1990 PARC DE LA VILLETTE, BERNARD TSCHUMI, PARIS

An infrastructure of canopies, bridges and 'follies' at regular distances of 100 m in two directions dotted over the entire park. An example making extensive use of welded tubular space trusses and undulating tubular purlins onto which corrugated sheets are fixed thus taking up the undulating form. The structure displays an interesting balance with a systematic and stylized design incorporating an expression of individuality.

1990 SAINT JORDI SPORTS HALL, ARATA ISOZAKI, BARCELONA

The domed roof structure consists of a space frame erected with different parts hinged together which are pushed up into position during erection and locked into place by additional tubes to form a rigidly connected structure. The short construction time for a structure of this size proved highly beneficial.



FIG. 34 Pedestrian Bridge in Parc de la Villette in Paris



FIG. 35 Saint Jordi Sports Hall in Barcelona

1991 STANSTED AIRPORT TERMINAL BUILDING, NORMAN FOSTER

The design of the Stansted Airport Terminal building is overwhelmed by the spreading arms of the roof structure, which is based on 36 modules in tubular structure. The outside modules are standing trees of tubular structure, which keep up intermediate roof modules of the same size that are connected along their edges. The 4 spreading arms carry the perimeter of a tubular triangulated framework shell visible as a vaulted ceiling. During construction the 4 arms were held together by ties, which are connected in a very crucial joint, onsite called the 'Jesus joint'. The primary tubular structure module is concentrated on ground level of the terminal in 4 CHS columns, welded in a majestic framework, which penetrates the lower stories through voids. The roof structures are clad in metal, but the tops are covered in glass to obtain overhead daylight of the terminal space, softened by perforated metal sheeting. The large overhead volume gives the building the feeling of one unifying space with smaller areas of activities.

1991 AIRPORT PASSENGER TERMINAL STUTTGART, GERKAN, MARG & PARTNER

The sloped roof of this terminal building is supported by a forest of steel trees, which are composed of circular tubes in a tree-like arrangement of stems, thicker and thinner branches that finally hold up the roof. The structure is characterised by welded intermediate steel castings to make a streamlined and natural transition from the smaller tubes into the thicker tubes and finally into the lower stems.



FIG. 36 Stansted Airport, London



FIG. 37 Passenger Terminal, Stuttgart

02.04

CONTEMPORARY TUBULAR STEEL STRUCTURES IN ARCHITECTURE

1992 EL ALAMILLO BRIDGE, SEVILLE, CALATRAVA

The prominent harp-like suspension bridge by Santiago Calatrava was built for the Olympic Games of 1992 in Barcelona. The bridge was held up by 13 guy cables attached to the prominent and purpose-made steel tubular section. The actual counterbalance to the cables and loads from the deck and cables is formed by filling the steel mast with concrete. Mainly the upper half acts as counter ballast. Dutch architect Ben van Berkel would later (1996) design a similar cable bridge in Rotterdam, the Erasmus bridge or 'The Swan', which is more facetted in form, constructed from a purpose-made hollow section, and includes two major stabilising cable at the back for counter balance instead of deadweight.

1993 WATERLOO INTERNATIONAL TRAIN TERMINAL, LONDON, NICOLAS GRIMSHAW

The high speed train terminal near the centre of London was designed by Nicolas Grimshaw as a large urban shed and inaugurated in 1993. The form of the structure had to follow the rails, which, in London, partly follow historic paths and are quite condensed and unavoidably curved in plan. In cross section, the structure is a truss with three pins. The left truss has a suspended cladding, the other half an upper cladding. Cladding is in metal decking and glass. The form of the roof – circular in plan with a large radius and a cross section with many different corners – resulted in a construction system that was flexible in form to allow for all possible geometrical deviations. Recently, the Eurostar ceased to frequent Waterloo.



FIG. 38 El Alamillo Bridge, Seville

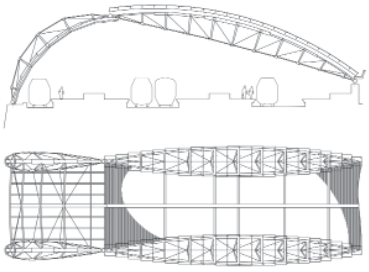

FIG. 39 Cross section of the Waterloo station, London

1994 KANZAI AIRPORT TERMINAL, OSAKA, RENZO PIANO, OVE ARUP

This airport in a densely populated urban area that was built on an artificial island, of which the underground was expected to deform considerably. This has been taken into account in the engineering plans of layout, schemes and details. The architect's plan for a long building and overviewable terminal volume resulted in a king-size hall where departure and arrivals are separated horizontally. The tubular steel structure in an elegant arched form hovers over the space. The structure itself has elegant details; some of which were made in cast steel and welded. The three-dimensional trusses govern the space; between them are ceiling membranes in a similar shape, which lead the flow of air through the volume. The details of the building have been set on rubber bearings. Other precautions were taken as compensations for earthquakes. The Kobe earthquake of 1995 did no damage at all and the terminal complex emerged unscathed.

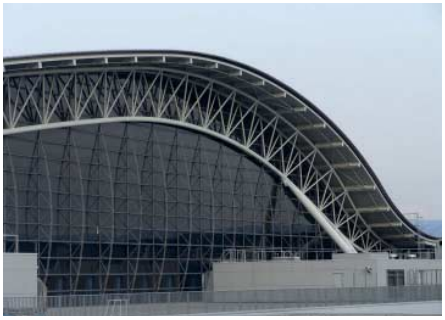

FIG. 40 Kanzai Airport, Osaka



FIG. 41 Interior

996 NEUE MESSE LEIPZIG, GERKAN MARG & PARTNER, IAN RITCHIE

A 90 metres span tubular structure in which the main trusses span in the 90 m span direction above the glass cladding below. The cladding is suspended via tubular purlins in 2 directions from which the spiders connect the laminated clear glass panels. The height of 30 m caused a natural airflow for ventilation like a chimney through space. Lower intake ventilation, upper ridge exhaust ventilation.

1998 LAW COURTS BORDEAUX, RICHARD ROGERS

A rather traditional set-up of trusses on columns with barrel-vaulted undulating roofs in between them, mainly in tubular structures; which, however, now is a complex late-modern building with stone covered lower floors in concrete and an upper volume in tubular steel enveloped with glass. Detailing is modern and state of the art. The conical space contains a court room. High-tech in an urban environment.



FIG. 42 Law Courts, Bordeaux



FIG. 43 Eden project, Nicolas Grimshaw

2000 EDEN PROJECT, NICOLAS GRIMSHAW

The covering of the Eden project in Bodelva, Cornwall UK, contains two large greenhouses accommodating public botanical gardens. The geometry of the domes is derived from regular polyhedra, intersecting in this case as giant soap bubbles. The space frames used are quite regular thanks to the pre-high-tech studies of late Richard Buckminster Fuller. The lengths of the space frame members vary around 4 to 5 metres. The cushions have a diameter of 4 to 9 metres. Cushions are made as triple layered ETFE cushions, with two air-inflated chambers.



FIG. 44 British Museum, Foster

2000 BRITISH MUSEUM ATRIUM ROOF, LONDON, NORMAN FOSTER

The inner courtyard of 92 m x 72 m with the elliptical, slightly asymmetrically positioned library. In this building Karl Marx wrote his famous book 'Das Kapital' as he could not afford a private writing place. This atrium covering has the form of a squared asymmetrical donut and has been designed, engineered and made onsite as a shell grid of a triangulated single skin space frame. Because of the visual flow of material elements and glass panels, the path was chosen for a strong but simple single layer of RHS square hollow sections. They were welded onto the RHS profiles onsite, after having been positioned exactly in situ by 3D surveying apparatus. Quite in contradiction to the development in the space frame world, this space frame was not regular or repetitive. That is the reason why all corners were snubbed off in a workshop off-site, coded and then positioned and clicked on in place. Only after the positioning of all tubes the welding could begin, which had to accommodate many distortions in the overall shell.

2000 MILLENNIUM DOME, LONDON, RICHARD ROGERS, BURO HAPPOLD

The Millennium Dome was a public project to show British awareness of the turn of the century. Like the Millennium Bridge it attracted a lot of attention. It became the world's largest tent structure. Prominent features are the tubular mast poles sticking out of the Teflon coated membrane fabric. Diameter of the dome is 365 metre. Long after the change of millennium the dome got another function: called the 02 dome after the sponsoring telecom company, it now serves as a temple for pop artists. Michael Jackson contracted 50 shows 'This is it' here, but passed away some weeks before the start.



FIG. 45 Millennium Dome/02 Dome, London



FIG. 46 Mediatheque Sendai, Japan

2001 MEDIATHEQUE SENDAI, MIYAGI, JAPAN, TOYO ITO

A five storey public building made of steel structures by a ship building company, with characteristic tubular columns, all in a different but outstanding form. Stairs and elevators are designed through these tubular circles of columns. This vertical traffic offers an unobstructed view of the different stories.

2004 FEDERATION SQUARE MELBOURNE, LAB ARCHITECTURE

An open environment on a well known place in the city amidst older 'heritage' buildings often causes tension amongst the public. It becomes a topic of intense debate. Such was the case with the 'Fed' Square. The entire assembly positions itself against the conservative parties. The theatre is the most outspoken part of those buildings in a fuzzy tubular network geometry with an even more complex glass covering. Fuzzy networks 'down under'. For the 2008 Olympic Games in Beijing, architects PTW Architects, CSCEC and Arup would design an indoor swimming pool stadium with a similar roof and façade system with 'fuzzy logic' in tubular structures covered with inflatable cushions.

2006 BARAJAS AIRPORT TERMINALS, MADRID, RICHARD ROGERS (MIKE DAVIES) / ANTONIO LAMELA

The new Barajas Terminals together form the international airport of Madrid, one of the largest in Europe and certainly one of the spacier airports to date. The construction consists of tapered tubular columns in changing colours indicating the gates, on concrete frames in a very smoothened design modus. The steel roof plane with bamboo ceiling undulates over the long double Y-stilts construction. The length of the terminals, the wideness, the gentle gestures of the columns and the changing colours of the stilts make these terminals almost a modern version of grand cathedral spaces and unique in the world. This 1.500 metre long sound barrier along the A2 near Utrecht, NL and 180 m long Hessing showroom for exclusive cars has a fluent free form design which blends in well with the sound barrier during the short time this building is seen from driving along the highway. The cross sectional shape changes over the entire length, is triangulated in a space frame and only the cockpit has a tubular space frame with clearly over-designed tubular members. Glazing follows the triangulation of the design grid.

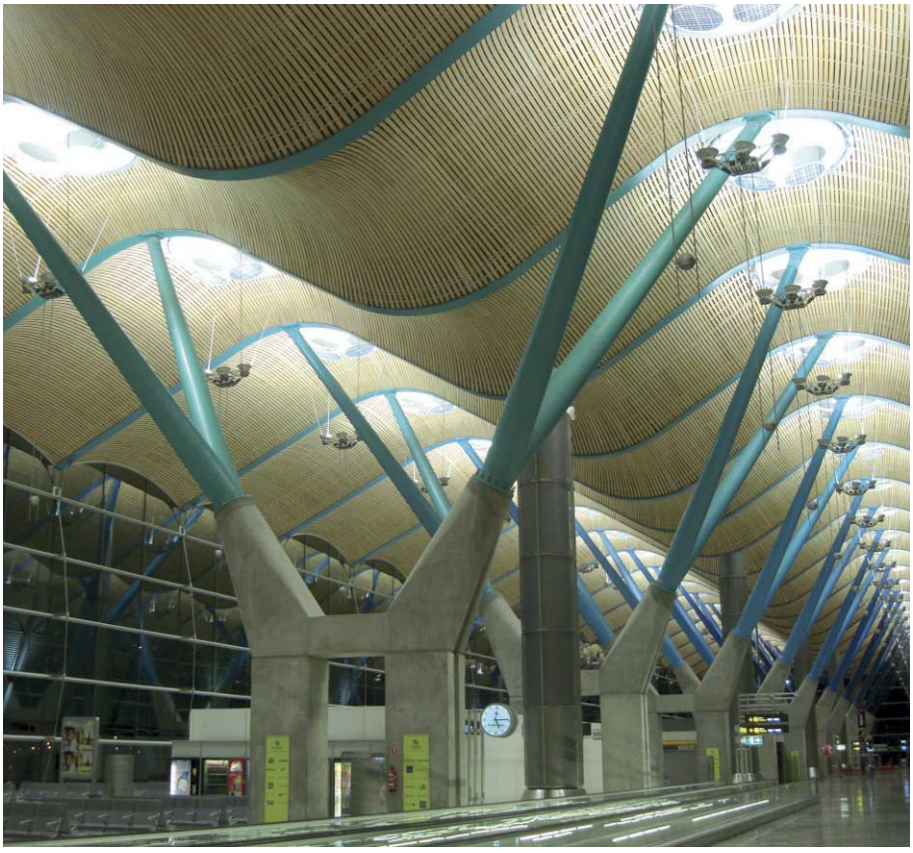

FIG. 47 Terminal 4 Barajas Airport, Madrid

2005 NATURAL HISTORY MUSEUM, LEEUWARDEN, NL, JELLE DE JONG

This museum of natural history was housed in a 17th/19th century building in the city centre and had to be covered to extend its museum collection and public meeting possibilities. After a design competition the architect created a design based on an experienced lightweight steel tubular grid, clad with insulated glass panels, stabilised by stainless steel rods from 4 long masts, penetrating trough the glass plane. The masts stabilise the roof plane upward for downward snow, deadweight and wind forces, and downward for upwind. The roof scheme is a table structure, independent form the existing buildings. The roof edges are designed on the top of the tiled roofs, but only a thin rubber flap is used as cover, no forces are allowed on the existing building, the edges all around have ventilating windows. The roof structure of the horizontal glass plane and the 4 prominent masted poles were accepted by the monument commission as an extreme structural state-of-the-art statement complementing the old buildings.



FIG. 48 Natural Museum, Leeuwarden, NL

2005 ALLIANZ STADIUM, MÜNCHEN, HERZOG + DE MEURON

This lightweight stadium is covered with EFTE cushions along all of its facades, illuminated in different colours: White for neutral football games, red when Bayern München plays and blue when 1860 München plays. The light is an integral message for the stadium that is often used in the darker hours of the day. The tubular structure of the football stadium functions as it should, serving the function of roof without attracting much attention.

2008 BIRD NEST INDOOR SPORT STADIUM, BEIJING, HERZOG + DE MEURON / OVE ARUP

The 'Bird Nest' stadium is the apotheosis of the use of tubular structures to date in the world. The geometry is no longer a result of structural optimisation in view of minimal use of material. The architectural concept of folded tubular elements (all of the tubes are purpose-made in rectangular and rhombic cross sections) was overruling, and the structural concept had to realise this architectural concept. As a result, it used 8 times more steel than an average stadium of the same size [Ref. 02.03], causing the world price for steel to skyrocket for a while elsewhere. The design was very outspoken, had the looks of a giant Chinese woven reed basket.

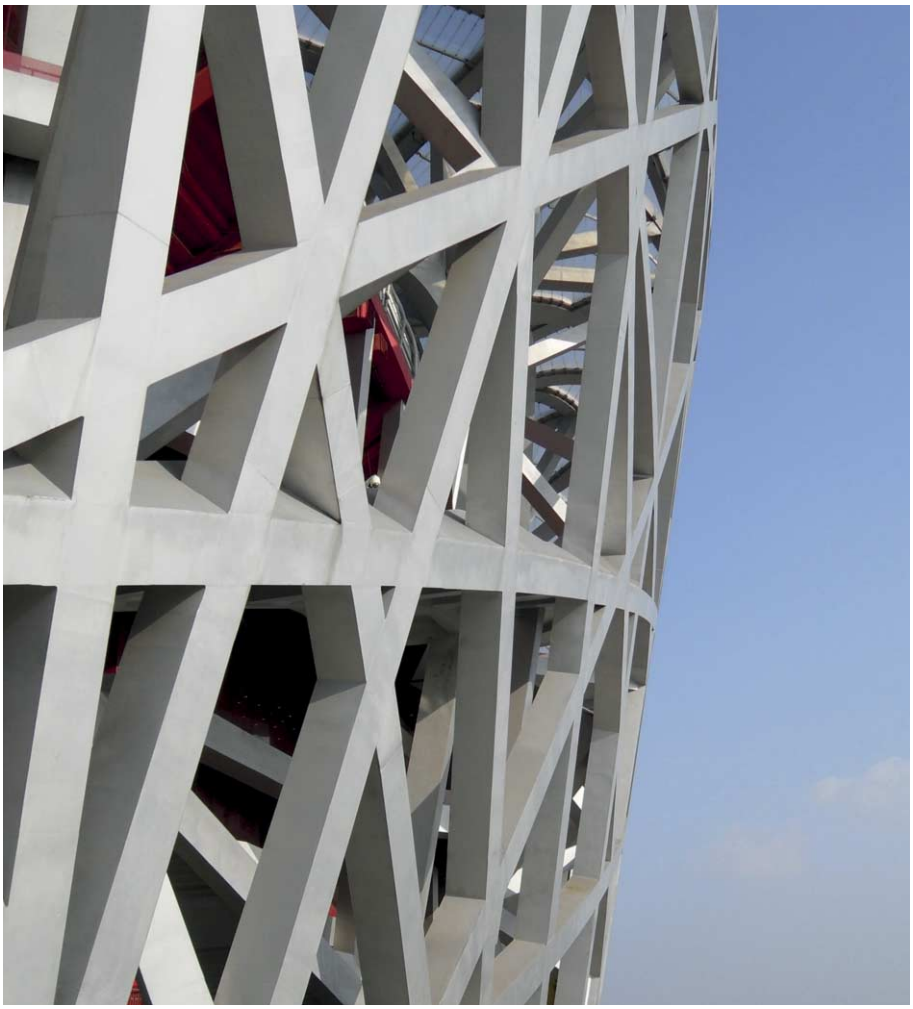

FIG. 49 Detail of the construction

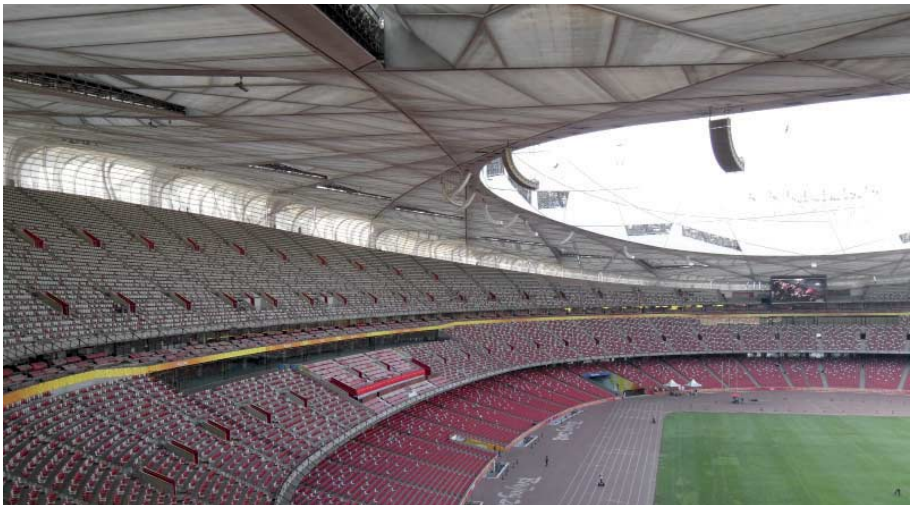

FIG. 50 Interior view of the stadium

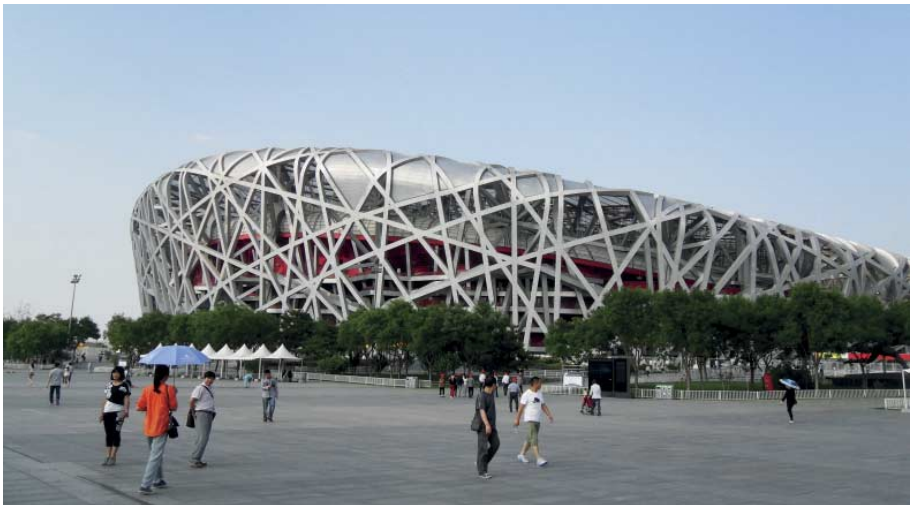

FIG. 51 Olympic Stadium, Beijing

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REF. 02.03 Massimo Majowicky

03 ON THE FUTURE OF SPATIAL STRUCTURES

Reflections at the closing of the fifth and last International Conference on Space Structures at the University of Guildford, Surrey, United Kingdom, August 2002 after receipt of the Pioneer's Award, published in the International Journal of Space Structures nr 2, 2003, page 129-136

03.01 INTRODUCTION

While attending this Fifth International Conference on Space Structures, and after receipt of the honorary 'Pioneer's Award' it came to my mind how this conference had shown an amalgam of standards by the various contributions and that the scope of space frames has long been established. Only the more profound and new interpretations are interesting; copies and engineering are of less interest. In the past hours, I have put my thoughts on the above matter to paper in the shape of a number of charts and diagrams. Based on these, I would like to share my thoughts on the future of spatial structures with you and, hopefully, this may bring about a discussion.

03.02 IS THE SCIENCE OF SPACE FRAMES A MATURE ONE?

The pioneers of space frames have all done their astonishing and spectacular work from the fifties up to the seventies of the last century. Worldwide acknowledged pioneers, i.e. Buckminster Fuller, Makowski, Mengeringhausen, Otto and Bird, surprised the world with their new types of structures. Since thirty years, which is one entire generation of professionals, no new types of structures have been added. Computers, though, have become faster and programmes became simpler. Nowadays, the average engineer is capable of analyzing a spatial structure by computer. The second generation of pioneers introduced a large number of stunning applications and refinements to the knowledge of the first pioneers' generation. They were the ones to sophisticate the already established

body of knowledge. Obviously, there is enough left to do for the third generation. The young researcher will always find a subject to accentuate his ingenuity. Tensegrity structures are not yet grown up and they are intellectual challenges, as much as moveable folding structures. In addition, the refinements are interesting. As long as one stays aware of the history and hierarchy of the pioneers, and not lapse into the mischief of making 'new discoveries' that, according to literature, were thought up and publicized already decades before. Furthermore, there is also a worldwide geographical spread of avant-garde, in need of reflection. This amalgam requires a close analysis, not just for the historical pioneer hierarchy (who stands upon whose shoulders?) but also for the various interesting layers of science and technology.

03.03 FOUR MAIN ARENAS

Every general conference on a particular subject has participants from various groups of professionals. It is interesting and confusing at the same time. This also goes for this conference on spatial structures. Each group may be compared with an arena, having its own players, its own conductors and its own rules of the game. The scientific debate in each of these four arenas has its own characteristics.

The different groups may be symbolized by 4 gear wheels that, each with their own speed, turn around and lock into any given cog. Thus, the gear wheel of Science can be distinguished, that of Technology, the wheel of Technical Systems and the one of Applications in Architecture.

These four gear wheels, each turning at their own speed, regularly make contact with the following and preceding wheels. An additional complication is that the arena of Applications is strongly controlled by clients with their finances and by architects with their designs of buildings. This wheel of Applications in Architecture can bring about unexpected influences when world economy is fluctuating and thus effects national economy. It can also happen that architects in a certain region lose interest in matured new technologies, of which the heroism and the adventure seems to be blown away, like sand in the wind.

So, in itself each wheel may represent a type of arena with players and rules. Therefore, it looks as if we have four different groups or four main types of arenas. Between Science and Technology lies fundamental (technical) research. Between Technology and Technical Systems lies technical system research & development. Between Technical Systems and Applications, there is application research & development. In reality, the number of wheels is much larger than the four main groups as described above. There are tens of (technical) Sciences, there are hundreds of Technologies, there may be thousands of Technical Systems and probably tens of thousands of Applications in Architecture. However, the point is that the nature of interest for each of the types of arenas is very different.

It is amazing that members representing different types of arenas sit next to one another at this conference. Looking at the variety in research & development, it is no surprise that the interest in each other's extremes only appears to be relative. Between the four types of arenas, an ongoing input towards application occurs: Science feeds Technology; Technology feeds Technical Systems, and Technical Systems feeds Applications in Architecture. However, there are feedbacks as well. For Applications, certain new Technical Systems are required, while others fall into disuse. When architects design in a fresh way (i.e. in the case of 'free form' architecture), new Technical Systems need to be developed. This is only possible if Technology will be developed in accordance, even up to the Science of, for instance, the 'pliability' of materials, where bent or twisted building components are concerned. But the different speeds give warning not to perform such a conversion or adding gear wheels in the short period of one single building project. It is better to bring into action the slower gear wheels of Science and Technology over a long-term development process, while in the short run only easy to accomplish transformations and innovations of familiar Technical Systems prove to be feasible.

03.04 INNOVATION

The four main types of arenas also show that the notion 'renewal' or *'innovation'* will not be welcomed with equal admiration everywhere. Scientific conferences are about progress in science, not about standstill or decline. There is a continuous quest for innovations and improvements of the existing body of knowledge. This innovation may be minuscule, small, medium, large or even extra large. Innovations are always of interest, because they are an aid to the efficiency in the personal atmosphere, particularly for competition. Small innovations are often not announced. In competitive marketing, however, small innovations are often exaggerated and are also undeservedly 'borrowed' or stolen. Some people are proud of their imitation behaviour. Imitation does not belong to a scientific conference. It may perhaps fit into an engineering congress that deals with applications.

However, a certain proportion of innovation can be interesting enough to be shown to a larger scientific audience. Companies keep certain innovations consciously on the shelf for years, in order not to transfer their advantages to the competition. In Science, openness of the entire discovery is common practice. Technology too, is the bundling of the collected scientific know-how, which cannot come about when lips are sealed. By contrast, Technical Systems are often surrounded with much secrecy: competitive interests are of great importance here and within companies, many protective patents are established. Besides, in the notion *'innovation'*, a decreasing series of newness has crept into common parlance. Something new may be considered as being pioneering and revealing *['absolutely new-new']*. One little step down, a product may be *new in more aspects*. One more step down, it may be *new in only one important aspect* as a

minimum. Innovation of an unimportant aspect does not count. Further down, it may only be *'renewed'*, an improvement of the existent, also in more aspects or at least one single aspect. Below, on the bottom step, is the category *'imitations'*: innovations which should be considered as personal improvements that, instead of contributing to advancing the state of technology, are prompted from considerations of self-interest. I follow this order of innovations in the teaching at my chair of Building Product Design at the Delft University of Technology, the Netherlands.

03.05 EARLY AND LATE DEVELOPERS

From marketing literature, it is known that a new technology has, in general, a widely varied audience of supporters. There is always a small group of avant-garde scientists and designers. After that, a group of early users follows, then an early majority, which is followed by a later majority and finally the dawdlers. This phenomenon seems to be so common that American researchers attach permanent percentages to these five groups of professionals. That would be pushing things too far here. But the message is that in every technology, such subdivisions can be made. Then why not in the technology of spatial structures as well! At this point, it would be sensible to mark the differences in interests, which may have to do with intellectual development, economical development and political development. The first conference, organised by Professor Makowski in 1966, had over a thousand participants. I assume that the majority of these came from the Western world. This current conference has a total of approximately two hundred participants and only a minority comes from the Western world. The number of early developers has decreased in favour of the number of late developers who, for that matter, have a very good reason for being 'late': usually a political economical reason. The transfer of technology from the early to the late developers is natural. At this point, I would like to refer to the recent book of the late Professor Ramaswamy and myself, written over a period of ten years of transferring technology from the Netherlands to India, from the West to the East [Ref. 03.01], a period we both enjoyed very much.

03.06 THE STRENGTHS AND WEAKNESSES OF STRONG PIONEERS

A small number of the early developers is formed by the true pioneers: the professionals who, despite disbelief and opposition, have acquired a view on the materializing of the specialisation and subsequently propagated this view by publications and building. The first

generation of pioneers was responsible for design and analysis, as well as for realizations. Generally, a second generation came along that could exceed the first generation in the sense of size and quality of the projects, but not in the sense of original newness. As a rule, the third generation has never communicated with the first and knows an ever-decreasing specialisation. Mutual understanding falls off and discussions falter. History must be taught to the fourth generation of pioneers, in order to prevent them from re-inventing the wheel of knowledge and publish this as their own invention. "Es ist nichts Neues, dass Wissen vergeht" or: *There is nothing new in knowledge getting lost"*, I heard Jörg Schlaich say in connection to this, at a conference at the Institute for Lightweight Structures in Stuttgart, 1988.

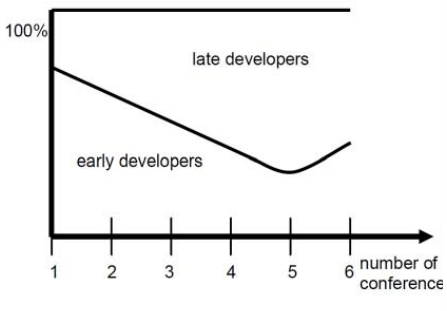

FIG. 52 Interest by professionals from different countries during the Space Frame Conferences

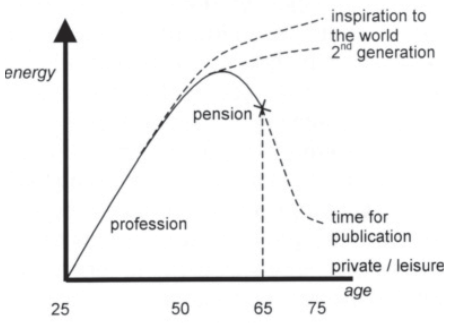

FIG. 53 Pioneers Graph

Back to the above mentioned first generation of pioneers. Their professional contribution to newness could very well be sketched into a diagram that resembles the stress-strain curve of steel, which will appeal to this audience. The steep starting curve represents the permanent ambition and success in the field of innovation, which will doubtlessly diminish by the end of the career to a horizontal line and will then gradually point downward. In the autumn of his life, the energetic pioneer may decide to go on publishing and lecturing (Zygmunt Makowski, Richard Buckminster Fuller, Frei Otto). He may decide to start playing golf (Helmut Eberlein) or wants to go sailing around the world (Mick Eekhout). He may see to the continuation of his success at the university or within the company (Max Mengeringhausen, Walter Bird). Anyhow, he will take care that the world can enjoy the results of his efforts. There are heroic examples of pioneers, whose tremendous inspiration and passion brought about a new development with great force, but after retirement from their professional life, this development would collapse with the same speed. This illustrates the power, ingenuity and pertinacity of the personality (Felix Candela, maybe also Heinz Isler). Shifting influences from economy play a role as well here, of course. Apparently, pioneers do not know the expression 'retirement'. They are super-animated people in their fields.

03.07 LAW OF DIMINISHING RETURNS

Together with the decreasing number of early developers, the innovation level seems to diminish as well, as does the interest from Western scientists. The common economical Law of Diminishing Returns claims that, with the maturing of a technology, each added research produces ever less newness, until the moment comes when, compared to the high investments, research will produce hardly any newness anymore. That will be the moment that we, as developers, must look for another horizon and another perspective, in order to make good use of our intelligence and energy. Then, a technology is considered to have passed the stage of adolescence and turned into the stage of maturity. In diagram *4*, the improvements that produced ongoing investments in a specialist field through the years, are curved. Efficiency goes downward, while costs go up. Strangely enough, usually the number of publications at scientific conferences and congresses increases goes up as well. However, this is only human and often has to do with the specific rewarding systems of universities. The key question I am trying to answer is: *"How will space structures go on, now that the specialist field has become clearly mature? What may we expect for the next conference in nine years?"* The energy for maintenance is far less than the energy impulse that was needed for growth. Besides all this, it is a compliment to all to observe that a specialisation has grown up!

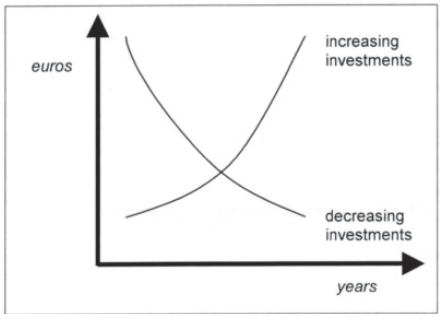

FIG. 54 Efficiency or Law of Diminishing Returns

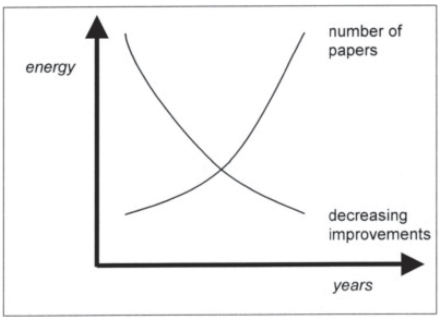

FIG. 55 Decreasing efficiency of scientific papers

03.08 PRODUCT LIFE CYCLE

In general, the life cycle of products in the science Product Development is regarded as a specific graphic curve, in which five typical phases can be recognized: Introduction, Growth, Maturity, Saturation and Obsolescence. In the introduction period, investments are made in an unknown future. After the acquisition of the first commission, the multiplications follow

with decreasing scientific profit, but an increasing economical efficiency and profitability. After maturity, too many 'me-too' competitors appear, and where the hogs are many, the wash is poor. Or, on the other hand, the interest from the market decreases until the moment has come to run down the product. The initial loss-making is also the outset investment. This is compensated in the life cycle by a higher financial profitability at a later stage. The scientific profit has a totally different curve: steep on the outset and going down from the stage of multiplications. Science as such is not served with the quantity of applications and economical profitability. Science and Applications (the commercial ones) are two extremes of our profession. These diagrams are commonly accepted in economy, and they also count in the fields of science of the various space structures.

03.09 SUCCESSION OF LIFE CYCLES

What to do if a life cycle begins to show a downward tendency? After the measures for playing along with the harsh game of standard building products 'high value for low money' have produced only a few positive results, there is nothing else left to do than taking a different initiative. Since my graduation as an architect in 1973, I have passed through a cycle of interests in my own professional career, going from architecture, stressed membrane structures, space frames, domes & barrel vault structures, tensegrity structures, glass structures and for a few years now, 'free form' architectural technology. That makes a total of eight cycles of characteristic products in approximately thirty years. I have always written many articles, but since my thesis in 1989, I wrote some ten books on a diversity of technical subjects. The focus was on the ascending curve, the intellectual challenge, set down as 'scientific results', according to the judgement of others. The continuous investment in research and development during these quests for newness was always funded by the profitability of mature products. As long as there is a balance between intellectual research and financial coverings, the pioneer is in high spirits. Companies invest parts of their profits in investments to remain existent in the future, by means of new product life cycles.

03.10 LIFE CYCLES OF SPACE STRUCTURE

Each type of space structure has a certain life cycle. Nothing is forever. These cycles can be distinguished by country and their totality can be added up to make a world sum. The average world consumption contains the extremes of the early developers, as well as the late developers. An example: the shell structures were developed in the Spanish-speaking countries with a strict Roman Catholic tradition with regard to joyous designs:

Spain had Eduardo Torroja and Mexico had Felix Candela. Subsequently, shell structures became popular in countries with a low economical level, because the labour there was cheaper in relation to the materials. Shells are still popular in countries where there is hardly any steel on hand, i.e. India. Ramaswamy has designed many brick shells with a minimum of steel reinforcement. Yet, in the Western world with its tendency to Modernism in architecture, from the sixties on, there was hardly any space for shells. In Switzerland, Heinz Isler prolonged the life of shells by strongly reducing the problem of local labour with clever wooden formwork techniques. Due to the free form architecture in the luxurious world of artistic architect-designers, shells are currently returning, but indeed in absolutely random 'free form'.

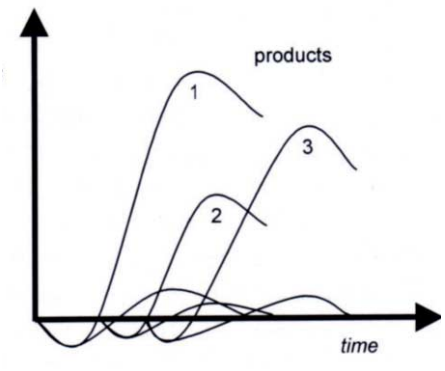

FIG. 56 Sequence of Product Life Cycles

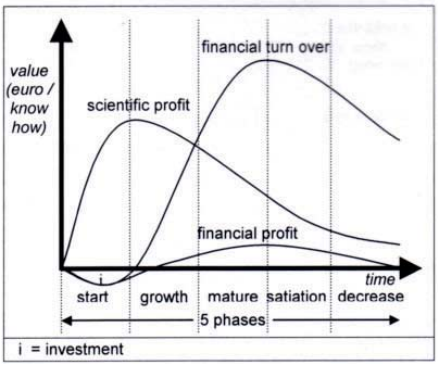

FIG. 57 Typical Product Life Cycle

Space frames, designed and realized for the first time in 1907 by the then already elderly Alexander Graham Bell, the inventor of the telephone, were only systematically discovered and developed by Max Mengeringhausen from 1942 on, and recognized by the world as architecturally acceptable building technical systems in the sixties. The world was enraptured by the thought of the flexibility that space frames were going to add to the use of buildings. Archigram sketched the dreams in the sixties and Renzo Piano & Richard Rogers realized these dreams in the Centre Pompidou, Paris, in 1973. For large free spans, exquisite design came about, combining plate action with shell action. Almost all of the current large-scaled space frames make use of shell action by their curved shapes. Mero's adage that bars should be interchangeable and therefore ready for delivery in only one ascending 2 size series, has become history long since. Nowadays, space frames are purpose-made for the project, with specific project joints and bars with many differing lengths and diameters. Prof. Kawaguchi showed us his ingenious multi-hinged assembly method, by which high roofs can be built without too much scaffolding.But from the Western world, the splendour that surrounded spatial frames has disappeared. Both Mero and Octatube, and even Space Decks sell ever less standard space frames. This has everything to do with the slow, but steady turn in the consumer industry, which also affected the building industry and changed it completely. It was the change from producer-

directed into consumer-directed thinking and approach, for the benefit of the latter. In our building trade, the wishes and demands of the consumer (read: 'the architect') become more and more frequently dominant. This caused producers of standard space frame structures to increasingly manifest themselves as specialist producers of all sorts of 3D project structures that are requested from the market by architects. With Octatube in the lead, Mero followed and even Space Decks changed its attitude. Obviously, in the countries of late developers, this trend will be followed later in time. Since the nineties, architects in Western Europe had hardly any interest in space frame structures. So finally we come to the overall chart. Figure 58 is not to scale. It was composed from my current insight and background information and it shows the curves of, respectively, shells, space frames, membranes (the climax being Frei Otto in the sixties and seventies of the last century), tensegrity structures (to please Motro) and finally the rapid rise of 'free form' architecture. The latter requires a mobilization because of its shape, and integration of designing and building in shells, membranes, space frames and tensegrities up to the ultimately invented, strongly shape-manipulated 'free form' architectural designs. The experiments in the field of deformable structures, still waiting for technical maturity and prototyping after the far too early decease of Piñero in 1969, have not yet been included. Both tensegrity and deformable structures are simultaneous challenges to the intellect and the Law of Diminishing Returns, but are still in the adolescence phase of the life cycle. Ever increasing technology, bringing along ever less added returns and ever increasing costs. Besides, both technologies huddle up to mechanical engineering, rather than civil engineering. Each chart has a pioneer-bound outset of the diagram and an average world-wide consumption, distinguished by a different use by the early developers (decreasing) and the late developers (increasing).

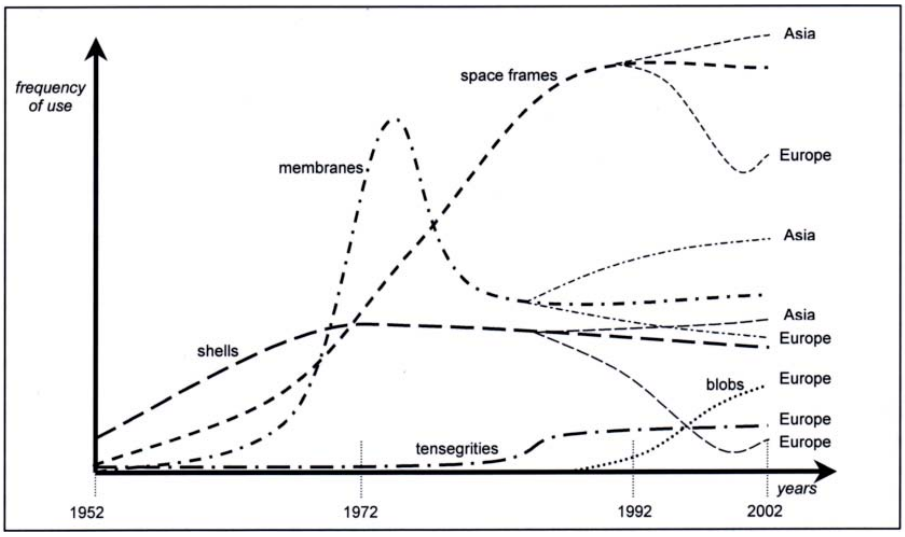

FIG. 58 Rise and Fall of Space Structures

In general, the majority of the application of space frames currently takes place in the countries of the late developers. In addition, the early developers are ready for the combination of forces from the various fields (even though these have been strongly neglected in the past years) to the new identity of the free form building technology. To a certain extent, free form designs may be compared to the evolution of the 15th century Renaissance to the 16th century refined Baroque and finally to the degeneration of the 18th century Rococo. Time will tell whether 'free form' architecture should be considered like Baroque as the intensifying of the Renaissance, or an affectedly manipulation like the Rococo style. It is absolutely certain that after the obedient period of straightforward designing of space structures, the manipulation of the first decades strove to arouse some amazement. The creativity of designers looked everywhere for a way out. In this respect, even in the design of the stadium of Kenzo Tange in Singapore one cannot deny a degree of manipulation, comparable to the Rococo style, since its design makes a mockery of all the laws of space frame structures. After all, it has the shape of a tent, realized as a space frame of which the two internal posts have been removed. Illogic follows logic, then again to be followed by a new logic. Or, as is known from the field of psychology: after the Thesis follows the Antithesis, which is followed by the Synthesis. We shall have to wait and see if, after the complex 'digital Baroque' and the affectedly 'digital Rococo', a period of neo-styles will dawn, or maybe a new Modernism?

03.11 CONCLUSIONS

1. The framework of the science of space structures was set up by the pioneers of the first generation, and globally interpreted with many applications by the second generation. Currently, it is refined by the third generation. Ever-smaller improvements require ever more energy.
2. In Western Europe, architects have globally turned away from the various straightforward types of space structures as they were developed by the pioneers of the first and second generation, because of the loss of splendour of newness and heroism. They look for combinations.
3. In the rest of the world, uncountable space structures are built, rather from application-directed engineering, than for the sake of scientific newness.
4. Only tensegrity structures, foldable structures and 'free form' architectural technology may delight in the intellectual interest of avant-garde designers and scientists. Practical applications still seem scarce.
5. From the experiences, acquired over the last years by architects who work in the relatively thriving sector of utility building, the current use of computer programs at architectural firms seems irreversible. There is no way back! The ease with which architects conjure up complex shapes of buildings and their layouts on their computer and win design contests, is an indication of the total revolution of the spirit of the times. Architects work on computers and are capable of getting away and winning competitions with the designing of buildings with a growing complexity.

6 Structural designers have to anticipate to answer architects with surprising structural solutions for free form designs.

7 The shapes of free form buildings are so complex that all the familiar and forgotten know-how has to be recalled. Therefore, mobilize all sleeping and active knowledge on 3D structural technologies!

8 For free form structures, only combinations of the formerly separately developed various types of space structures can offer a solution. Combine and integrate 3D structural technologies!

9 Since cladding becomes just as important as structure: develop multi-material design solutions on both the cladding and the structural level, where every material has its function and is designed in an integrated way.

10 As for the younger generation: study the literature of the first pioneers!

11 Make use of the current body of knowledge!

12 Honour the inventors and pioneers and stand upon their shoulders!

If we activate and combine the acquisitions of the past in this way, we can transfer the free form architectural designs into material and realize them in an intelligent way, too. We will then have bridged the classical field of knowledge of space structures and the rebellious sculptural manipulation urge of the free form designing architects!

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04 'ZAPPI' OR RESEARCH IN THE STRUCTURAL USE OF GLASS

Lecture originally given for Architecture Association in Cape Town, South Africa, September 2009

04.01 INTRODUCTION

'Zappi' was introduced in 1992 [Ref. 04.01] as the yet unknown, fully transparent, structurally reliable material for safe structural design in architecture. I have worked on this topic at the Chair of Product Development with staff and students. It started in 1988 with the research on the structural design of glass, initiated by the graduation project of civil engineering student Rik Grashoff. Since roughly that time I designed in my design & build company a stream of experimental glass structures. My engineers did material research on glass, detail research on the connection of glass and steel structures and new structural designs like the diagonal tensile 'tensegrity' arrangement, the fish bone structure and the pre-stressed 'tensegrity' truss. In 1995, gluing glass panels onto a steel structure was realized with the aid of the Delft Gluing Institute at the Faculty of Aeronautics. In 2002 the aluminium space frame for the aluminium centre in Houten NL was realized thanks to the assistance of friends from the former Fokker company: Sergem of Ypenburg. They took care of the gluing of aluminium end pieces to aluminium tubes. In the meantime staff member Dr. Fred Veer supervised students on Zappi, amongst whom Joost Pastunnik. It was this student who discovered that a 400 mm high, 40 mm diameter tube of laminated glass could withstand 11.000 kg before it broke, enough to carry the deadweight and life load on a roof of 10 m x 10 m. The idea was 'borrowed' by Schott and built in the form of glass compression tubes in a Foster building in London. Over the last two years Zappi gained in reputation in the research portfolio of the Department of Building Technology. It became the nickname for all new materials and technologies in the building industry, as the scope was widened from structural glass only to cardboard, brick, aluminium and glass fibre reinforced resins.

In 2001, Karel Vollers completed his dissertation 'Twist & Build' [Ref. 04.02], comprising simultaneous studies in urban design, architecture, building technology, production

design and material research. It all related to twisted building facades. This dissertation was a prime example of 'design by research'. In the mean time the topic of fluid building designs in architecture, also called 'Blob' designs, came into the picture not only in the international architectural magazines but also in real projects at Octatube. The gap between dreaming architects with new digital skills on one side and the building industry with its traditional orthogonal building systems and materials on the other opened progressively. The department of building technology realized it had to start to close the gap by inventing new technologies to realize these 'fluid' designs. Up to then the building industry saw them as 'fluid design nightmares'. We could start with technology transfer from the nautical and aeronautical engineering industries, where fluid forms have always been very functional. Fluid designs in architecture primarily result from a change in fashion of design, provoked by the possibilities of the new 3D computer design programs. Thus, the 'Blob' research group was established with staff members, PhD students and graduates around the many building technical subjects on the realization of Blob designs. This lecture displays the different Zappi techniques that have been developed in the different design, development and research processes, and particularly for the architectural Blob designs of late. The listing contains a mixture of realistic short-term design & development projects I supervised in the company, and the medium/long term research & developments undertaken in the department of building technology. All to give you a picture of simultaneous research, development & design.

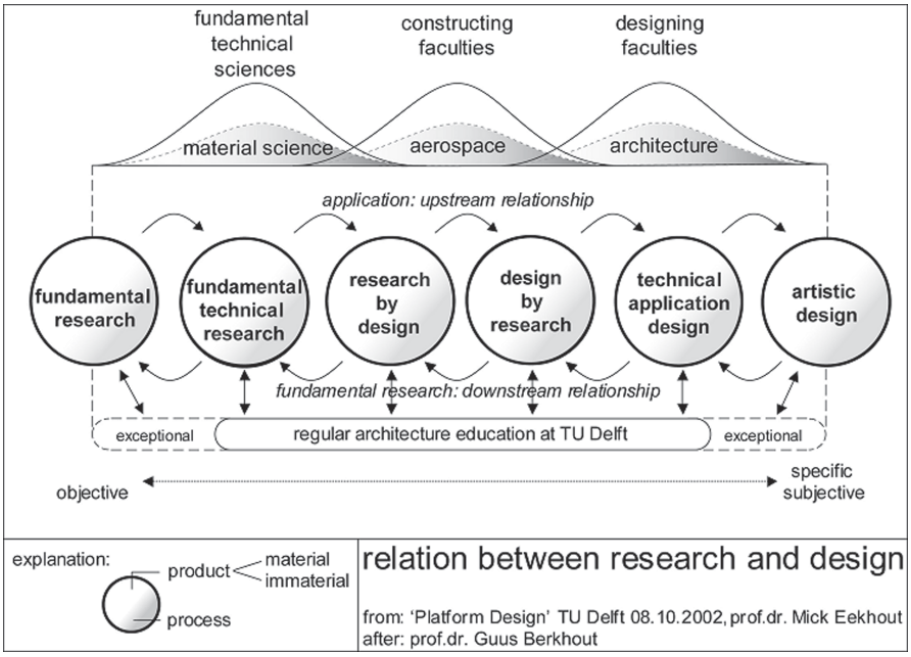

FIG. 59 The relationship between Research and Design; Fundamentals and Applications

04.02 RELATIONSHIP BETWEEN FUNDAMENTAL RESEARCH & APPLICATION DESIGN

For the Design Platform of the TU Delft a scheme was proposed, inspired by the graphs of Prof. Dr. Guus Berkhout [Ref. 04.03] displaying the connections between the two extremes of Fundamental Research and Application Design. This figure indicates that the intermediate domains of Fundamental Technical Research, Research by Design, Design by Research, and Technical Application Design (= Architecture) all have a mutual relationship with their neighbouring domains with fundamental on the left side and application on the right. Each domain, like an arena, has its own laws, set of rules, habits, its own players. In general, there is admiration for the fundamental brothers on the left hand side and condescending looks toward the application side. Architecture, as it is, has been built for millenniums, fulfilling one of the basic needs of society. The first book on architecture, *'De Architectura'* by Roman architect/writer Vitruvius was written in 15 BC, and was re-discovered, illustrated and re-edited by Alberti in 1472 AC, just 1500 years later. Vitruvius was not a great architect himself, but wrote about the Greek and Roman architectural rules and building technology of temples and houses. His famous '*Firmitas, Utilitas, Venustas'* still inspires us today as 'Technology, Functionality and Form'.

04.03 ARCHITECTURE AND NEW MATERIALS

The primary needs of society have always been fulfilled with contemporary technical means of the time. Vitruvius used natural stone and bricks. These materials have dominated architecture for at least 1800 years. One of the most important current primary building materials, reinforced concrete, is already 100 years old and quite mature as a construction material. Research in reinforced concrete, like many other materials, suffers from the economical 'Law of Diminishing Returns'. We have to invest ever more energy to gain ever smaller gains. Why would an architect bother about new materials? Concrete is quite satisfactory as a basic material. Young architects think that reinforced concrete is also quite boring. It has lost its material expression. It no longer seems sexy, no longer attractive to use. In architecture, a generational change is occurring that we cannot neglect. The young generation of abstractly educated architects, who tend more towards artistic design than to functional, technical and economical harmony in their architectural design, looks at materials as a library from which they can afford to make a selection to suit their artistic design. The economical situation in The Netherlands does not stop them. The intellectual climate does not stop them. This is one of the reasons why we have to concern ourselves with new materials. At the faculty we cannot do this alone, we need transfers of technology from nautical and aeronautical sciences. Networks such as the TU Delft Materials Science & Engineering Platform inspire us on the fundamental side. We, in

turn, can cater to the application side. We feel very stimulated in the TU Delft environment with so many colleagues from different sciences influencing our material selections: the Delft network. I would call this Materials Science & Engineering Platform a *'Bond of Brothers'*, as Horatio Nelson put it 200 years ago. Over the last century, an increasing impact has been made by the urban planning of architecture, the politics behind it, by economics but also by sociology and psychology and the dynamics in society. Architecture therefore is a multi-facetted sport and one that is not easy to determine with scientific eyes. Complexity of the design problem overwhelms each architect. Hence the art of architectural design is making an accurate analysis of all problems at hand, and proposing an acceptable compromise with enough surprise and obstinacy in its design, but also beauty, adventure, and harmony with the environment of the building, so that the urban environment around the building has a satisfactory character as well.

04.04 DESIGN, ENGINEERING, SCIENCE

Going back to the relationship between design and research one could comment that most of current architecture is in fact not much of a science, but rather engineering: working out patterns and programs that have previously been invented, experimented with, evaluated in times of endeavour. I have to admit that most of contemporary architecture does not have the capital 'A' of 'Architecture', but is the result of architectural engineering. And hence is not worth to be called a science. But then, most of civil engineering is engineering after all and not much of a science either? We all know that a great part of our work is 'engineering'; only a smaller part can be called 'science'. This reasoning leads to the conclusion that mainly new and experimental architecture needs science in order to be developed and be interesting in a scientific way. I combine architectural and technical design with experimentation and trying to find newness in many different aspects and on different levels. There is ample experimental architectural design that is worth being called 'scientific design', linking the Technical Application Design from figure 59 in communication with Fundamental Technical Research if need be. The disdain of fundamental scientists toward applications and architecture is misplaced as Design of Applications is tunnelling Fundamental Research to society.

04.05 STRUCTURAL USE OF GLASS

The structural use of glass was one of the topics of my work as a scientific designer during the last 15 years of designing, research & development. I have called this quest to unveil and develop ever newer possibilities of using glass as structural components in

architectural engineering for the end goal of a structural transparent and unbreakable material and elements and components made of this material: *the quest for Zappi*.
The origin of this quest was the question of the late professor Dick Dicke (1924-2003), my static analysis professor at TU Delft, who asked me during my promotion session in 1989 [Ref. 04.01] to describe the ideal transparent structural material. As a professor for 4th year students he proposed to design a structure with an imaginary material 'X' having a confusing set of characteristics, derived from those of the well-known materials. In his opinion one could even use 'gingerbread' as a structural material as long as one knew its properties and could design a structure with regards to these properties. Some 30 years later, in 2002/2003 I have indeed developed a cardboard dome of 28 m span after the design of the Japanese architect Shigeru Ban, taking this 'gingerbread' principle as a guideline. The quest for Zappi was officially announced in the inaugural speech in 1992 [Ref. 04.05]. In line with our management and marketing dominated times Zappi had a name before it had designer properties and a firm material identity. The marketing worked so well that even one year after publication, Ashai Glass from Japan sent scouts to get information on the progress of our Zappi research. In 2001 the Zappi research project was complemented by the '*Blob designing & research*' project, which indicates a field of research of fluid design buildings and more applications of special building components with specific 3D forms, fitting in the total composition of a Blob building. These Blob designs directly relate to the new 3D design programs of a select group of avant-garde Blob architects and designers. They originate from the introduction and use of new computer presentation and design programs such as Maya, Rhino, 3D Studio Max and so on. Within a few hours a skilled computer designer can generate such complex building shapes that the collective engineers of the building team have years of work on their hands. Understandably, these 3D programs widen the gap between the ambitions and wishes of the architects and the capacities of the largely 2D producing building industry. The growing gap between these 3D design programs on the one side and the customary mechanical engineering programs on the other, plus the usual, certified production technologies has to be bridged. This is the main goal of the Blob research group at TU Delft under my supervision, consisting of post-doc Karel Vollers, 3 PhD students (Martijn Veltkamp, Bige Tunçer and Tuba Kocaturk) and some 10 Master students in Building Technology.

I have started the quest for Zappi with the development of my structural glass projects at Octatube from 1988 onwards. Because of the limited resources at Octatube and also later at the Chair of Product Development, the only approach I could follow in both environments was typically an incremental approach: as Renzo Piano said "step by step". Over the years it has shown to be a slow, but continuous process, stepped up by the 3 basic attitudes and beliefs I have developed in the company [information www.octatube.nl]:

1 Continuous development of new building products and systems;
2 Synergy of architectural, structural and industrial designing;
3 Integration of designing, production and realization.

The Chair of Product Development engages in developing new building products, mainly with new and lightweight materials: standard products, building systems and special

building components are developed, both in methodology, marketing, material science, production technology and in innovative applications of building technology in architecture. Similar subjects are dealt with in teaching and in research. The Bachelor students are informed and sometimes respond with new ideas. The Master students and PhD students in turn play a role in upgrading the state-of-the-art of building technology. The chair has a small staff and my engagement in the chair is only 2 days per week, including the usual and overwhelming administrative tasks that hardly lead to worthwhile organizational innovations. Innovation is the new topic everywhere, it seems. Even architects speak about innovation, but they confuse 'innovation by composition' with my 'innovation by invention'. The practical design & development projects and issues of my company design office are usually directed at short and medium term, although in dialogue with avant-garde technical architects in the Netherlands we are typically amongst the first to pick up a tendency in design and to prepare the material solutions for it. This was the case in space frames in the late 1970s and frameless glazing in the late 1980s. During the last 5 years, however, we have turned toward the subject of designing building components for Blob designs and became heavily involved in developing 3D structures and 3D claddings, like the GRP stressed skin structures on foam cores for large free spans up to 30m.

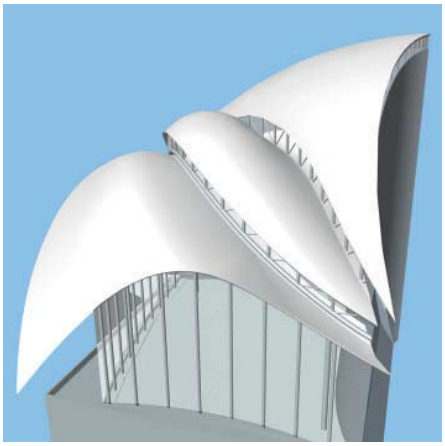

FIG. 60 The Great Hall of the Rabin Center, Tel Aviv



FIG. 61 GRP stressed skin mock-up for the roof

Some of these application directed design & development projects in turn trigger more theoretical research & development items, to be performed by my engineers. More universal topics are excellent projects to be worked on by my students with their own slower pace with deeper results in a more fundamental approach. The practice of the company design office illustrates and provokes the academic world, while at the same time the application world offers a wealth of possibilities for each graduation student to incorporate at least a practical project in their final Master study. The quest for 'Zappi' and the Blob Designing and Research Group have produced new knowledge, abilities and insight, spread over different aspects, which will be explained in the following text in more detail.

04.06 BENDING AND NORMAL FORCES IN THE GLASS PANELS

Glass panels in facades are usually stressed by horizontal wind and bending loads. Roof glazing is subject to bending loads from snow. Structural glazing refers to an unusual structural use of glass beyond the usual bending. In the 1970s it was the full chemical edge sealant which was unusual, hence: 'structural glazing' is silicone glued glazing: the aluminium profiles are bonded to the glass panels by silicone. One step further was published by the 'Serres of the Citée du Science et de l'Industrie' of La Villette, Paris, designed by RFR and completed in 1986: its glass panels were suspended and loaded by the lower panels: hence these panels carry tension and bending loads. This structure lacks the deadweight suspenders. Vertical deadweight forces were transferred to the upper steel tubes above each row of 4 panels by the glass panels themselves. Wind forces were transferred by horizontal pre-stressed stainless steel cable trusses, using typical H-formed stainless steel connectors. This project highlighted a promising way of developments. The price of this frameless glass façade was much higher than the average price affordable in the Dutch architectural scene. So a more economical alternative had to be developed.

In 1988, civil engineering student Rik Grashoff developed in the Octatube office a system of combining 9 square glass panels of 2 m x 2 m to act as one big glass panel of 6 m x 6 m by means of bolted and pre-stressed connectors and cables, which was the start of the in-house developments at Octatube toward the goal of structural glass facades and roofs.

From there on the next steps were developing structural systems with bending plus compression in the glass panels, then bending plus shear forces and recently bending plus torsion. The first application of tensile loaded glass panels was the Glass Music Hall in the Exchange of Berlage (1903), inaugurated in 1990, illustrated with a book 'Product Development in Glass Structures' [Ref. 04.06]. Size of this glass hall: 9/13 m wide, 9 m high and 22m long. The glass facades were suspended from the roof, 5 panels of 1,8 m high. The glass panels were made of 8 mm thin fully tempered glass. The stabilization was done by super slender steel tensile trusses of 10 mm thick solid rods. These slender dimensions were achieved due to the internal position of the glass hall as the first application of a new system; without wind loads, snow loads on the roof and water tightness problems due to heavy rainfall that would occur in an outside situation. The wind pressure calculated for was only 30N/m^2. The stabilization system and the panels loaded on tension were already experimental enough. Architect of the renovation of the Berlage Exchange, of which the Glass Hall was only a smaller part, was Pieter Zaanen. He foresaw a completely independent glass volume, as the acoustical envelope for concerts for 200 visitors and rehearsals for a 20 men chamber music orchestra. The 8mm thin glass proved to be exactly the required acoustical reduction of 25 dB needed. Acoustical advisor was Rob Metkemeier of Peutz Associés. Despite the hard reflection surfaces of the glass, the internal acoustics were designed successfully thanks to metal perforated absorbing components suspended on the inside and the acrylic domes in the ceiling.



FIG. 62 Serres of La Villette in Paris



FIG. 63 First Structural prototype of frameless glass Octatube.



FIG. 64 Detail of the frameless glazing



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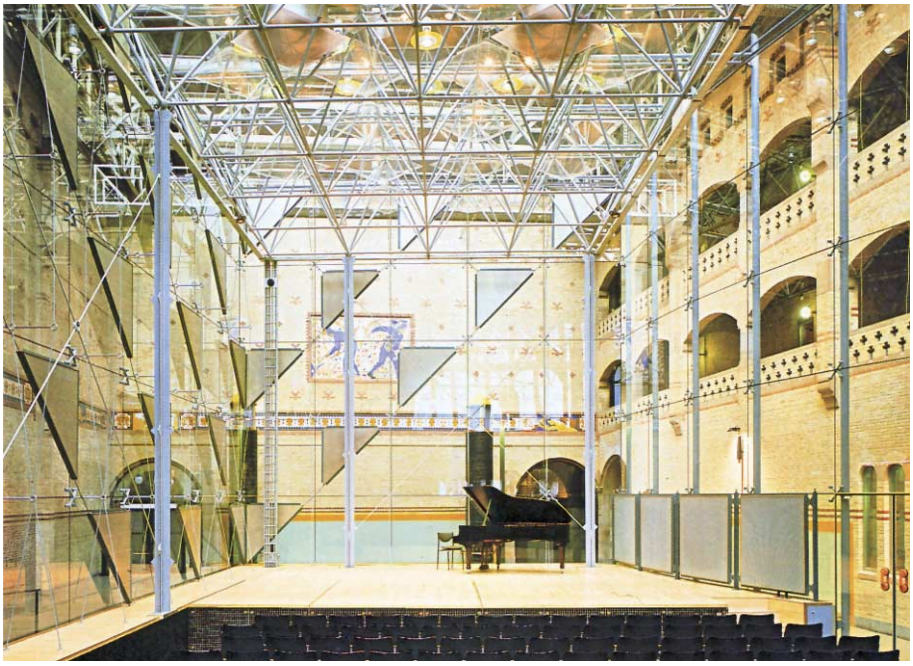

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FIG. 65 Glass Music Hall in the Beurs van Berlage in Amsterdam

BENDING AND COMPRESSION IN GLASS PANELS

The canopy of the Evoluon in Eindhoven NL was an experiment in compressed glass panels, post-stressed by a tensile rod system from 1995. Architect was Gert Grosveld (Philips Architecture office, Eindhoven). The canopy, sized 10 m x 10 m, is composed of 25 panels, each 2 m x 2 m, some are cut on their diagonal to form the 4 drainage ridges in the roof. The main steel tubular structure resembles a tree, with cantilevering stem and branches, from which the outer glass panels are cantilevering, stabilized by tensile spokes downward and upward. These tensile spokes introduce enough pre-tension to generate compression as normal forces in the glass panels. The glass panels were made of monolithic 10 mm fully tempered glass, grey tinted. A later thought was to have 2 panels of 5 mm or 6 mm laminated, as this would increase safety in case of glass breakage. But economics would not allow it. Fully tempered glass explodes, for example, after sudden breakage from nickel sulphite inclusions. Particles fly as far 10 to 20 m distance. In case of the Eindhoven canopy, the falling height was only 5 m, so this risk was considered acceptable at the time. It was only later that in Germany laminated heat strengthened glass (TVG) became obligatory for overhead glazing. After a recently closed dispute following 5 collapses of glass panels, the monolithic overhead glazing in the Waterloo Station in London, designed in 1992, engineered in 1993 and realized in 1994, was to be replaced by laminated and heat strengthened glass panels



FIG. 66 The Canopy of the Evoluon in Eindhoven

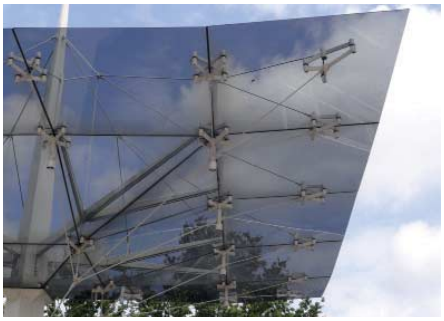

FIG. 67 Detail of the Canopy

BENDING, COMPRESSION AND TENSION FORCES IN GLASS PANELS

PhD student Jan Wurm from RHTW Aachen designed, engineered and built as a research fellow at TU Delft a prototype of an all-glass dome in 2002. He worked with five Building Technology students on a frameless glass dome without steel structure or external/internal nodes in a shallow silhouette of 20 m span. The detailing was the main point of study. The prototype model was made on a scale of 1 to 5. The connections between the glass panels were made in metal between the joints for the mock-up and the design detail for the full size dome. The detail connection would be primarily based upon the glued connection of the metal strips to the core of the glass panel in the seal area. The actual dome would have insulated glass panels of which the laminated lower panes in heat strengthened

glass would have the developed frameless structural connection. The weather seal between the upper panes would ensure complete water tightness over the structural joint in the sealant area.



FIG. 68 Dome scale 1:5 trial erected in the laboratory



FIG. 69 Detail with 6 mm fully tempered glass

BENDING, TENSION, COMPRESSION & SHEAR FORCES IN GLASS PANELS

Architect Pi de Bruin designed the Dutch headquarters for Swiss Life in Amstelveen, NL. The building has the shape of an H. The two open faces had to be closed off symbolically with glass louvers spanning 21 and 27 m wide with a height of 25 m. They were composed in the tender design prepared by ABT as three laminated glass panels of which the central 15 mm thick one was thought to be the load carrying panel, protected against damages from the outside by two outer panels of 6 mm annealed glass. The connections between the upper and lower corners of the panels, needed for transfer of dead weight, were bolted into steel plates. The transverse stabilization against wind loading was ensured by a system of glass compression bars, connected by pre-stressed cables. The tender envisioned the subcontractor to take over both the design responsibility as well as the product responsibility. Octatube as the sub-contractor took her work very seriously. It was the very reason why this time I acted as project leader myself, which I seldom need to do.

After the tender a process of redesign, engineering, testing of detail connections and prototyping followed. The glass panels were changed into 15 mm fully tempered glass. Glass panels fully strengthened and laminated/fully strengthened were deliberately broken, suspended in a tower crane at 25 m height. The so-called 'safety particles' shattered all over the place, but also plates of particles half a metre in size fell down, creating grooves in the soil of 50 mm deep before collapsing entirely into particles. This could be lethal! The second deliberate fall of a double broken laminated panel after half an hour of tearing and breaking out the holes in the PVB film occurred much like an autumn leaf zigzagging towards the ground. This was also the reason why the upper panels breaking out of the Hancock skyscraper in Boston in 1972 caused several lower panels to be shattered on their way down. The open windows were filled with plywood. The nickname 'plywood skyscraper' became a professional nightmare because of Murphy's Law. Only after 2 years of intensive

research the real reason for the glass panels falling out, was discovered: a too flexible steel skeleton. As fully responsible design & build contractor, the memory of Boston haunts me and warns me every time before I start a new experimental adventure. Warned by what we saw and the similarity of the Boston Hancock Building we concluded that glass falling from that height had to be avoided at all costs. The building team concluded that the results of the breakage tests from the tower crane were made to ensure that glass panels would never break and come down. Remember; this was the Dutch headquarters of the Swiss Life Insurance Company! One of the glass louvers was suspended right above the main entrance of the building.



FIG. 70 Hancock tower ‚Plywood Palace' in Boston 1972, architect I.M. Pei

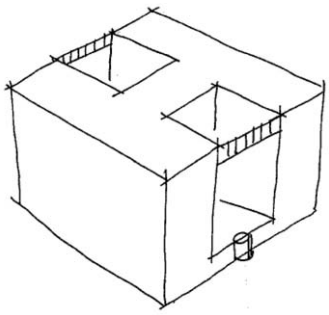

FIG. 71 Swiss Life building in Amstelveen (NL) with glass louvers at 25 m height

The first and biggest problem was, of course, that the original design would collapse if one of the panels would fail. I doubted the second route in the original design. On top of that it would be very costly to replace a panel that was broken, even if it was kept in place. A full scaffolding over 25 m in height would have to be built and a 27 m long suspension boom to take over the load from the building on to a mobile crane, which, after completion of the project, could hardly remain near to the building: a gigantic crane would be necessary. The costs would be consequential to the production that had to follow this dictated design, for which the responsibility was to be absorbed by Octatube as well. Who would carry these huge costs? Octatube? The client? The glass insurance (which was not even included, only in the form of the Swiss Life Insurance client, but they were intending to insure the glass elsewhere)? The designers of the original scheme, (who had foreseen an auxiliary cable in a horizontal tube), dictating that the development would not differ from the original? Thus followed a 2 year long cautious development and continuous debate between ABT and Octatube, backed by the main contractor. All that time we had an alternative in our pocket, which the engineer/architect/client deemed unacceptable. We proposed in vain to get a second opinion on the safety behaviour by a certified German 'Prüfungsingenieur' such as Prof. Dr. Wörner, president of the Technische Hochschule in Darmstadt; this was not accepted by the client and his advisors either. It would have been the one case that the phenomenon of the Prüfungsingenieur, absent in the Netherlands, would have been beneficial to a Dutch project.

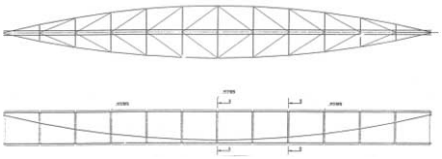

FIG. 72 Octatube's alternative proposal of the glass louvers with 2 suspended cables for deadweight



FIG. 73 Mock-up scale 1:2 in Octatube Laboratory just before abortion of the experimentation process

The connection details of double glass holes were developed as diameter 60 mm holes, with plastic material infill between the glass edges and steel bolt shafts. The maximum connection forces never exceeded 60% of the required value for a safe structure, according to tests performed at TNO Delft, considering a safety factor y of 4. At this time, we had a heated discussion about safety, which sometimes got personal; all because there were no standards and a sound engineering way of thinking and responsibility had to prevail. At the end of 2 years of development, a 1:2 scale prototype was manufactured as well as 1:1 prototypes of all important details with simulating correct stress loads in water basins in order to get the real connection forces; when the project was aborted. After another 2 years of display for students the 1:2 scale prototype was dismantled. Experimental engineering and testing had taken up 80% of the project budget and the result was not yet a realistic structure. We were sorry that we were not allowed to use our design alternative, which was a double hanging cable to create the primary span, between which glass panels were to be suspended as non-load carrying panels that could be replaced more easily in case of breakage. At a height of 25 m, the double suspension cables are virtually invisible.

Looking back, the project with the glass louvers was not elaborated completely in the design, went to the market too early for tendering, and left experimentation over to the subcontractor. In such experimental cases, both engineering parties need each other more than ever. At the time of tendering the design phase was not yet over. The better solution would have been to award the development of the louvers to a specialist contractor long before the entire building would have been tendered for. It seemed a game of cards with one card titled 'loss of face', and the question was: who would get this card? With the quality of the building or the glass structure at stake, the best solution would have been a pre-engineering contract for the specialist contractor, so that ABT and Octatube could have developed these louvers in close collaboration long before the general contractor started work onsite. Rob Nijsse published his vision in his book [Ref. 04.06], which is answered in this lecture. As part of the scientific debate. The main problem with the Swiss life louver was mainly caused by the fairly restricted load-bearing property of glass. Not because of shortcomings of the glass, but because of the unavoidable points where the forces have to be transferred to the glass. At the time, the existing connections designed for this purpose were too weak, unreliable and sensitive to creep.

During his graduation in 2003/2004 at the Faculty of Civil Engineering at the TU Delft, Fokke van Gijn developed a new pre-tensioned adhesive connector that copes with the inherent problems of these hitherto widely used shear connections. Nowadays, this pre-tensioned adhesive connection is a reliable and strong glass connection for structural applications. With a lower bond strength of 173 kN, it is 20 times stronger than a standard point fixture for frameless glazing. But what really sets this connection apart is, besides the high strength, that if the 19 mm glass fails because of overload of the cross-section the glass is pulled in half instead of an unpredictable stress concentration. The reliable failure mechanism and the warning before failure by plastic deformation of the stud bolt, which goes through the connection, makes this a safe connection when applied carefully and with the necessary attention.



FIG. 74 Design for 12m glass pedestrian bridge and pre-tensioned adhesive connection (Fokke van Gijn)



FIG. 75 New design for the glass louvers of the Swiss Life headquarters by Octatube

BENDING AND TWISTING IN LARGE FLEXIBLE GLASS PANELS

Architects have a tendency to demand visible technical innovations without having an idea of the consequences. Glass panels are designed to be larger and larger. Limitations are due to restrictions from the production plants, limitations due to deflection by wind and snow loads on ever growing spans, increasing glass thickness and more complicated details.
The limitations put forward by the glass industry in the form of 2.140 mm wide and 3.600 mm long tempering ovens and the lamination autoclave (oven) no longer seem to withhold them from designing wider and larger glass panels. One-storey high glass panels grow to a size of 3,6 m length. The initial solution would be to support the 3,6 m long panels at $1/5^{th}$ of the overall span from both ends (720 mm), so that they have a cantilevering scheme. For a width of 1,8 to 2,0 m, the thickness for wind pressure under 1.0 kN would be 10 mm. If, on the other hand, the span would be a blunt 3,6 m in height, the deflection of a 10 mm thick panel would

be 200 mm, which could be reduced by mounting the panel connectors in the corners, so that instead of 200 mm, the deflection would only be 50 mm with considerable vertical stresses on the connection points. Thus, these different conditions lead to quite different materialisations. An example of a large frameless glass façade without a stiff load-bearing substructure is the famous Kempinski Hotel in München Airport, designed by architect Helmut Jahn, Chicago. These facades are 30 m wide and 12 m high, filled with panels of 1,8 m x 1,8 m. The load-bearing structure is a single pre-stressed cable structure. This structural idea, engineered by Jörg Schlaich & Partners allowed for large horizontal deflections and special dilatation connection details on the side of the glass façade and the stiff building parts. Since large deformations would occur in some areas, the fully tempered glass panels would be subject to a twisting deformation. As to my knowledge the project never received a building permit, thanks to the reputation of Prof. Dr. Jörg Schlaich, but was widely published and copied all over the world.

04.07 CONNECTIONS BETWEEN GLASS AND QUATTRO'S

In principle, the connection between the glass panels and the load-bearing structure in frameless structures are point connections. The first connections in the Glass Music Hall in 1990 were developed as straight holes with outside discs, connecting the glass panel to a spider-like connector at the inside of the glass, which was part of the metal structure. The glass panels in this project were suspended vertically, so with the usual safety factor 4 the highest glass panel had to carry a deadweight of 30 kN, which was too much for a normal bolted connection. So a pre-stressed bolt connection was used with sand paper for higher friction between the disc and the glass. Thanks to the interior situation, this was feasible.

HALF MECHANICAL, HALF CHEMICAL CONNECTIONS TO DOUBLE GLASS PANELS

The next step was double glazing, for which we carried out developments at the project of the Netherlands Architecture Institute. The double glass units were connected in a half mechanical and half chemical manner. The inner pane was drilled and connected by a stainless steel disc in the void. The outer pane was structurally connected by the sealant between inner and outer pane and water tightened by the silicone sealant around the perimeter of the double glass panel. The advantages are fewer possible leakage spots.

GLUED CONNECTIONS TO DOUBLE GLASS PANELS

However, while going from 2 perforations to one perforation was a firm step, the next step was to have no perforations at all. So the next development was complete chemical

bonding of the internal glass surface to a stainless steel disc by means of high-tech glue, selected by an aeroplane industry related gluing institute at the TU Delft. The selection was done from well known aeroplane glues and tests were done on the basis of short term compression, tension shear and bending tests. We found that the compression, tension and shear tests resulted in approximately similar test results, but that the maximum results of the bending tests only accounted for 10% of these values. Hence the detailing of the glue connection has to result in minimal bending stresses in the glue connection. These tests were followed by long-term tests. The glue application is done under higher temperature to have a curing time of around 8 hours, after which the bonding is tested individually. The glue connection was patented in a number of European countries and has been applied first in the roof of the Court of Justice in Maastricht, NL in 1996 and 2 years later in the façade of the Glass Hall of the Prinsenhof Museum in Delft, NL. Most of the projects with double glazing and Quattro frameless glazing involve glued connections. In Germany, special "Zulassungen im Einzelfall" are prepared and accepted for this purpose.



FIG. 76 Single glass node in the Glass Music Hall in Amsterdam.

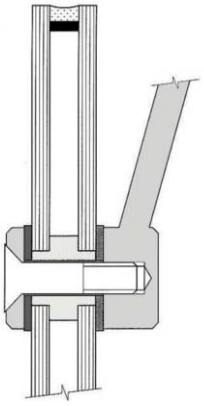

FIG. 77 Double perforated glass node.



FIG. 78 Half chemical, half mechanical connection in NAI in Rotterdam.

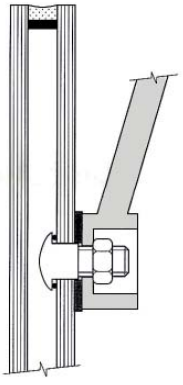

FIG. 79 Single perforated glass node.



FIG. 80 Details of glued connection and spider web arrangement

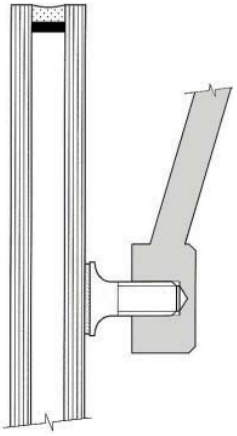

FIG. 81 Glued connection scheme



FIG. 82 Lower perspective of first glued insulated glass panel roof in 1995 (Gerard Passchier arch)



FIG. 83 Upper perspective of first glued insulated glass panel roof in 1995 (Gerard Passchier arch)



FIG. 84 Glass roof and façade, both with glued connections in the Prinsenhof in Delft in 1996



FIG. 85 Detail of the glass roof and façade

04.08

THEORETICAL RESEARCH: NEW STRUCTURAL POSSIBILITIES OF GLASS

TUBULAR GLASS COLUMNS

From 1992 onwards this quest for Zappi involved the work of several graduation students in Building Technology at the Faculty of Architecture. Most of them were guided by Dr. Fred Veer, material scientist at the Chair of Product Development. The most exciting work has been done by student Joost Pastunnik in 1998. He developed compression tests on laminated tubes of borosilicate laboratory glass. The inner glass tube was loaded under compression. The outer tube was a little shorter, not loaded by compression and acting as the fracture shield of the inner tube. The space between both tubes was filled by clear acrylic resin. From the tests appeared that even fully broken tubes could resist a compression force of 110 kN. They would break and buckle at around 120 kN. We considered this a break-through in safety engineering of the use of glass for structural compression elements. After the work of this student the phase of upscaling the columns to real building sizes would follow. We negotiated with Schott, and it was a few years later that we learned that Schott found other partners in Germany to follow this line of work. In 2003 Norman Foster realised a building in London using this 'cited' technique. Anyway, we learned that our principal research had a positive application.



FIG. 86 Laminated glass column

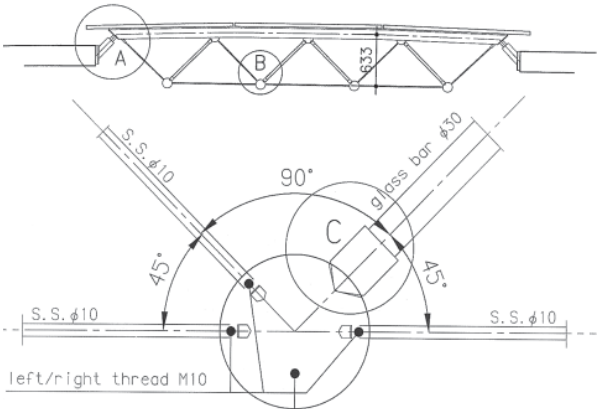

FIG. 87 Details of glass louver, design ABT and production Octatube

TRUSSES WITH GLASS STUDS

The first application of glass studs were required in trusses in the Amstelveen headquarters of Swiss Life, mentioned under chapter 6.3. ABT had made a design with glass compression studs, which we engineered as solid bars, with stainless steel caps ending in a central point

to avoid any bending in the connection and in the shaft. [Ref. 04.07] Similar glass studs, but now 3 m long; thus requiring an external stabilizing system to prevent buckling. They were also applied in two glass canopies at Schiphol Airport, NL. In this case the 30 mm diameter rods were stabilized against buckling by three steel rod stabilizers. The alternative would be to use larger diameter tubes or rods: there is no preference either way.

THEORETICAL RESEARCH ON TENSEGRITY GLASS STUDS

Chinese research fellow Dr. Li Zang participated in the research into glass bars in 2001 at TU Delft under guidance of Prof. Dr. Jaap Wardenier (Civil Engineering) and the author. She analytically researched the possibilities of the behaviour of glass compression studs versus steel compression studs in a number of different 'tensegrity' arrangements: diagonal, orthogonal, radial arrangements. The outcome of her studies was published on the Surrey Conference on Space Structures in 2002. She found that the use of glass studs was as reliable as the use of steel studs in the different arrangements [Ref. 04.08].

DUTCH DOUBLE GLASS FACADES

PhD student Paul de Ruiter reports in his ongoing research 'Chameleon Skin' a system of double glazing on the outside, and a solar screen, as the inner skin allowing air flow to maximize the energy savings without large investments (1994). After 2 years he interrupted his PhD study as he had won an architectural competition for a series of office buildings with ecological character. Since then he has built a number of buildings in Nijmegen (Mercator) as a practicing architect according to this scheme. A number of these buildings are monitored regularly so as to find out whether they reach their building physical / economical target. After the monitoring had been worked out, the cycle of system, design, application and feedback has been completed and time has come for him to finish his PhD.

EVALUATION OF DUAL WALL GLASS FACADES

Student Dominique Timmermans has analyzed the many double facades of the last decade and came to the conclusion that in spite of the high ecological ambitions there is not a single double façade building that has an economical balance between high investments and energy savings in the mid and long range (2001). He works now for Permasteelisa, the largest European curtain wall manufacturer.

GUGGENHEIM/DEUTSCHE BANK, BERLIN

The double glass façade for the Deutsche Bank/Guggenheim Museum Unter den Linden in Berlin was designed by architect Novotny & Mähner, using its reflection to smoothen out the difference between the existing stone façade and the new double steel/aluminium topping up. The glazing was monolithic, clear, fully tempered glass with stainless steel frames as projections of the existing window scheme. We found out that the huge building tolerances of this two centuries old building made by hand led to ingenious detailing to achieve a uniform appearance. Realized in 1997.

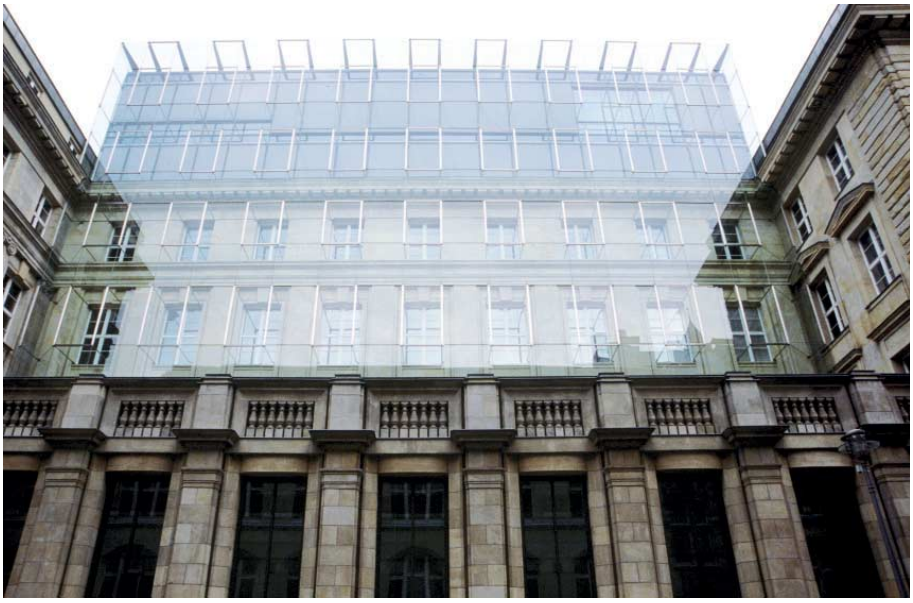

FIG. 88 Façade of the Deutsche Bank unter den Linden in Berlin, architect: Novotny and Mähner

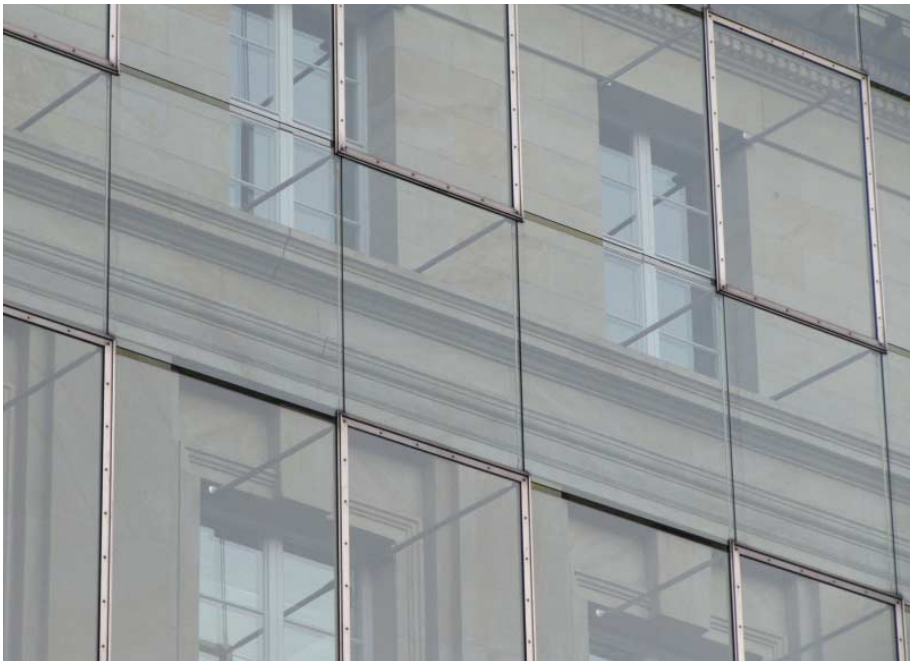

FIG. 89 Details of the façade of the Deutsche Bank

XXX DUAL WALL FAÇADE SYSTEM FOR RENOVATION

The XXX system, designed in collaboration with a development group in Langen, Germany, foresees enwrapping existing office buildings with new glass facades to renovate skin performance, to individualize ventilation, heating and cooling while the office spaces can still be occupied and used. This design concept is especially suited for the technical renovation of 30-40 year old inner-city buildings: the glass sound screen can give old stucco buildings a completely different appearance and can even be provided with a specific screen-print in a graphical design. The acoustical function of the screen is not disturbed by the fresh air apertures in the skin.

04.09 SUPER SLENDER LOAD-SUPPORTING STEEL SYSTEMS

OZ BUILDING IN TEL AVIV

Several systems of lightweight steel structures were designed, engineered and realized; such as the fish bone structure with solid rods, as applied in the OZ building in Tel Aviv, designed by architect Avram Yaski. The system consisted of horizontal tensile trusses, each 3,6m at floor height for easy connection to horizontal reaction forces from the floors and a secondary system of vertical stabilizers at the intermediate points at 1,8 m distances, in vertical direction. This weave of horizontal and vertical tensile trusses was completed with straight vertical deadweight suspenders, leading the complete deadweight of the glass façade up to the roof structure of the building. The height of the façade was 52 m; the span in horizontal direction 16 m. The glass panels were 6,2 mm thick clear laminated glass panels. Both maintenance and replacing of glass is done from the roof with a suspended cradle. The façade has a northern orientation. Later information from the Centre of Desert Research corrected the assumption that the northerly orientation would avoid solar radiation. Due to dust en desert particles in the air the indirect radiation on the north side is almost as high as it would be with any other façade orientation. The entrance of the Museum of Modern Art in Tel Aviv used much the same principle in two dimensions.

SQUARE SPIDER ARRANGEMENT OF TENSEGRITY SYSTEM

Starting with single diagonal arrangement we have developed a stabilization system of a square ground plan, subdivided into 3x3, 4x4, 5x5 or 6x6 glass panels, with tensile rod trusses ending in the corners of each square. Normally, they are directly connected to a surrounding tubular framework, so that the tubes are (almost) only loaded under compression. These diagonal arrangements can be repeated to cover larger surfaces. The micro stabilization is then complimented by a macro arrangement of intersecting horizontal tubes supported on each crossing by columns or by flying studs. The square

diagonal spider arrangement of tensile trusses are developed in several projects such as the shopping centre Overvecht, supported on a 8 m x 8 m grid of columns, designed by ONB architects, Utrecht. One year later we realized a free spanning version of 28 m x 28 m in the roof for the Droogbak office renovation project in Amsterdam, designed by architect Joop van Stigt.

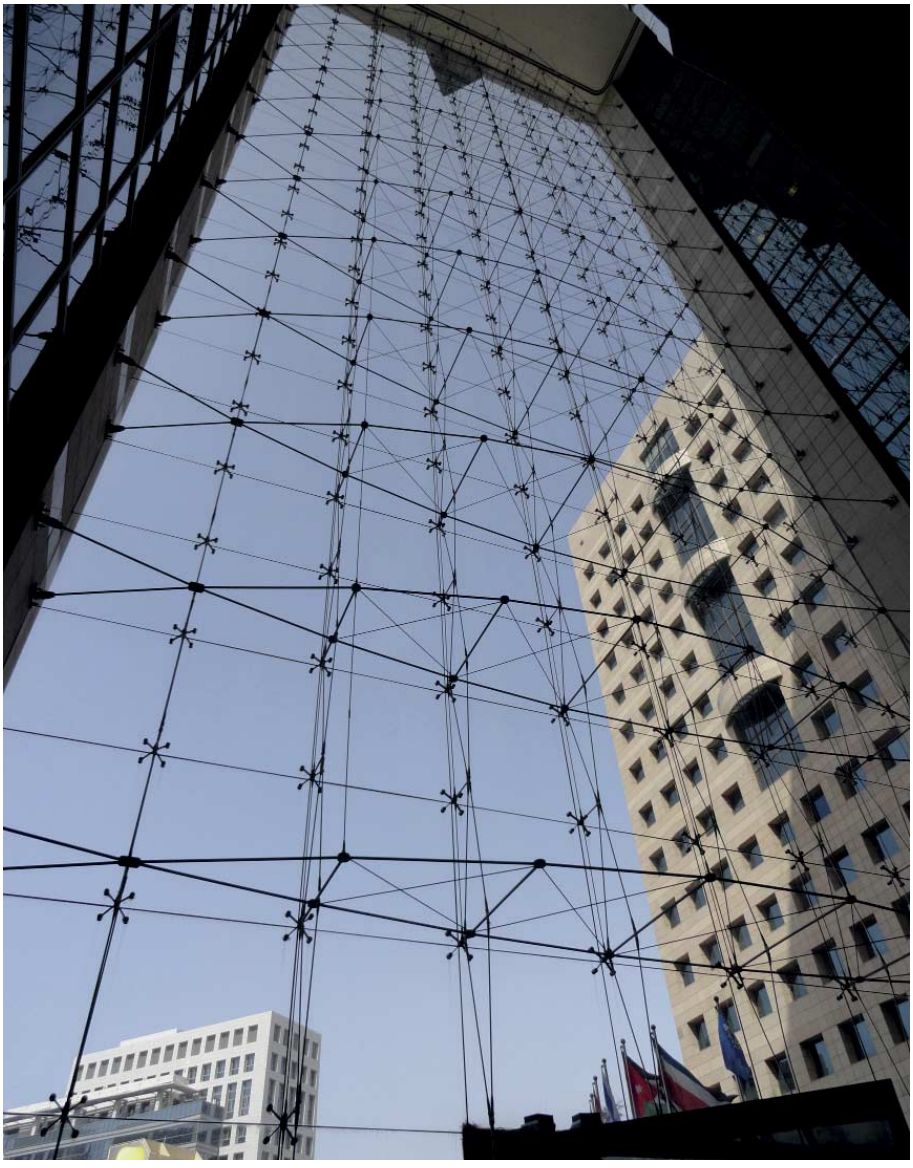

FIG. 90 OZ Building, Tel Aviv arch.: Avram Yaski



FIG. 91 Cubic hall of the Museon, arch.: Dan Eytan



FIG. 92 Droogbak in Amsterdam, arch.: Joop van Stigt

04.10 PRINSENHOF HALL IN DELFT

Many applications of frameless glazing for roofs are designed in existing buildings and some of them in monuments. Adding a glass roof is one solution, whereby it is usually impossible to request reaction forces from the existing building. So these structures have to be self-supporting. This is the reason why the super-slender tensile trusses cannot be applied to monuments, unless one provides for the necessary compression forces. It is possible to introduce a central compression tube in the lenticular tensile trusses; so that in all cases of downward and upward loading the tensile truss with central tube acts as an independent beam, while maintaining its elegance. The double bow string truss for the Glass Hall in the Prinsenhof Museum (1998) was realized in this manner, architect Mick Eekhout. Its trusses are spaced 2,5 m apart to accommodate the covering double glass units at 2,5 m. The glass panels are composed as 8mm top and 5,2 mm bottom layers, supported at $1/5^{th}$ of their length from the corners, and barely stiff enough to apply the sealant. The trusses are supported on two continuous CHS beams, which in turn are supported on CHS columns at 5m span, which were in line with the masonry buttresses of the mediaeval brickwork between the windows. In order to support these slender double glass panels the top member of the trusses were fitted with wide glass supports, 1 m wide.



FIG. 93 Prinsenhof in Delft

THE FLYING KITE OF ROTTERDAM

Three years later, in 2001, the roof over the café street of the Westerlijk Handelsterrein in Rotterdam was designed with architect Jan van de Weerd and Mick Eekhout in the shape of a flying kite of similar trusses, spaced at the same distance as the brickwork walls perpendicular to the street walls for stability reasons. On top of the trusses a system of elliptical tubes was mounted onto which the glass panels were fixed. The glass panels were also meant to carry shear forces resulting from wind: there are no steel wind bracings.



FIG. 94 Glass roof, Westelijk Handelsterrein Rotterdam

THE GLASS SAUCER IN MADRID

For a 30 m diameter circular roof, designed by New York architect Kevin Roche for the Bancopolis headquarters near Madrid, we designed a radial arrangement of tensile trusses, surrounded by a steel ring of RHS 350 x 350. The upper and lower rods were designed to be 30 mm and post-stressed for the required stiffness. The vertical elements were designed in stainless steel as well, although an alternative in the shape of glass bars had been offered but was perceived as possibly too experimental for a bank building by the representatives of the client. Research fellow Li Zhang spent one year working on the comparison between glass and steel compression studs in these types of tensegrity arrangements and concluded that glass tubes are perfectly trustworthy structural components [Ref. 04.08]. Architect Kevin Roche judged my technical proposals with the stainless steel tubes so favourably *("excellent work")* that I did not bother experimenting with glass tubes in order to convince him.

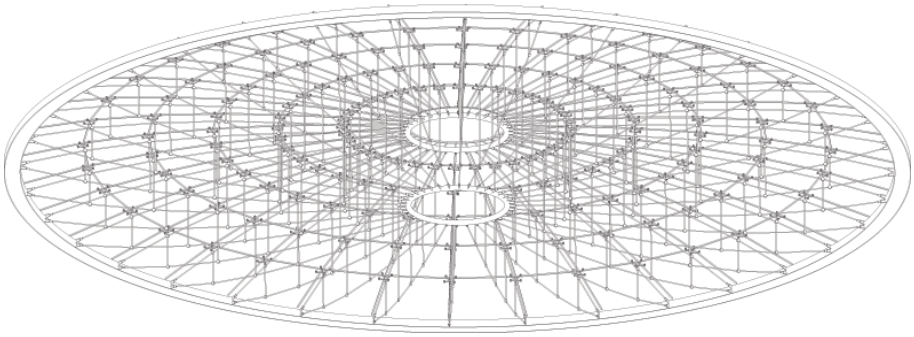

FIG. 95 Glass roof of the Bancopolis in Madrid, Spain

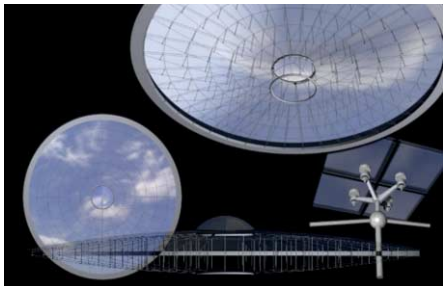

FIG. 96 Renderings of the glass roof of the Bancopolis



FIG. 97 Detail of the connection

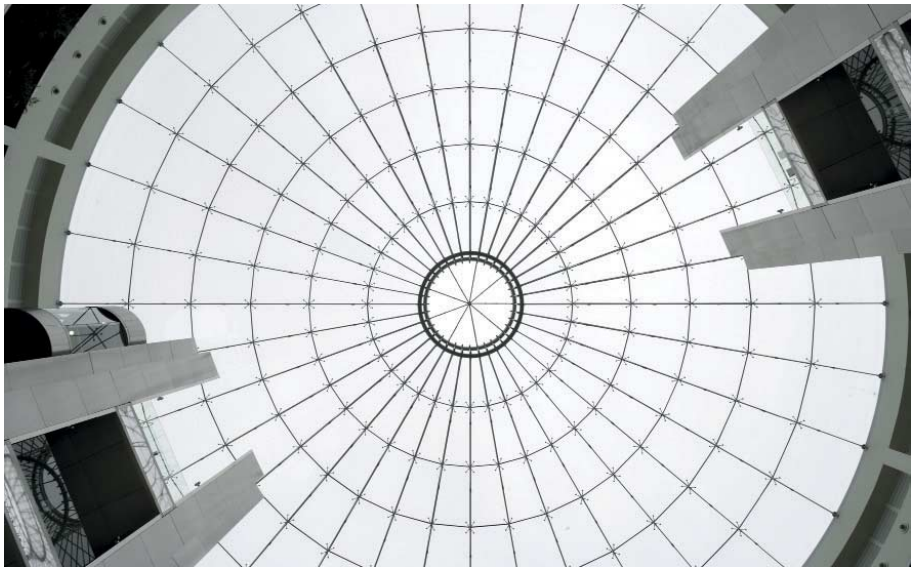

FIG. 98 Photo taken after completion in 2004

04.11

RESEARCH AND DEVELOPMENT IN LIQUID DESIGNS OF BUILDINGS

TWIST & BUILD BY KAREL VOLLERS

PhD student Karel Vollers received his doctorate in 2001 with his dissertation 'Twist & Build' on the urban and architectural design of twisted buildings. He developed the necessary building technical tools for twisted buildings. Amongst these are the building technical compositions, the physical deformations, the material specifications of casting in deformed moulds or deforming flat plates, the production engineering of cold and hot deformed/ twisted glass and the window details belonging to this engineering. After these technical developments he went back to architectural design and designed architectural applications of twisted buildings.

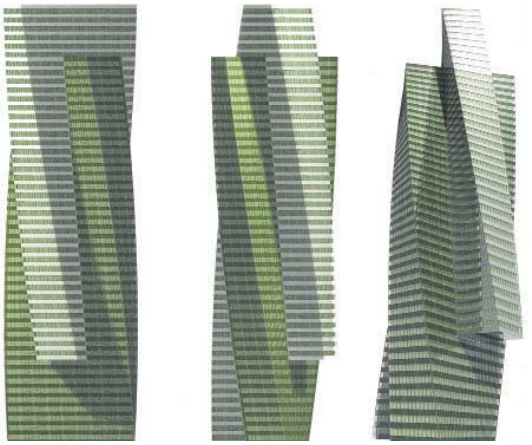

FIG. 99 Design of a twisted office tower in Amsterdam, Karel Vollers



FIG. 100 Mock-up of a twisted façade as developed with Reynolds

BLOB RESEARCH GROUP

Karel Vollers accelerated further studies as the post-doctorate head of the Blob Research Group. Some 10 students join this Master program per year. The figures show some of the most remarkable studies.

FLOATING FLUID PAVILION OF SIEB WICHERS

One of the Blob graduation students was Sieb Wichers, who designed a shell structure with curved glass on the front side. From a building brief he developed a functional

program, a sculptural architectural form that subsequently was translated into a self supporting structure with an intelligent dual stressed skin structure. The spatial effect of this architectural and technical design is surprising. This student mastered both design, drawing, structural design and analysis as well as building technical design. He now calls himself an 'archineer', a blend of architect and engineer, working at the office of Moshe Safdie, Boston.

GLUED CONNECTIONS BY BARBARA VAN GELDER

Barbara van Gelder did her final thesis at Octatube and developed a glued connection for a multi-facetted façade. This design was flexible in its corners so that polygonal bodies of buildings could be accommodated. She also did a project with glued nodes in frameless glazing in this same period in Brussels and currently works as the head of the sales department of Octatube and as a design engineer.

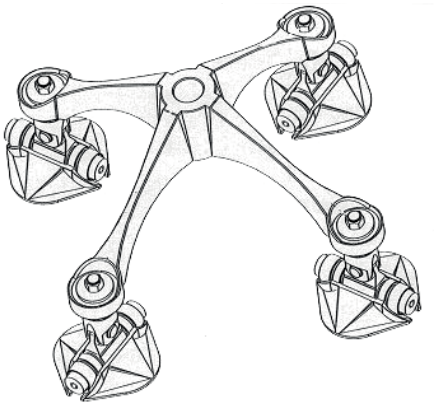

FIG. 101 Quattro glued-connection developed by Barbara van Gelder



FIG. 102 Quattro glued-connection developed by Barbara van Gelder

REGULARITIES OF COLD TWISTING OF GLASS BY DRIES STAAKS

The cold twisted double and laminated glass panels in the town hall of Alphen aan den Rijn was taken up by TU Eindhoven student Dries Staaks as a point of departure to discover, research and develop the regularities of cold twisting of glass (2003). He discovered that glass panels can be cold twisted elastically, deforming in a symmetrical way into a hypar surface as long as the enforced deformation out-of-plane is less than 16 times the panels' thickness. More twisting will evoke a change of deformation pattern resulting in unidirectional bending along the shortest (stiffest) diagonal axis. This change in deformation is caused by an instability phenomenon. The double curvature of a twisted plate causes membrane forces: pressure in the middle and tension along the edges. For increase of twisting the membrane forces increase exponentially until the pressure

causes the plate to buckle, resulting in the change of deformation. The amount of twisting at which instability occurs proved to be linear related to the panels' thickness, independent of material and size except for the length/width ratio. For small amounts of twisting (panels' thickness) stresses are uniformly distributed. This stress is linear related to the panels' thickness. A thinner panel will cause equally lower stress. For increasing twisting the stress will increase more than linearly due to the growing influence of the membrane forces. In general, twisted geometries with a deformation up to 10% of the panels' width are possible using pre-stressed glass.



FIG. 103 Cold twisted glass panels

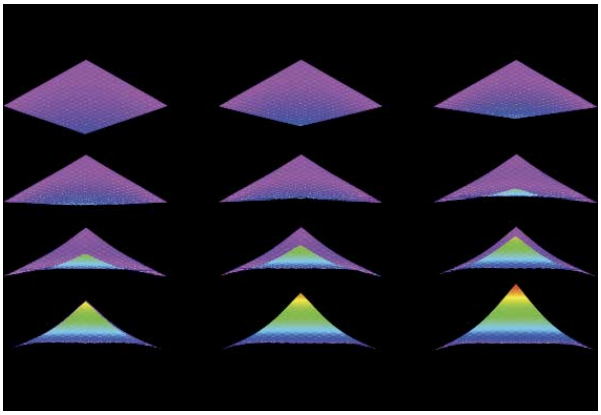

FIG. 104 Cold deformation between elastic behaviour and buckling by Dries Staaks

PRODUCTION MOULD FOR 3D GLASS BY KAY VERKAAIK

Hot deformation of glass panels using a flexible mould usable without materials waste was studied by Building Technology student Kay Verkaaik (2003). He developed a moulding system of parallel axes in a grid with circular saucers on the top to form the desired 3D mould on which the glass can be heated and deformed, and developed the necessary engineering tools for it.

RESEARCH & DEVELOPMENT OF STRUCTURAL SYSTEMS FOR LIQUID DESIGNED BUILDINGS

PhD student Martijn Veltkamp works since 2002 on the development of structural systems applicable for liquid designs for buildings. The free-form of these liquid designs and the deviations from good professional practice gained from decades of development of lightweight structures (from the 1960ies to the 1990ies). Even the most logical errors that had to be avoided in those days seem to be more of a standard rule these days. Between these conflicting rules of material efficiency and sculptural 'mannerism', Veltkamp will develop new structural systems, for short spans (3 m to 10m), for medium range spans (10 m to 50 m) and for large spans (50 m to 100 m). A quite impractical but visionary conceptual idea of the London based Auckett architects for using oversized dressing dolls as building forms is used as a base for his studies at this moment.

04.12 APPLICATION EXPERIMENTS FOR LIQUID DESIGNS IN GLASS

Over the last years, a number of 'liquid design' buildings have been realized, typically with very complex 3D geometries, and for some of them I was able to experiment with glass applications such as:

WATER POND FOR FLORIADE PAVILION

The glass water pond of the municipal Floriade pavilion in 2002, designed by Asymptote architects of New York, is loaded with 14 kN water weight/m². It was originally designed as a 3D-curved frameless glass composition. The glass would have been heated, curved in pairs, chemically pre-stressed and laminated with epoxy or acrylic resin. Due to time constraints it was realized only as flat laminated glass panels; this technical composition won a honourable award of the Du Pont Benedictus Award 2003.

COLD BENT LAMINATED GLASS ON POINTS SUPPORTED

On the south side of the same pavilion there are three large window glazing's, each 6 m x 6 m, composed of nine glass panels of roughly 2 m x 2 m each. The south windows are flat. The two side windows have a large curvature which was attained by cold bending of flat laminated and fully tempered glass panels from their four corner connectors by screwing out two rubber pushers on the upper and lower edge, fixed on the curved steel CHS beam on the inside. Lamination was thought to be a safety precaution against sudden explosion in the face of the workers on the outside when stressing up the panels. No panel broke. The analysis resulted in high bending stresses: up to 50% of the allowable bending stresses. The other 50% were good enough for stresses from wind loading. Thus a system with an economical purchase price and a curvature was realized. The maximum radius to be attained in this manner is 4,5 m.

SUPERYACHT, LONDON

For a hotel consortium in London naval architect Tim Saunders designed a floating 5-star hotel in the form of a super yacht of 170 m length, in the best of the Mediterranean design fashion. The structure will be built on a steel pontoon as a skeleton with steel beams and columns, the hotel rooms will be completely furnished and prefabricated in Dubai and the cladding with 2D / 2,5D aluminium and 3D glass fibre reinforced polyester (GRP) panels plus flat glazing (2D), bent glazing (2,5D), and some 3D pieces of glazing are to be made to the latest state of the art by Octatube in Delft. The experiences in 3D cladding deformation, frameless glass structures and bent and twisted glass panels come together in this masterpiece.



FIG. 105 Glass water pond of Floriade building in the Haarlemmermeer



FIG. 106 Cold bent glass laminated panels in the Floriade building Haarlemmermeer



FIG. 107 Superyacht, a five star hotel in London. Rendering by naval architect Tim Saunders

COLD TWISTED GLASS PANELS IN ALPHEN

The back part of the town hall of Alphen aan den Rijn had a double curved surface for which glass lintels were designed by architect EEA. As these glass lintels did not run concentrically, many of the composing glass panels had to be twisted. This was solved by cold twisting of the glass panels on site. Upper and lower profiles were U-channels. The insulated glass panels had a maximum dimension of 900 mm x 2000 mm and consisted of an 8 mm outer layer fully tempered and an inner layer of 4,2 mm, also fully tempered. The silicone seals were regular butt seals. The glass was twisted out of its plane by a maximum of 40 mm. This work proved to be realizable at very economical costs, with larger risks than normal (300% breaking of panels on site compared to the normal practice). After having completed the job, we wondered what we had done. It took student Dries Staaks one full year to discover and describe the regularities of cold twisting of glass panels.

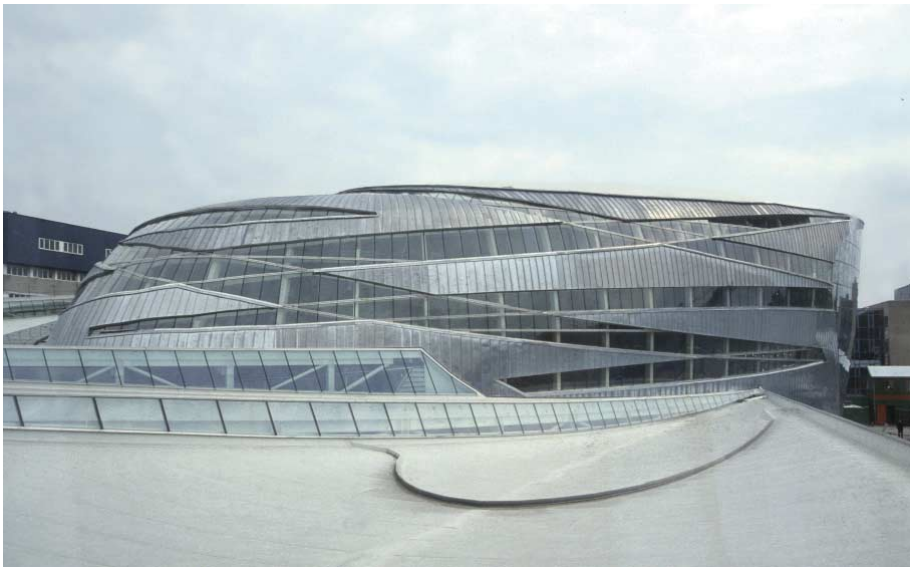

FIG. 108 Construction phase of spaghetti facade with cold twisted glass in the Town Hall of Alphen a/d Rijn.

04.13 ZAPPI AS AN ETERNAL AMBITION

The more research, developments and designs are made, the more obvious it becomes that we do not know enough. The quest goes on. In the case of Zappi, the quest started with a market-directed intriguing description of an unattainable mix of characteristics. In the case of the Blob designs the market provoked us: practising architects dared to throw projects on the market without comprehending or mastering the issues involved in leading to realisation. This caused a staggering technology vacuum into which the Blob research group stepped to bridge the gap between design & realisation.

In the meantime the research in Zappi has taken two different paths: under leadership of Veer a number of graduates worked on separate topics without a coherent design formula. This group is mainly devoted to research and does not involve itself in designing. Practical projects, however, always depart from design and need research and development to be realised. Without an internal cohesion in subject and material, the outside and inside world cannot profit much from our research activities. They would remain the sole joy of occasional participants of conferences like the ones in Tampere. Safety in design and safety in use are major topics for Zappi, but perhaps the best remedy for the disease of sterile research is joy in design, joy in performance, vigour and wit. The world is expecting quite something from the young Zappi and Blob engineers of Delft.

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05 CARDBOARD DOME FROM IDEA TO CERTIFICATION

First published in Cardboard workshop, TU Delft 2008

05.01 DESIGNING IS COMPOSING AND INVENTING

Designing is an incredible experience. Looking for new solutions for posed problems challenges to keep you on improving yourself and others. It is a continuous course of action. You will always look with 'designer eyes'. It often results in passion and enthusiasm. The TU Delft is a University of Technology where technical ingenuity scores high. The previous Rector Magnificus Dr. Nico de Voogd intended to transform the TU Delft into a 'research driven university'. However, the next Rector Magnificus Professor Dr. Jacob Fokkema acknowledged design as a respectable activity. The definition of design as a result of designing at the TU Delft (ARTD) is: *"The (technical) design is a record of principal and/or eventual working method and/or shape of a technical and realistic solution for a described problem"*. The Faculty of Architecture is proud of its focus on design. In 1988, the Faculties of Architecture in Delft and Eindhoven agreed that Delft would focus on the design process, whereas Eindhoven would focus on the realisation process. Well-known architects such as Jo Coenen, Sjoerd Soeters, Rudy Uyttenhaak and Frank Wintermans were all educated as architects in Eindhoven and therefore seem an exception to this rule.

What signifies design in the Faculty of Architecture and more specifically in the Master program Building Technology? What exactly is design? A precise and comprehensive definition is nowhere to be found. So let us considers design from different points of view.

Functional: The goal of design at the Faculty of Architecture is a material solution by inventing an architectural composition for a posed architectural problem.

Composition: Design is composing parts into a larger whole (artefact). Architectural design is composing elements and components into a material artefact. Depending on the three levels this could be: urban design, a building design or a building component design.

Artistic: Design is creating an original spatial composition. The material and immaterial means are usually familiar; the originality in the position of matter in space transforms a building into a piece of applied art.

Technical: Design is inventing and ingeniously developing new material elements, components, systems and products for urban design/architecture/building technology and the integration of those parts into an artefact.

Process: Design is the process of analysis, synthesis and development, starting with a problem statement and ending in a material solution.

Economical: Design is seeking a balance between demand, formulated in many wishes and requirements, and supply of a possible technical execution with the required financial means.

Philosophical: Design is seeking an optimal compromise between ambiguous demands and desires.

Every designer will describe design in a different manner. I will try it from my point of view. In a TU Delft symposium on Design Methodology in 1998 [ISBN 90-5269-255-6] I have described design as: *"The applied technical design is an original, ingenious and material solution for a technical problem, acquired by means of an efficient process of making decisions from initiative until execution"*. Ever since my first day at the faculty I have been interested in design as a collection of activities with a path-breaking result. Novelty is at the top of the list. Not only for yourself (which is quite common when you're a student and still learning) or for the national group of architects and technical designers, but even directed towards a patented world novelty. Novelty for yourself, your friends, the Dutch scene and the world are entirely different concepts. These environments could be compared to arenas with different rules of the game and different rewards. Confusing these arenas can cause disillusion. If you, for example, admire your heroes and even identify yourself with them, you skip several arenas and an unnecessary confusing identification arises which will unavoidably lead to a big disappointment and a qualitative goal and recognition that will never be attained.

Design is, in many cases, just a 'fata morgana' if the designer gets trapped in dichotomous demands and desires, as a result of which only a meagre compromise can be achieved. Design is often seeking the best compromise. Young and ambitious architects, who primarily strive to attain the maximum amount of novelty in their design and at the same time their own fame, have their own idea of the concept of compromise. They have to win design competitions. You cannot win those competitions if you blindly obey all dichotomous demands and desires. The design should have something bold, exceptional, reckless in order to be noticed by the jury of the competition. So a certain balance between character and compromise is necessary. Character to be noticed and compromise to fulfil most of the demands of the client.

I take pleasure in composing as an interpretation of design (which is essential and unavoidable for architects) but from my very first design sketches as a student onward I felt more like an inventor. In my first year of study I already designed glass fibre reinforced polyester shell-like walls and roofs for a gatekeepers building at Calvé in Delft, which was an exciting technical adventure. Thirty years later, in 2005 we developed a GRP shell roof system for architect Moshe Safdie from Boston. See lecture 06.

I alternate composing and inventing. But I get the most pleasure form inventing, maybe because so few people can do it. I consider myself more as an inventor-architect than as a composer-architect. In that respect I am called an 'architect-engineer' in Belgium. But I do not know whether their flag covers that statement. In the city hall of Bolsward (built in 1614-1619) a text on the entrance portal of the council room says *"geijnventeerd"*, which is a 17th century reference to the entanglement of the notion of invention and design. Nothing new under the sun. Perhaps the Ecole de Beaux Arts stressed composing too much two centuries ago, as a result of which the word *"ijnventeren"* moved to the background. In any case, the technological designers we educate should be able to become designer-inventors.

Many inventions can only come to existence by prompt but most of all in-depth and methodical work without the fear of failure. That kind of design is more scientific compared to the more artistic component that composing possesses. This process of design should be transparent, so it can be verified, for yourself or your team, so you can discuss it and make the right decisions at crucial moments. Design as a science is hard to achieve whereas primarily composing requires many intuitive decisions. Scientific design can be achieved in some cases and in other cases a part of the entire design and engineering process can be recognized. In the 'Koninklijke Nederlandse Akademie van Wetenschappen' (Royal Dutch Academy of Science) I will first substantiate scientific design to subsequently gain an understanding for design as a process of composing. Many Dutch architects argue that a composer should be creative but doesn't necessarily have to be an inventor, since an inventor is a technician. Just like a composer doesn't have to invent musical notes in order to make a composition, an architect doesn't have to invent materials ('musical notes') or constructions ('musical bar') in order to make a good design. Composing alone is already enough. The attitude of architect Jan Benthem derives from of this position: take smart materials and systems that have already proven their quality and reliability, and subsequently use them to compose. With that attitude he gained a respectable portfolio. But there are also architects who see it as their job to design, research and develop the means (elements, components, systems, products) with which they shape their buildings according to their design. The interest of these architects is both focusing on innovation in architecture and in technology. They are focused on both the development of material means to build as composing a surprising artefact into a building. These designers position themselves both at the producers-side as the consumer-side of technology. Think of British high-tech architects, Renzo Piano, Santiago Calatrava. In the past decade Piano and Calatrava both received an honorary doctorate of the TU Delft.

05.02 INVENTING AND COMPOSING IN CARDBOARD

This lengthy introduction was necessary in order to comprehend the backgrounds of the designers of the cardboard dome: Shigeru Ban and Mick Eekhout. Both of them are used to invent and compose: to research and design, research by design and design by research. When I was a student, Professor ir. Dick Dicke proposed to design a structural system with a fictive material possessing the most diverse properties you can think of. This could have been 'gingerbread' for all I care, but you had to figure out to make some sort of construction with it. The aim of the exercise was of course to appreciate the properties of materials without thinking in rigid patters. When Walter Spangenberg (ABT) called me for the first time about this cardboard project, I immediately thought about considering cardboard as a sort of gingerbread. I was eager to start working on a material I never would have considered otherwise and in which I had absolutely no experience or any prejudice. Shigeru Ban had already realized several projects in cardboard. For the Dutch cardboard industry – thinking primarily of increasing their own market – it was evident that several steps had to be taken in the field of fundamental research and development in order to establish new applications. The adventure started in the field of architecture. We first had to think of new systems. Therefore it was necessary to expand the cardboard industry. This expansion and foundation occurred by more fundamental research concerning the relationship between strength / humidity, elasticity modulus, buckling and bending strength. Only after this process of investigation and research was completed, we could think of new structural systems and experimentally developed them, so new applications could be designed.

05.03 THE CARDBOARD DOME DESIGN

Japanese architect Shigeru Ban was responsible for the design of the Japanese pavilion at the World Exhibition in Hannover 2000. The structure consisted of long cardboard tubes that were bent over each other. Jeanette van der Steen attended a lecture by Ban in the NAi (Dutch Architecture Institute) and became fascinated with his designs. She asked him to design a temporary dome for her theatre group on IJburg near Amsterdam. In the fall of 2002, Ban made a design consisting of a 16frequency icosahedron in the tradition of Richard Buckminster Fuller. An icosahedron consists of 20 regular surfaces: a complete sphere is built up of 20 regular triangles, which were applied 5 times in this spherical roof. Later on I will further address this. Dr. Pieter Huybers of Civil Engineering TU Delft has published many studies on these polyhedra. The shape of the dome (span versus height with folded edges) is identical to the 60 metres span Aviodome at Schiphol and the Toyotadome in Raamsdonkveer. Compared to recent experiences with fluid design at Octatube, this dome was a reasonably easy, nearly historic design. Time flies by. The experiences with Blob design & engineering make dome structures look simple.

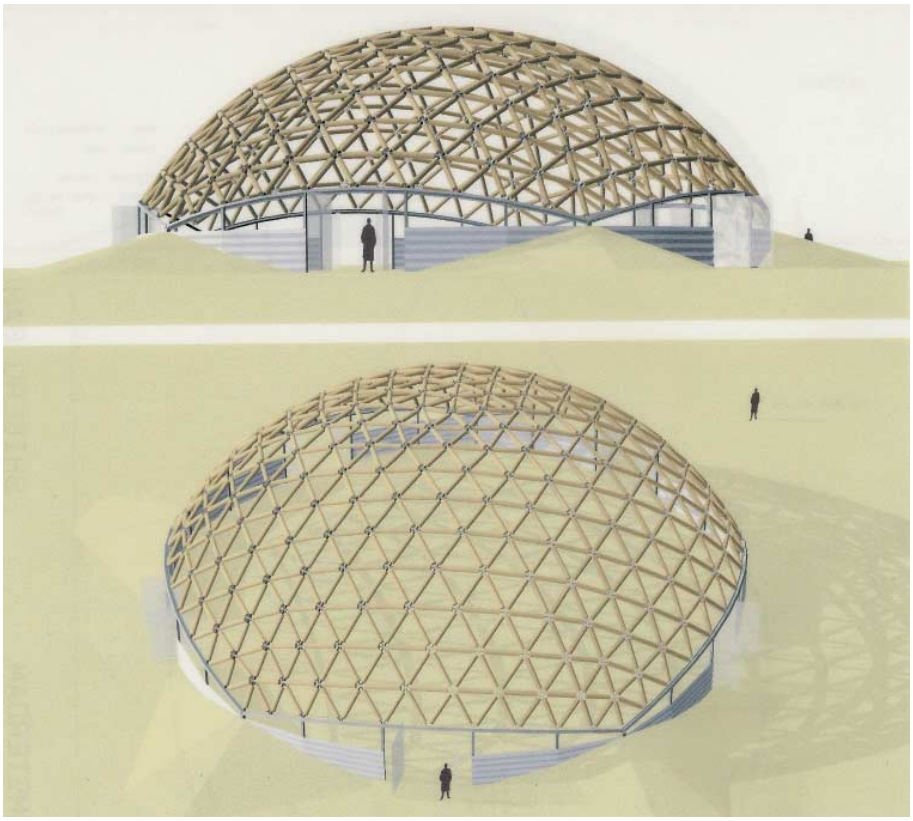


FIG. 109 Layout of Cardboard Dome (Shigeru Ban / Octatube)

Ban's design went through a violent process to gather sufficient sponsoring from the side of Mime Theater Groep Van Steen. At the same time, a thorough material research project and material development on part of Octatube, the chair of Product Development and also the design group 'Cardboard' of Professor Fons Verheijen was involved. Ban was represented by architect Wouter Klinkenbijl. Despite earlier experiences of Ban in construction with cardboard, this type of cardboard use seemed to surpass the available amount of knowledge when issues like tension and weight load are involved. The sporadic technical data from Japan was definitely insufficient to make an independent, engineer's judgement about the behaviour of cardboard as a structural material. Despite repeated requests it seemed impossible to acquire structural data from design teams and contractors who participated in the construction of the Japanese pavilion in Hannover (the municipality of Hannover, Buro Happold, cardboard supplier Sonoco and architect Ban). In Stuttgart, I heard my colleague Professor Dr. Jörg Schlaich proclaim: *"Es is nichts Neues, dass Wissen vergeht"*. But two years seemed a rather short period. It was more of a refusal to cooperate.

Hence, for this dome design in cardboard all material data had to be determined from our own research. In November 2002, the development was initiated. This included the process of material research based on tests in the Laboratory of Product Development (PO-lab) and the Octatube Laboratory and a process of material design: determining the exact geometry, tube lengths, node detailing and so on. In this case research and design could be described as a split: far apart, yet influencing each other. In November and December 2002 numerous cardboard tubes, supplied by Dutch companies, were tested in the PO-lab. The results of this research were compared with the required load from the construction analysis, which was executed several times and sent in by computer in the mean time. Over and over the results of practical tests proved to be disappointing. The tubes already cracked at the diagonal seams at minor loads. But the horizontally wrapped tubes weren't that much stronger either. The utilised glue proved to be the decisive factor in construction use of cardboard. On a Boosting meeting in December 2002, colleague designer Friso Kramer suggested to utilize a melamine composite to reinforce the cardboard, instead of using the inferior glue. A clever idea, yet this would make recycling of the cardboard impossible.

The tubes consisted of 15 to 22 mm thick material, with a diameter between 150 and 200 mm. Tests during the Christmas holidays 2002 proved cardboard's high sensitivity for creep, resulting from the sensitivity to moisture. Halfway, the decision was made to raise the security level from 2 to 4. This was achieved by applying an internal (invisible) compression tube (with a diameter of 50 mm) in the 5 main cardboard tubes, which would protect the visitors if the dome would unfortunately collapse due to the effects of creep. The cardboard industry was not amused, but our social responsibility may not be forgotten.

After two months of research and a long period of waiting for new tubes from the Dutch cardboard industry, we were still not convinced of the feasibility of the cardboard tubes for this dome design. In the end, the German company Sonoco was able to supply us with cardboard tubes that were 40% stronger than all other tubes previously tested. This extra strength was primarily achieved by the use of new instead of recycled paper; a learning stage for the entire cardboard industry. Of course the tested tubes are developed for packaging and not for construction.



FIG. 110 Exterior of the Hannover pavilion



FIG. 111 Interior of the Hannover pavilion

The final design process that followed the design of Shigeru Ban was executed at Octatube under my strict supervision. The initial divisions of Ban's dome were based on a 16-frequecy subdivision. Because I have designed over 30 domes worldwide – all in steel and aluminium – I know what repetition factors mean. Consequently I proposed to reduce the frequency from 16 to 8, or even 6. The number of tubes could be reduced to a quarter or even less. Ban, however, seemed to be in love with cardboard: the more the better. This was opposed to my minimalist principles including cost efficiency. But Jeanette van der Steen honoured the original design despite the fact that costs would increase if the dome would be realized in its original design.

A different issue concerned the edges at the bottom of the dome. The circumference of the dome would have 5 arches with a height of 1,5 metres; too low to walk underneath and use as an entrance. During that phase I proposed to deform the geometry and assign a height of 2,5 metres to the edge arch. This way the 'feet' could rest on the foundation plates and assure good accessibility. Subsequently a deformation came to existence with a regular geometry derived from an icosahedron. We could make a 'rubber banding' manipulation and design an alternative geometry with the help of computers. A slight 'blobby' edge to it, one could say. Nowadays, this is quite easy with contemporary computers, but in the days of Buckminster Fuller a similar deformation would be impossible. Ban was relentless; this proposition was no good for him. It was decided to stick to the original geometry and to build 5 corner nodes on 5 elevated tetrahedron-shaped supports.

05.04 CARDBOARD ENGINEERING

By e-mail, several discussions arose between cardboard lover Ban and metal tiger Eekhout about several aspects of the design, including the design of the node. Twenty years ago I developed a useful node for an aluminium dome in Jeddah that was covered with a double membrane and transparent insulation. With the help of a similar node design it was possible to connect the bars and the tent membrane that could be fixed and stressed. Ban kept stressing a wood-filled node, probably due to a Japanese tradition. The final design of the dome was based on a compromise: Ban determined the geometry with a relatively short tube-length (a 10-frequency dome) and Eekhout determined the detailing.

The detail consisted of a steel head on both ends of the tube with a flat perpendicular plate to fix it to the nodes. Connection tests proved the weakness of the cardboard at the transverse screws and bolts. In Hannover, Ban didn't use screws because the tubes crossed each other. Because the IJburgdome is composed of different shorter tubes and not continuous tubes, the geometry is defined by the nodes. Just like with metal space structures, the devilish question arose: *"Why would you shorten a factory-produced tube of 6 metres to let's say 1,5 metres, to eventually come back to 6?"*. Of course the answer is: utilising continuous tubes eventually results in tubes that have to cross each other.

The structural engineer prefers an axial connection. Nonetheless, the design would have gained better cost efficiency. Yet Ban vetoed this proposal of continuous tubes crossing over each other. In the final budget the costs of the steel components were 4 times higher than those of the cardboard tubes! Ban's Hannover pavilion had continuous tubes, but the tubes were only loaded to a tension of 25% compared to the IJburg dome. The limitations of the current state of technology concerning the use of cardboard in construction have notably increased because of this.

05.05 PRODUCTION AND INSTALLATION OF THE CARDBOARD DOME

On April 1st 2003, after 5 months of researching cardboard as a structural material, only 5 weeks were left before the opening. The client had built a house of cards of numerous sponsorships. That particular day the biggest sponsor (the VSB fund for culture) cancelled. Other sponsors threatened to leave the project since they only wished to participate on a co-sponsor basis: the house of cards was about to collapse. The deficit was €50,000. In a telephone conversation, while driving to Belgium, I proposed to split the shortage in three (Group van der Steen, Octatube and the Municipality of Utrecht, being the 2nd location of the dome). This created three risk-bearing parties that all had to carry a clearly defined risk. So the band could start rolling. The following Monday it was decided to start production immediately. Note the enormous difference in time between the initial material research & design development (5 months) and the production & installation (3 weeks). An experimental process has to be given ample time to develop!



FIG. 112 Test on pressure



FIG. 113 Test on pull

05.06 FINAL DETAILING

The last test concerning the type of connection between the tube ends and the heads of the node showed that bolted connections, screws and steel pins – all based on the principle of shear force – work highly inefficient when applied to cardboard. Using glue is also out of the question since it will only connect the inner layer of paper and will therefore easily lead to collapse. This is exactly the same for threaded connections. Dot-shaped connections should be avoided in these kinds of cardboard constructions with high loads.

One of Octatube's structural engineers, Luis Weber, introduced the brilliant idea to apply a steel tensile rod within the cardboard tubes. Pressure is locked up in between two steel head plates. The tensile rod accommodates the tension. In the factory the two galvanized steel heads were twisted in two right-threaded props with a 10 mm stainless steel thread and manually pre-stressed. True and high pre-tension cannot be applied: it wouldn't work because of the sensitivity for creep. The cardboard tubes (180mm diameter and 20 mm wall thickness) were fixed with steel 100 mm head ends within the tubes and connected to a star-shaped node with the help of two vertically aligned bolts in order to acquire a moment-stiff node. The star-shaped node consists of six steel plates welded on a round steel tube. The threads of the membrane connection in the star-shaped node can be adjusted in height in this arrangement. Further development would have to include connections in a cardboard like material, pressed laminated timber plates or timber composites in order to make a more harmonious material usage of cardboard. Still a route to go.

The edges of the dome consist of steel IPE220 profiles that are folded side-ways, but the heart of the body is placed in the axial plane of the dome bars. The IPE profile has steel tabs on the outer shell to tension the membrane that is placed over the tubes; protecting the cardboard form the water. The five folded edge profiles are hollowed to be placed on tetrahedrons: stabile corner columns with outward and sideways supports. All steel tubes are bolted down with steel plates on the concrete foundation slabs.



FIG. 114 Cardboard tubes with steel head plates.



FIG. 115 First frequency of the cardboard dome.

05.07 SHOP DRAWINGS AND PRODUCTION

After April 1st, 2003, a majority of the total engineering department of Octatube was occupied for two weeks, making the final design, production drawings, element drawings, the cutting lengths for the cardboard, the erection drawings and the anchor drawings for the foundation slabs. The steel parts were subsequently sawn, drilled, twisted, fixed and welded in small lots and sent to the galvanisation plant. The cardboard tubes were perfectly sawn by Sonoco. The cardboard was treated with varnish on its outer shell, the cut ends and 100mm inwards in order to cope with small amounts of moisture. The galvanized tube ends had to be slightly smoothened by hand, since they couldn't fit in the tubular ends. All parts of the dome were coded to simplify the erection process. There were 18 different types of nodes and tubes in 18 different lengths.

The membrane was engineered by Rogier Houtman of Tentech Delft (a small engineering company in the 'Silicon Valley' of the TU Delft) and produced by Buitink in Duiven. The membrane was a sand-coloured PVC coated polyester fabric. The assembly of the membrane took place with the help of small dishes on threaded rods directly through the centre of the nodes. The whole fitted exactly as planned and the membrane was stretched by twisting the threaded ends underneath the dome, so the dishes were pushed outward (subsequently stressing the membrane).

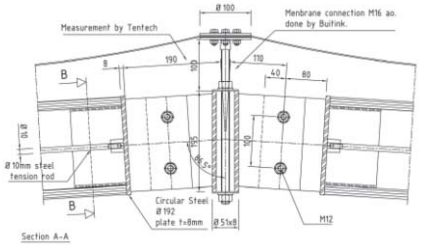


FIG. 116 Details of the connection nodes

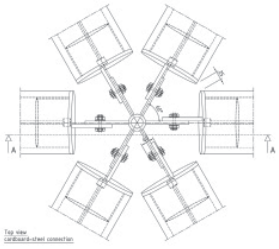


FIG. 117 Details of the connection nodes

05.08 ASSEMBLY

Initially, we intended to repeat a successful assembly method that was used 20 years ago by Octatube for an onion-shaped dome in Singapore right next to a mosque. A temporary mast was used to hoist the first ring, then the second, third etc. This made it possible to assemble the whole dome from the ground.



1



2



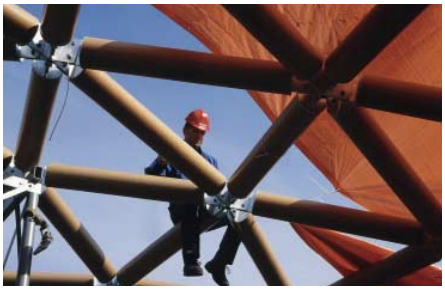
3



4



5



6



7



8

FIG. 118 First time build up of the cardboard dome in IJburg

We chose for a different kind of erection because of the relatively high dead weight of this dome (20 kg/m^2 opposed to 10 kg/m^2 for steel and aluminium domes). In addition, because of the rain, we required sails to cover the assembled dome parts and 5 supports for wind bracing. The build-up started from an elevated location of 5 supports on a container, tightened with leashes and gradually building outwards and downwards.

This assembly took place directly next to the construction site. At the same time the concrete foundation slabs were placed, the anchor holes measured, drilled and 5 foundation tetrahedrons were built with bent IPE beams. Days before hoisting the dome to its final position, on the 7th of May, the lower ring was assembled with bars on a steel circular beam. As a precaution, the dome was hoisted with 15 cables from a mobile crane to prevent peak-tensions in the structure.

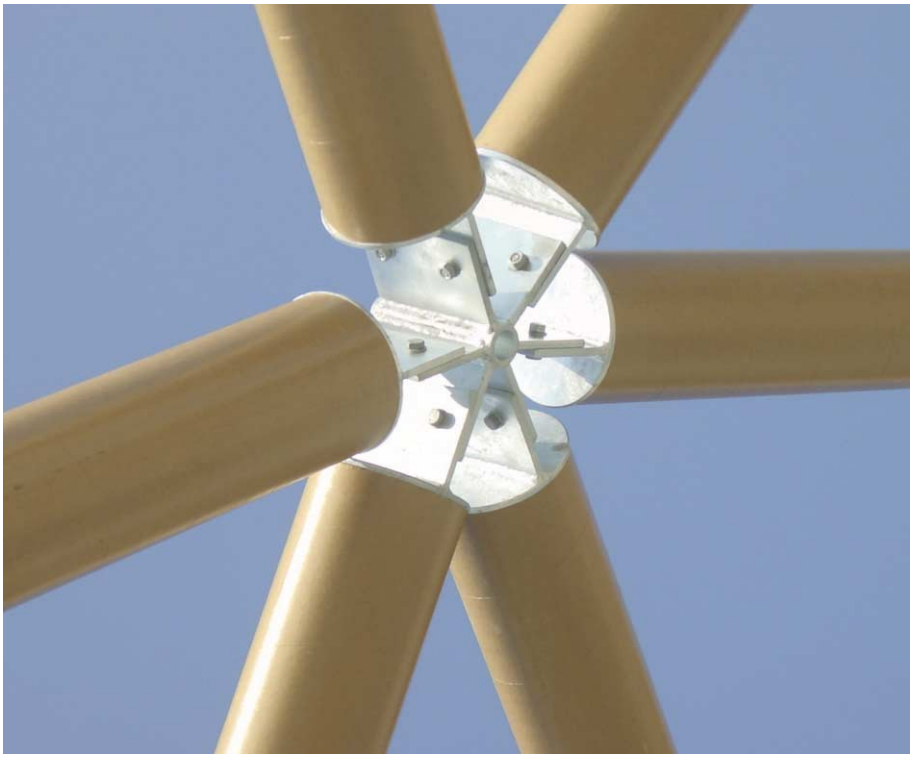


FIG. 119 Detail of the construction

05.09 HUMIDITY ASPECTS

Already during the research & development phase it was clear that next to creep, relative humidity also influenced the strength of the cardboard tubes. That was the reason to seal off the tube ends with a layer of varnish. But what is the influence of rain? If it rains during the assembly, water could trickle towards the tube ends and eventually get sucked inwards. A capillary effect between the steel shaft and the cardboard is no fiction either. The first week of the assembly it was beautiful dry weather, but the second week was very uncertain: rain and strong wind gusts up to 8 Beaufort. There was virtually no other choice than wrapping every individual tube with package foil or covering the finished part of the dome with a covering sail. We chose the latter option, but it seemed like covering the finished parts took as long as assembling the nodes and the bars. However, the result was a dome with dry bars. And the result is certainly a cardboard dome. Cardboard rules.

05.10 CLEAR DEVELOPMENT TASK

Constructing and assembling the hemispherical shaped cardboard dome turned out to be a relatively easy task compared to the experiences in the current turbulent Blob era. All parts of the architectural and structural design, choice of materials, component drawings, material research, production, assembly, disassembly and rebuilding were already figured out during the stage of design. A professionally executed design process is the secret of this type of structural task. Design, development and research were integrated to enhance the current affairs of technology. By publishing the results of our knowledge, ability and insight, it is possible to generate a far larger dispersal area; a mission of the chair of Product Development.

05.11 DISASSEMBLY, TRANSPORTATION AND RE-ASSEMBLY

In the late summer of 2003, the dome was disassembled and transported to Leidsche Rijn (near Utrecht) as an exhibition space. Disassembly, assembly and eventual protection against moisture again depend on the weather conditions. A fast solution could have been to double the number of 5 central ribs. This way the dome could have been disassembled in 5 triangular parts and transported on three trailers to the shore of the nearby Amsterdam-Rijnkanaal, then on a ship to Utrecht, 2 kilometres over land, to be reassembled in Leidsche Rijn. But to double the number of ribs was out of the question for the architect, who

preferred a more even character for the surface of the dome. This way the dome has to be taken down in smaller parts or bars and nodes in order to re-erect it. The transportation of the dome when still assembled (20 tons of weight excluding the steel IPE's, 26 metres wide, 9 metres high) is virtually impossible, but still an appealing alternative that was discussed during the design stage. The construction within the steel edges is rigid enough to be transported. The dome will be re-erected in Utrecht in 2004.

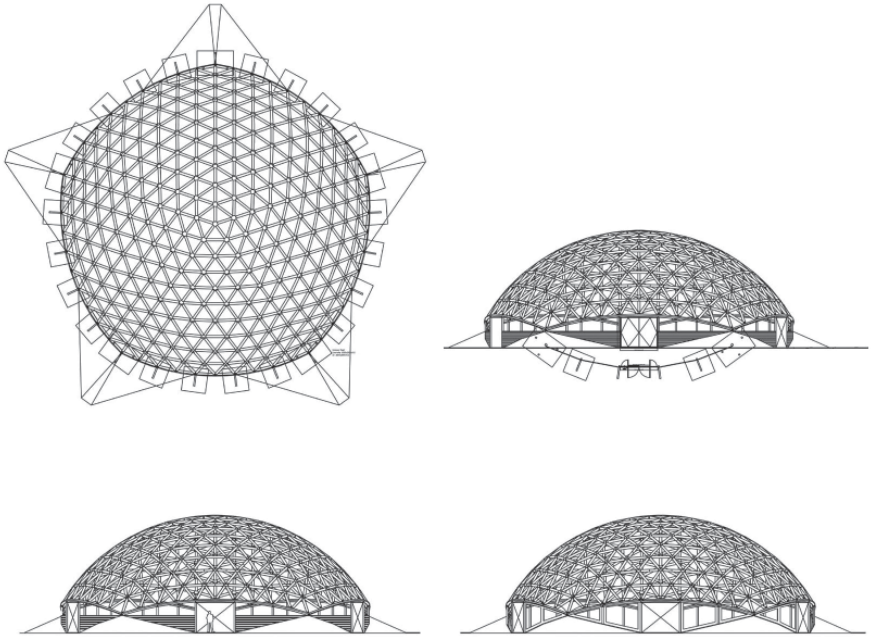


FIG. 120 Final drawings (as it was executed) of the dome

05.12 LESSONS LEARNED

An unusual material like cardboard, not produced to be used as a structural reliable material, had to be developed to become reliable. The selection and material research and development of the nodal design took 5 months; after that period the vocabulary was known and the dome could be produced and built with a normal time of 1,5 months. The material vocabulary had become mature. It was only later that the engineer of Ban's Hannover dome visited Octatube and informed about the engineering analysis. Since we did

not receive any information on how the Hannover dome was engineered prior to our work, we were not very generous with information either. After the dome had been built in IJburg, Amsterdam, it had been moved to Leidsche Rijn, Utrecht where it would stand for 7 years without any problem.



FIG. 121 Dome in Leidsche Rijn



FIG. 122 Interior view

06 GRP SANDWICH ROOFS FOR THE RABIN CENTRE, TEL AVIV

Original lecture for Delft science in Design, TU Delft 2007.

06.01 INTRODUCTION

Technical design of roof and façade structures for architecture has accelerated over the last 3 decades from well-known traditional solutions to technically innovative solutions. After the development of stretched membrane structures in the 1970s, systemized metal space structures in the 1980s, sophisticated tensegrity structures in the 1990s, glass envelope constructions and load bearing glass structures of the last decade it is now 'Liquid Design', 'Free Form' or 'Blob' architecture that caught the interest of young architects. The description of this type of architecture originates from a free form geometry, non describable with any regular mathematical formula. In a sense it is a direct consequence of technology driven interest of architects. Having learned the newest generations of 3D design and engineering computer programs, they are now capable to design (geometrically) complicated virtual 3D buildings that seem completely real on the screen without even being built. Yet the route to realisation is paved with numerous technical (and some social collaboration) experiments to produce the technical 3D components of these 'Blob' buildings. Often these components will be 3D-curved. Usually they are one-offs in their shape and non-repetitive. The extreme contradiction is the request for custom-made components versus the low budgets of the building industry on the one hand, and researching and developing technological innovations at the speed of a real time building project process in order to acquire the new technology just-in-time on the other hand. The aid of other design professions like aeronautics, ship design and industrial design is very inspiring and necessary in order to develop a new 'Blob' technology with the 3D forms, yet fitting within the modest average m^2 budgets of the building industry. Extension of the building industry's traditional integration is necessary in order to develop suitable CAD/CAE, CAM/CAB procedures and special production and surveying technologies. In this case, producing one-off GRP stressed skin sandwich components

made it possible to create larger spans for the roofs, though in an arbitrary form in order to become true 3D roofs.

Designing structural systems for use in architecture – including the necessary research & development, but always leading to actual realizations – is the core of the author's personal attitude towards designing. Many of the structural and constructional designs made as an architect, as a pioneer of space structures and as a structural designer, have followed an incremental approach of step-by-step with ever increasing know-how and elevated insight. This started for smaller projects in the Netherlands and led to applications of increasing scale both in the Netherlands and abroad. This approach is adapted to the (smaller) scale of projects in the building industry, their ever deviating character depending on the designing architects, their real time planning schedules and the desired degree of experimentation of the technical designer. The projects are performed as 'design and build' contracts in the Octatube company at Delft and sometimes in the architect's office. The position as professor of product development at the TU Delft and the range of collaborating faculties within the Delft University of Technology itself offer excellent opportunities for contemplation and sharpening of the mind amidst scientific design colleagues from different disciplines. This particular second congress of Delft Science in Design enables us to continue the debate on the merits of scientific design at TU Delft. To discuss the merits of design, development and research and to discuss the valorisation side of designing, developing and researching as the major activities of the TU Delft. Design is able to funnel results of scientific research to society. The relationship between research and design are mutually indispensable.

06.02 INVENTIONS, INNOVATIONS AND A COMPETITIVE MARKET

Amongst the ever-recurrent obstacles in component design and product development in architectural projects are the low thresholds in the building industry, the lack of interest in entrepreneurial experimentations and the overall tendency for copying the results of the experimentation of others, minimizing the experimental expenditure by the lazy policy of 'wait-and-see' or the 'me-too' effect. This is counter-positioned by the experimenting designer, dragging an office and a company behind him that follows his whims, willing and able to undertake all technical adventures in the process. This has been a life-long attitude.

After the initial product design and developments of a new generation of structures has resulted in successful applications, professional publications are written. After publication, new clients become interested but the competition has been awakened, too; this flow of events haunts every new invention. It was this framework that made the Europeans invent the protection system of patents in the 19th century. But with many different systems

at hand and even more differentiated applications, patents do not protect inventive development work in architecture. The number of repetitions is low and the variety asked in different projects is high. The eternal fate of the architectural and structural designer is to look for new horizons: either new markets for existing products or new products for existing markets. Luckily, a number of 'me-too' competitors, for example in Israel, made a mess of their copied systems, but alas these projects were lost in the tender stage any way. For the Hashalom (Peace) project in Tel Aviv the client regretted his decision to subcontract an Italian glass company for frameless glazing, changed his mind, withdrew the contract from that consortium and contracted the original designer company, who redesigned, engineered, produced and installed the project in a miraculously short time. Because the building calendar has its own speed. Over the last years prices for frameless glazing systems are dropping due to competent and incompetent rivalry. Although experimentation with a large distance between production and building site adds to the possibility of a negative outcome, the composite wings of Tel Aviv are an example of a well-defined experimental component design & development for one specific project. After successful completion this could lead to an entirely world-novel technique of engineering and producing roofs for liquid design buildings. In turn, this hopefully leads to the establishment of a new Dutch consortium of small and medium-sized enterprises (SME). It is further to be expected that after duplication, multiplication and systematization of the developed technology the laws of economics will interfere and that the enterprising structural engineer has to develop ever new products and systems.

06.03 STAGE OF TENDER DOCUMENTS

In November 2002, the client 'Friends of Yitzhak Rabin' issued tender drawings and specifications of a design by architect Moshe Safdie from Boston, USA, as a part of the Yitzhak Rabin Centre in Tel Aviv. The design of the building was an elaboration and extension of a former auxiliary electricity plant near a university campus of Tel Aviv in order to become a memorial building for the late Prime Minister Yitzhak Rabin who was murdered in November 1995. He was seen as a peace maker and was rewarded the Nobel prize for Peace in 1994. His activities led to the so-called 'Oslo peace talks'. The entire building was tendered out in different lots. This particular tender provided for two building parts: the 'Great Hall' and the 'Library'. These two big rooms both have large glass façades facing south towards the Ayalon valley below. Both hall designs have remarkable and plastically designed roofs to resemble dove wings as a tribute to peace maker Rabin. Moshe Safdie is well known since he designed the dwelling complex 'Habitat' of Montreal as a part of the World Exhibition of 1967 when he was 27 years old [Ref. 06.01].

This was the author's second collaboration with architect Moshe Safdie: the first one being the conical glass wedding hall of the Samson Centre in Jerusalem, overlooking the valley adjacent to the old city of Jeruzalem near the Jaffa Gate. Safdie is an almost prophetic

designer who designs beautiful spaces with dramatic interiors. During the last decades he redesigned the Jewish quarter in Jeruzalem. The Samson glass dome, overlooking the ancient city with its golden colour in the afternoon, is used for marriage feasts and other celebrations, and is a great success. The hall is used for weddings twice a day. Safdie was very satisfied with the alternative design proposals for the cone and with the realized technical accuracy. For the new project, the complicated liquid design roofs of the Rabin Centre contained in the tender were analyzed by ARUP New York. They proposed a welded grid of steel beams in a rather arbitrary running of the open steel profiles covered with a layer of concrete. The specification left the roof cladding up to the contractors. On top of this, the architect requested a seamless solution over the entire roof. Not a very appealing specification for a design & build company which had to transport all items over a distance of 5.000 km. For two months, the tender drawings and the thick specification booklet were not given much attention. The 'seamless' requirement would make any prefabricated system very difficult to apply, and the success would depend entirely on local labour and supervision, which a producer of industrial and prefabricated systems does not like. However, the client and his building manager kept on reminding of the tender date and even postponed the tender.

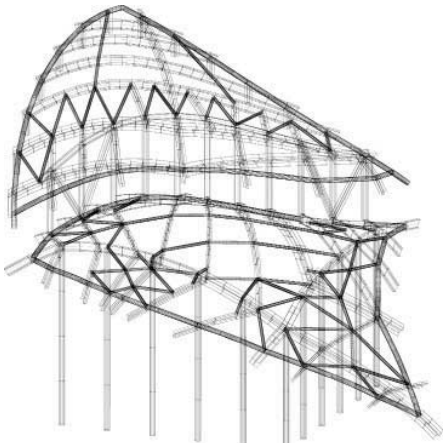


FIG. 123 Tender drawing of 'The Library' made by ARUP

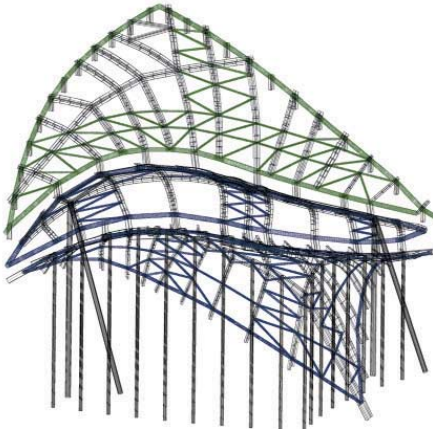


FIG. 124 Tender drawing of the'Great Hall' made by ARUP



FIG. 125 Architectural model of the Rabin Centre, Tel Aviv (courtesy: Moshe Safdie & Associates)

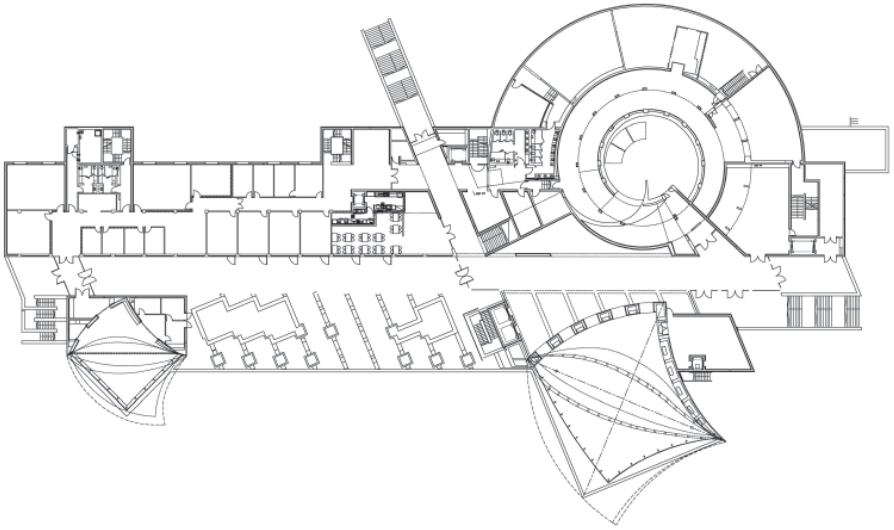


FIG. 126 Plan of the Rabin Centre, Tel Aviv (courtesy: Moshe Safdie & Associates)

06.04 DEVELOPMENT OF CLADDING SYSTEMS THROUGH PROJECTS

When struggling with an alternative technical design for the new cladding of the Atomium of Brussels (dating from 1958), TU Delft's professors Adriaan Beukers and Michel van Tooren (Faculty of Aeronautical Engineering) stated in their inaugural speeches that

"aeroplanes always leak and condensate" [Ref. 06.02], [Ref. 06.03]. This one sentence inspired the quest for a re-cladding concept of the 9 spheres of the Atomium. The end result was that in the technical proposal each of the 18 m diameter domes was to be clad with 2 x 8 spherical segments in the form of half an orange peel, size: 14 m long, 8 m wide and 3 m curved. This resulted in a solution in which the total length of the seams was restricted to only 20% of the original joint length, which was 20.000 m. Even a low leakage percentage of 1% would result in 100 m of leaking upper seams. In the developed proposal, the joints were detailed much like the old-fashioned 'Double Improved Dutch Roof Tiles' with double internal joints that never had to be replaced or maintained. Leakage problems would belong to the past with this solution. A patent was applied for. So in this case, an unexpected impulse from aeronautics helped to develop a new concept. Alas the politics around the tender were quite obscure and the contract for execution was awarded to a Belgian party. The design proposal maintains its value, however, and is published here for its inspiration, returning to the alma mater of the original inspiration.

One year before the tender date of the Rabin Centre, the design, engineering and building of the Municipal Floriade pavilion (now named Hydra Pier) of Asymptote Architects from New York was completed. One of the three experiments in that project were 3D-aluminum panels of 5 mm thickness which were deformed through explosion on negative concrete moulds (based on machined positive polystyrene moulds). This production process originally seems to have been used in Russian submarines in the 1960s. The paths of technology transfer can be curious. This process took place at the premises of the Exploform company in Delft. This complete production procedure from engineering drawings, via Styrofoam negative moulds and reinforced concrete moulds, the explosion process, the measuring and fitting on timber moulds up to the finished and installed watertight and coated panels proved to be a feasible, but also a laborious process to fabricate as 3D-curved panels. It was the first time in the world that 3D aluminium panels for architecture were produced along these complicated paths. Although the cladding was successfully realized in this Floriade project, the m^2 price of the 3D panels was too high for another project in the building industry (which – in the Netherlands – was also on the brink of recession at that time).



FIG. 127 Close-up of the Atomium, Brussels



FIG. 128 Scheme of the proposed division: 2 x 8 spherical segments in GRP

A cheaper system had to be developed for the next project. Haiko Dragstra, a very inventive mechanical/electrical engineer co-operated on this project from his company Complot, Delft and came up with the idea to take thinner sheets of aluminium, laminate a foam panel with parallel transverse sleeves and an epoxy laminate as the inside skin in order to make a strong and stiff panel. So these panels were half aluminium, half composite sandwiches. One step further was to make the complete panel out of two composite skins with a foam core and have the outside skin coated, if needed in an aluminium metallic colour. One does not see the difference from painted aluminium or steel panels and polycarbonate components in cars. However, at the time Asymptote Architects did not like the idea of mixing different materials, according to the contractor. It was this line of thinking that brought the development further. Haiko Dragstra was able to machine foam blocks into any desired form with machines he built himself. Machining according to CAD data is possible both for the top and bottom layer of the foam. The total surface of the roof was subdivided in blocks and glued with the machined blocks of foam. Subsequently structural layers of glass-fibre reinforced polyester were applied to each side. These experiences came on the table when brainstorming the new principles for the 3D wings of Tel Aviv.



FIG. 129 Exploformed aluminium panel



FIG. 130 Fitting of a panel on a mould

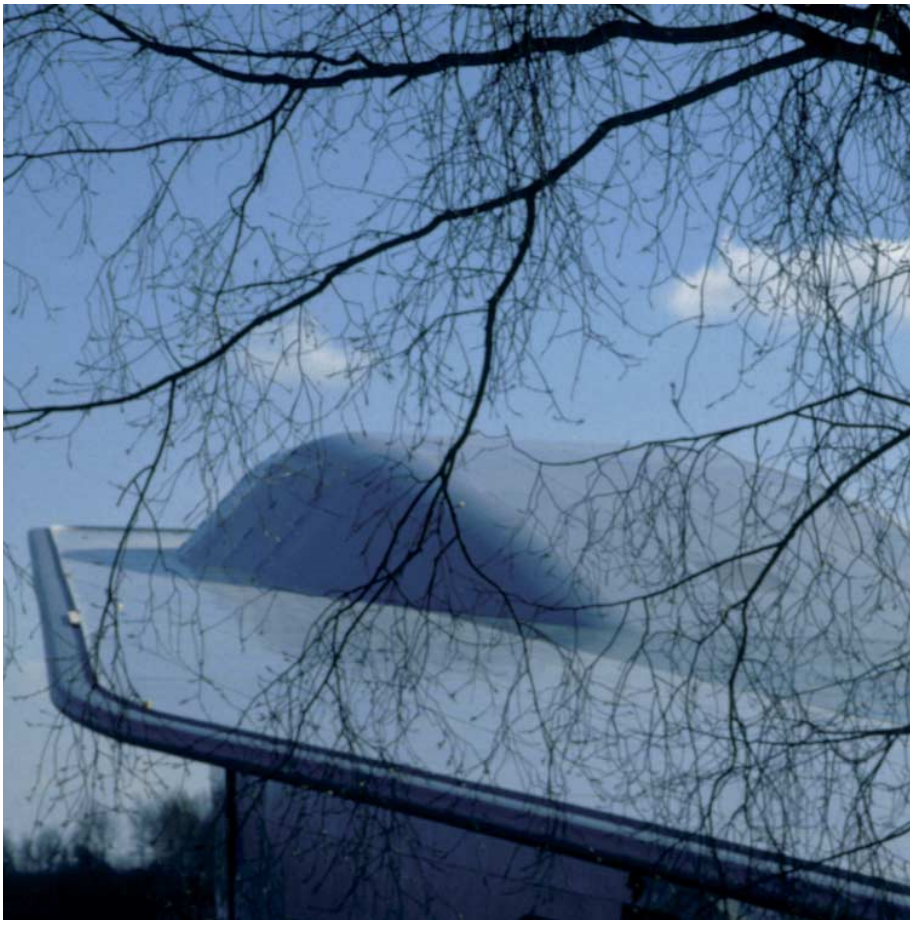


FIG. 131 3D curved roof of the Hydra Pier, Asymptote Architects

06.05 GIANT STRESSED SKIN SANDWICH CONSTRUCTIONS

So in a few brainstorms between designers and co-makers of different background, collaborating in a tender consortium, this was the basic idea: make the roofs as giant surfboards of foam with stressed GRP skins on both sides. The size of the roofs, subdivided into 5 different roof wings was maximum 30 m x 20 m. The company Polyproducts of Werkendam and its engineering office was invited to join the tender team of Octatube, as well as Haiko Dragstra. In a month's time, three successive brainstorms were organized on the product idea, the structural concept and the logistics & pricing. It was decided to work out and price the revolutionary stressed sandwich skin alternative as well as the original tender specification of the steel structure with a non-described, free covering as the variation. The steel deadweight of the steel structure was estimated by ARUP, so a price of the original design with the steel structure, supposed in curved CHS (circular tubes) with cladding variations in different foam layers, levelling and top layers was feasible from existing data and a little imagination. The cladding proposed for the original tender design was derived from the mega-sandwich idea, but now in a thinner scale version of 50 to 80 mm sandwich thickness, as it only needed to span the space between the steel structure elements (max. 3 m).The budget calculations came out on a level of 2,5 million Euros for the original design with a thin 80 mm thick GRP sandwich cladding instead of concrete. The alternative design with the full load bearing stressed skin sandwich would add up to more than 4 million Euros, largely due to the high estimates of the production of the polyester parts. The producer had never done a project of this magnitude but knew how to operate the production of sandwich panels using vacuum injection methods. It was argued in the final brainstorm that the maximum extra costs would not be acceptable to exceed the sum of one million Euros extra, resulting in a total alternative price of 3,5 million Euro. It was foreseen that any architect would fall in love with the alternative idea of the self-supporting stressed skin sandwich. This was the solution faxed to Israel, just in time before the tender closing date, accompanied by a letter explaining the two quoted systems: the original specification (with a variation on the tubular structure and the cladding) and the alternative for the composite sandwich panels.

06.06 AMAZING SOLUTION!

Only two days after the tender closed a telephone call was received from the local representative architect Zachi Halberstadt, speaking on behalf of Moshe Safdie. He gave the compliment that the architect saw the alternative proposal as "an amazing solution". Halberstadt invited for an immediate meeting in Tel Aviv the next day, so that the idea could be presented to the entire building commission. At this presentation, the polystyrene

models that Haiko Dragstra had machined in a demountable model scale 1 to 40 were shown. The models also proved that the corner details in the design had not yet been accurately designed and that the overall stability was not satisfactory. The design needed considerable attention to design perfection. But the enlarged scale model showed the seriousness of the tenderer.

The building commission was astonished after hearing the explanation of the construction and the consequential logistics of the alternative proposal. The five big wings would have to be constructed in one of the empty ship building halls in the Netherlands, like at Krimpen aan den Ijssel. This size of hall was necessary as the wings would have to be turned upside down after application of the stressed skin layer on top in order to apply the lower layer. The milling polystyrene machine had to be moved nearby this production hall and to be installed adjacent to the assembly area. After gluing the polystyrene blocks, the top skin could be applied. That is, if the polystyrene blocks would form a roof wing in horizontal position. After completion of the GRP top skin, the object had to be turned over and the bottom skin had to be applied. After the completion of the surfaces of the shells, they would be loaded on an open inland vessel and towed to the port of Rotterdam, where the cargo would be loaded on a specially chartered ship in which the 5 finished shells could be stacked vertically.

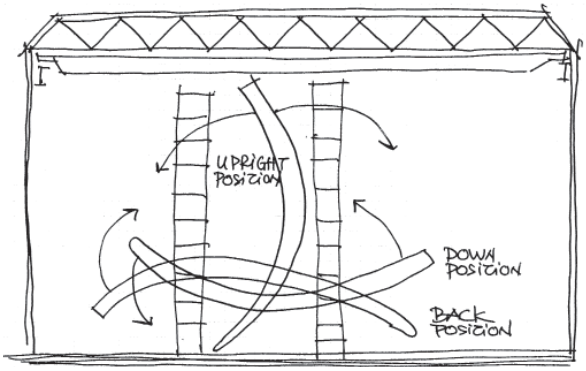


FIG. 132 Schematic drawing of a shipyard building with roof-wing positions



FIG. 133 A 'wing' transported by helicopter (photomontage)

This ship would sail to Tel Aviv and anchor at sea in front of the city. From this location a giant freight helicopter would lift the roof wings individually from the vessel to the shore, 5 km inland during the night, to position the roof wings on the flat open building site. A mobile crane would then swing the roofs on top of the columns. The whole shipment and air transport was rather special and expensive. After explanation of the logistics of this alternative proposal, the representative Boaz Brown heard architect Moshe Safdie mention to the chairman of the building team in Hebrew: *"you should try to get the one million extra"* or words of that meaning.

06.07 EXTREMELY INNOVATIVE, BUT EXPENSIVE

The client's building commission went into a separate meeting. After one hour of fierce discussions, the outcome was that the tender original with the thin GRP covering was practically on the average tender price level. On the other hand, they noted that the alternative proposal with the composite sandwich constructions was indeed very attractive from the viewpoint of its extremely innovative design and construction, but was priced one million Euros over budget. By the way, from a selling point of view and knowing the intellectual value of the alternative proposal, it would have been stupid to sell it at a lower price than the tender proposals. Usually, technical alternatives are more efficient solutions for the contractors and tend to be lower in price than the original. A more expensive alternative is rare and hence extraordinary. Starting with the highest price and the best technology, may end with a contract at a compromised price. 'Avant-garde' designers also loose projects to competitors as these can copy the new technology after one completed project and execute it without the necessary research and without the higher Dutch labour costs of Octatube. But in the case of the wings, there was no suitable technology yet in the world. The alternative idea was to become a technical world novelty and Moshe Safdie understood this.



FIG. 134 Sydney Opera House, architect: Jørn Utzon



FIG. 135 Detail of the Sydney Opera House

The discussion at hand with Safdie was about the Sydney Opera House (built in the 1970s) and how lucky architect Jørn Utzon would have been if he could have used stiff GRP sandwich panels instead of the heavy concrete shells and ceramic tiles. But still, the realization of the Opera House meant a major step in the history of structural engineering. The Sydney Opera House, with its problematic realization, its extended build time, budget explosions, growth of Ove Arup Engineering and the architect's dismissal from the site, is now the most admired building of the continent of Australia. These discussions showed that the marketing concept had apparently worked. Safdie ascertained his belief in stating that he thought the idea was amazing and never done before to his knowledge. If someone

could make it work in his opinion, it was to be Mick Eekhout cum suis. The response of the chairman of the building committee was to come up with different logistics for the GRP sandwich proposal in a manner that the price level could be lowered to 2,5 million Euros. He suggested that it might be possible to transfer the foam machining and the GRP production to Israel in order to reduce costs for shipment and labour at the same time. This was the message taken home on 29 of April 2003.

06.08 RETHINKING THE ALTERNATIVE

Back in Delft the consequences were discussed with the in-house engineers and the external consortium tender team members. The plan was born in the airplane from Israel to the Netherlands. If the GRP sandwich roofs could be realized, it would be a hit on the world market. It should be possible to transfer more labour to Israel in order to reduce costs and talk to new Israeli partners if the current partners would let the project down in order to realize this proposal. The first idea was to try to decrease the big wings into transportable components, which could be assembled on-site on a jig, smoothen the visual surfaces between the individual segments, to finish the outer GRP layers and give the shells a final top-layer or top-coat. Complot could machine the polystyrene blocks locally and Polyproducts could set up an Israeli GRP plant in Tel Aviv on the building site. The most likely position to assemble a wing would be in a vertical position. This way, both outer skins on the polystyrene core foam could be treated simultaneously and the shrinking of the foam could be controlled. Subsequently, the roof wing could be easily lifted by a mobile crane from between two 20 m high scaffolds.

However, after a few more meetings it appeared that machining the polystyrene blocks in Israel seemed very expensive. The subcontractor was not experienced in estimating larger productions than mock-ups. He had never exported his products and felt uncomfortable in unknown areas. The bottom price of co-maker Polyproducts in Israel did not give much hope either. So the co-maker would presume a high degree of innovations in this project and kept his price high. At the same time, the usual squeezing of tender prices had set in, which forced the sales department to land on another price level altogether. For sake of financial negotiations, another point of view had to be considered. It was decided to put the initial emphasis on the original design with the internal steel structure and sandwich coverings. To take an internal and hidden steel space frame with a locally made sandwich panel system on top and bottom, forgetting for a moment the attraction of the possible world novelty of the stressed skin sandwich constructions, just to stay in the race. Based on this price and on the technical abilities, Moshe Safdie was still convinced that Octatube could do the best job. Therefore Safdie pressed the client to take a wise decision: to issue an (experimental) pre-engineering contract to execute the design development and make material prototypes. A separate pre-engineering contract (or prototype development contract) was drafted for redesigning some steps on refinement of the roof models, and

investigation in prototypes for different composition, to convince the makers themselves of the attainable quality and subsequently the architect and the client. After this decision, the process went into redesign development and developing prototypes of segments of the construction of the Great Hall with the most complex wings, assuming that the details of the Library would follow those of the Great Hall.

06.09 REDESIGNING, PRE-ENGINEERING AND PROTOTYPING

In the course of the design development of this first prototype development contract, the redesign had to follow the rough contours given in the tender stage by Safdie's office. The official data of the three wings of the Great Hall were handed over by the architect's office as a Rhino scan from a material 3D model. The data within this model needed serious converting, since they proved to be inadequate and too inaccurate for further engineering. Through analysis of different cross sections of the model and connecting these in fluent lines, a new and usable 3D model was developed. This ensemble was redesigned in another modelling program: Maya (3D CAD software). This software turned out to be an excellent medium for designing the different components. Also, the same software enabled constituent parts to be defined and combined into the total composition of the project: five sandwich roof wings, the steel columns, the three skylights and glass panels in the 4 glass facades. At the same time, a global structural analysis was made of the structural behaviour of the GRP wings and the steelwork. During this time, the two quoted construction types were both worked on: the original version of a tubular steel structure of systemised CHS circular sections, covered with a thin GRP sandwich as the roof covering and the alternative designer's option of the structural sandwich composite structure.

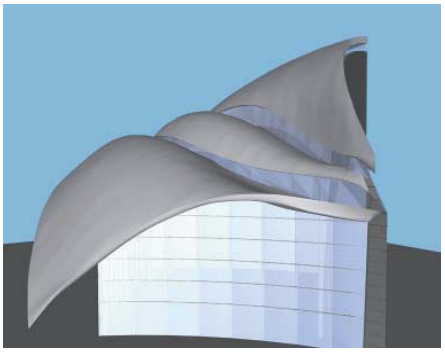


FIG. 136 The Rhino model of Moshe Safdie & Associates

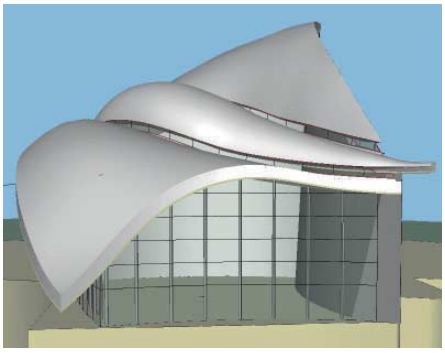


FIG. 137 The first redesign in Maya by Octatube

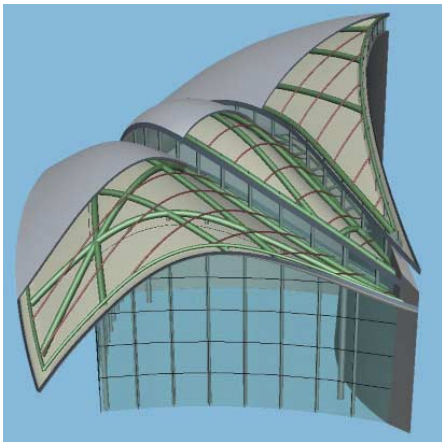


FIG. 138 A steel structure of CHS circular sections.

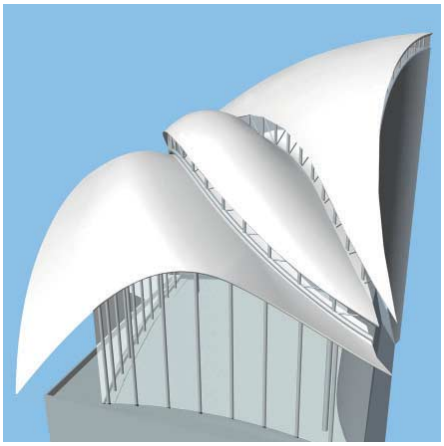


FIG. 139 The structural sandwich structure

Sales negotiations with the client had resulted in an unavoidable change on the purchase side of the co-maker for the polyester work. The price of Polyproducts remained fixed on a too high level and they were terminated as a co-maker in the process. Holland Composites Industrials (based in Lelystad, NL) was invited as the polyester co-maker in their place. They had previously made hulls of motor yachts and sailing yachts in glass fibre reinforced polyester (GRP) up to 30 m long with the vacuum injection method. This was an excellent starting point for the development of the structural sandwich panels. They employed the firm Solico Engineering (based in Oosterhout, NL) who started to globally analyse the GRP roofs. The two structural analyses of Octatube and Solico were compared and matched.

At the same time, prototypes were made of both construction types: the tubular steel structure with a light composite sandwich polyester covering and the alternative designer's solution of the integral composite sandwich. Both prototypes were shown to architect Moshe Safdie, together with the first results of the Maya computer redesign work in July 2003. In the mean time, this pre-engineering work had indeed resulted in a dramatic reduction of the cost price as the engineering team became more and more familiar with the experimental aspects and how to resolve these. The original quotation was reduced to around the original average price level, thanks to the results of this pre-engineering contract. So the pre-engineering contract, as it was seen by all involved in the process including the client, was a wise decision. Such pre-engineering prototype contracts are often proposed for experimental projects in the Netherlands, but hardly ever rewarded. The effect is that both sides get accustomed with the characteristics of the experiments at hand, and that the makers loose uncertainty, which would result in adding high contingencies in the global price. Clients mostly refuse these pre-engineering contracts out of fear for monopolisation of the involved contractor. In that case the client could also have the architect undertake such a prototype development contract with restricted legal conditions. And indeed, monopolies are almost a natural consequence of specialization.

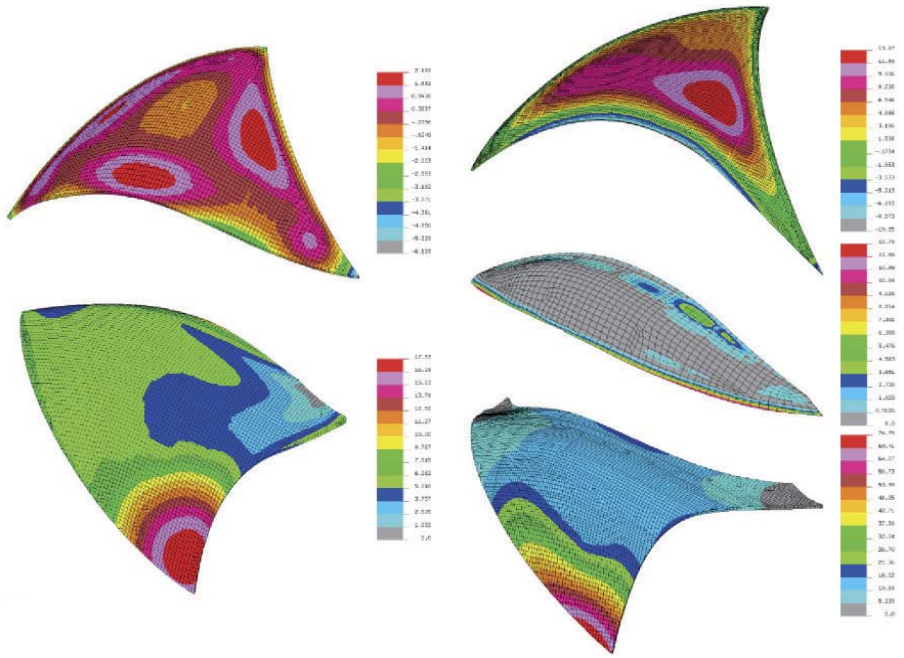


FIG. 140 Structural analysis of deformation of the GRP sandwich roofs made by Solico

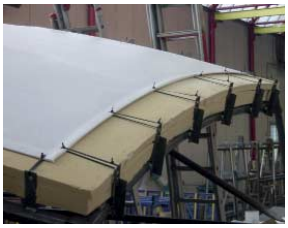


FIG. 141 First prototype with a stressed membrane



FIG. 142 Third prototype to be locally produced



FIG. 143 Fourth prototype, a prefab sandwich construction

06.10 RESULTS OF THE PROTOTYPE DEVELOPMENT

The route from redesign, pre-engineering and prototype development to final design took one year, involving 5 to 6 engineers. The architect visited the development laboratory in Delft twice during that time to check the progress on the design and the new prototypes that were made on his specific instructions. It was agreed that, in contrast to previous projects

involving Blob structures at the engineering department, there would only be one party involved with computer work. In this case, the engineering department would be in the lead and the architect would only supervise and give instructions behind the monitor. It would also put the legal responsibility on the same table as the technical development responsibility. The impulses from the development of the prototypes, the production methods involving moulds and injection production plus the future assembly of the structural seams and the structural behaviour of the total wings, all had a deep impact on the final design and had to be fixed by the responsible 'design and build' contractor. The described innovative developments followed the three axioms of the contractor: "Design and build in one hand", "Integration of architectonic, structural and industrial design" and "Development of new and experimental products". Respecting the wishes of the architect, an intensive design and engineering path was followed; mastered in the engineering department, co-ordinating Holland Composites and Solico Engineering as indispensable co-makers. The urge for new product innovation, courage, spirit of enterprise and a certain naivety (not to know beforehand what hindrances would come in the future years of development of the project) prepared the embedment of an engineering course with multiple degrees of innovation. During the entire process, the design methodology as development for special components, consisting of 3 main phases, as published by Eekhout [Ref. 06.04] were followed quite literally:

- Design Concept,
- Prototype Development
- Production Preparation,

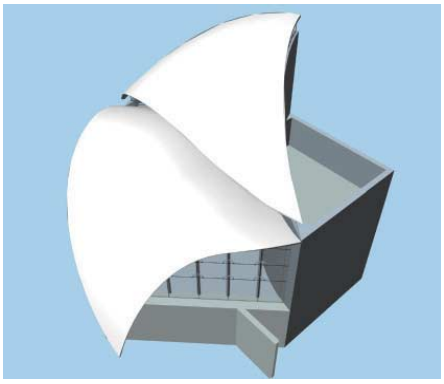
06.11 TECHNICAL ENGINEERING AND PROTOTYPE TESTING

After the first year of experimental work and prototyping, the final 'design & build' contract was agreed upon on the basis of the adapted quotation and the approval of architect Safdie on the quality of the prototypes. The final engineering started on the basis of AutoCAD and Mechanical Desk Top.

The final analysis incorporated:

- Final production methods of the GRP wings,
- Testing of the connections of the sandwich panels on de-lamination,
- Assembly connections loading deformations,
- Fire resistance,
- Logistics in the Netherlands,
- Transport of the sandwich segments in special open containers,
- Assembly of the segments on special moulds on the building site,
- Jointing and finishing the wings,
- Hoisting of the completed wings into position.

After the prototype development phase of the first year, final engineering including prototype construction testing in the laboratory also took one full year. On the Israeli side, approvals became very complex, however. Due to political change in government from the Labour party of Rabin to the Likud party of Sharon, all proposals were reviewed by the local government bodies with extreme attention, so that many unforeseen and sometimes unnecessary problems were detected by the governmental bodies and had to be neutralized by the engineering parties. Many people in Israel apparently wanted to see the project uncompleted or stopped half way. This also led to the involvement of the two experts in the field of glass fibre reinforced polyester: two professors of the TU Delft, faculty of Aeronautics, Prof. Adriaan Beukers and Prof. Dr. Michel van Tooren, who played an inspiring role in the Atomium re-cladding project. They were invited by the client (The Friends of the Rabin Centre) directly to draft a second opinion on the supplied engineering, and played their role in this project honourably.



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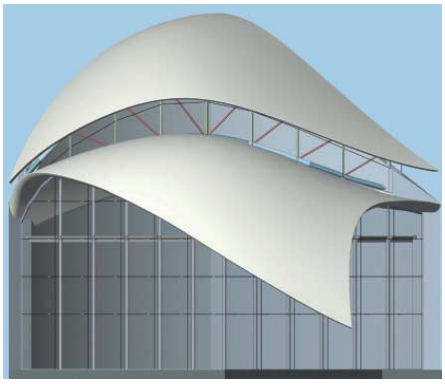

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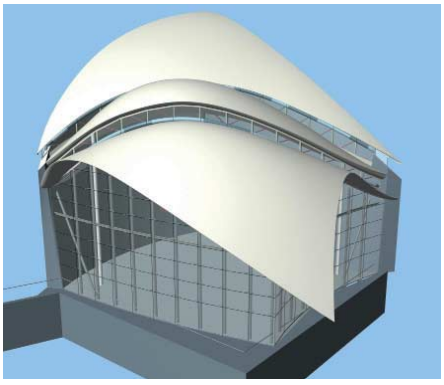

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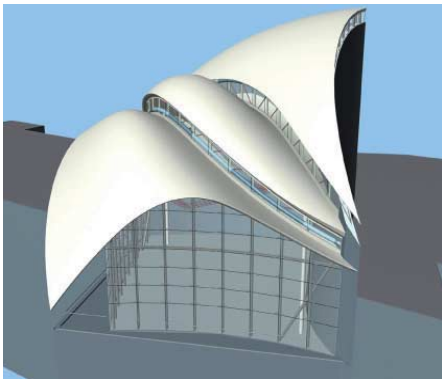

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FIG. 144 Birdseye and frontal views of 'The Library' and 'The Great Hall'

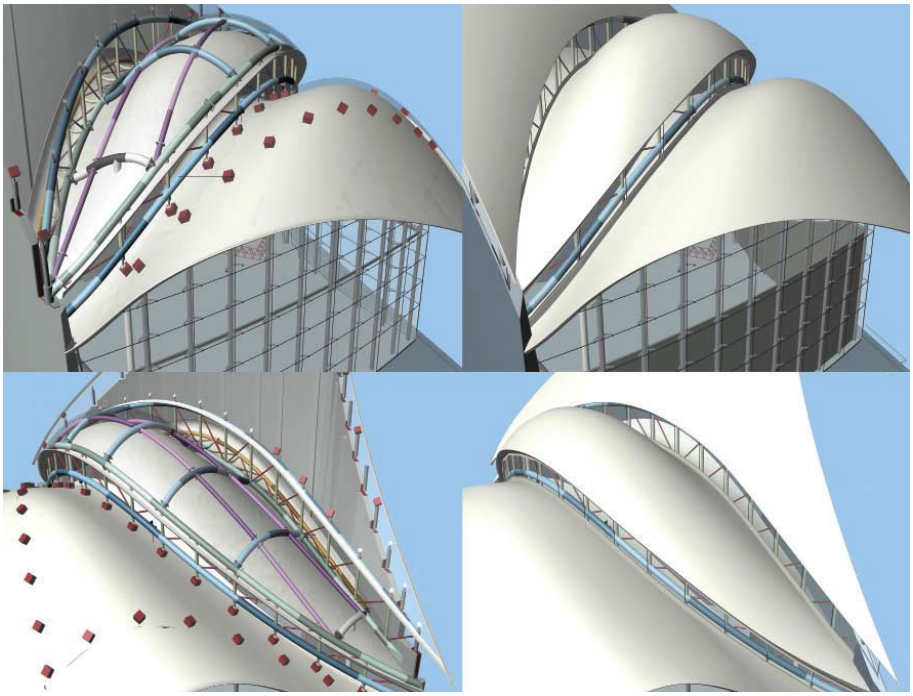


FIG. 145 Close-up of 'The Great Hall' wings with insert points for connectors to connect the wings to the columns

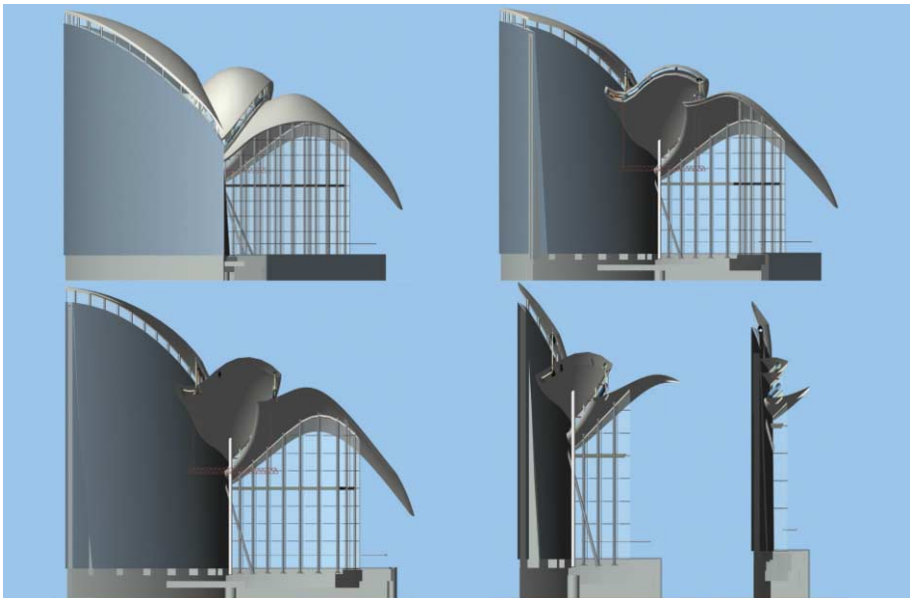


FIG. 146 Five sections of 'The Great Hall'

06.12 PROTOTYPING, PRODUCTION AND INSTALLATION

After two years, in January 2005 the go-ahead was given for production. From that time onwards the production of the composite segments went into operation. Hence the third project year of production and assembly started with the experimental production of the components on the negative moulds. It was decided that production would start with the smaller roof of the library; one reason being that the client had in the back of his mind to build the Great Hall only eventually; just in case the costs of the sandwich construction operation would be too high. So seen from the learning curve in the production development, the production of the two smaller roof wings of the library was taken up first.

The production technique used in this case has been taken from standard production techniques of producing sailing ship hulls, such as Holland Composites had produced its integral mono-hull ship hulls. The base of the vacuum injected production was a good point of departure. In case of the sandwich wings, the second dimension of the largest wings of 30 m x 20 m (compared to the 30 m x 5 m boat hulls) and the impossibility to sail the completed wings independently to the site like a sailing ship, proved to be a major experimental challenge for the GRP production. It was decided that the entire wings would have to be produced in more or less rectangular segments, to ship them out stacked in containers and to assemble them in the form of the completed wings onsite and finally hoist them in as wings. This meant that the segments had to be produced individually in their deconstructed shape of one-off forms. Each segment form was different.
All segments had a different form and some had long asymmetrical points. The shrinking of these segments after curing of production proved to be an unforeseen adventure. Shrinking of each segment appeared asymmetrically, always in a different direction, and during production one could wonder how all of these twisted panels could lead to a smooth form.

Unusually for the co-maker, the production necessarily proved to be very engineering intensive. The foam blocks of polystyrene had been milled accurately by Marin bv, specialised in moulding ship models for hydraulic testing, to negative moulds from CAD/CAM files. After the milled moulds arrived at Holland Composites, the surface was first topped with an epoxy skin to work on, and then covered with a plastic foil. In the vacuum-injection procedure, glass fibre is impregnated with polyester resin by sucking the plastic envelope around the fibre weaves and foam core blocks vacuum, and by feeding polyester from the other side to enter into the cavities of the construction: in the fibre weaves and between the foam blocks. Since the resulting layer of GRP on the mould side describes the desired form of the roof in the best possible way, this side had to become the upper layer of the roof. From the prototypes it was concluded that the segments had to be produced top down: the upper surface needing the most accurate form in the opinion of the architect as the sun would shine over the upper surface and would always result in tangential rays over the surface. Hence all regularities would be ruthlessly visible. Less so on the lower side with its indirect day-lighting. So the upper surface had to be made on the mould side and the lower side would have to be made as the top layer and hence a little less accurate and flush. The fire proofing tests resulted in an extra internal layer of gypsum rich finish, which would

increase the fire proofing characteristics of the inner face of the wings to the required level. This implicated that the inner face had to be smoothened after assembly any way. So production with the upper surface on the mould side was the consequential procedure.

It was also decided to pre-cure the top layer as a single layer of fibre weaves with polyester resin before vacuum injection of the complete package of the segment construction. After the top layer of resin soaked fibre was cured, the core of the fire-resistant polyurethane blocks was sawn and arranged to the roof layer. Between these foam blocks, long glass fibre strips were placed in vertical position to act as stringers between the upper and lower skins. These stringers are the structural ribs in the sandwich as a replacement of the original steel structure or as a stiffening of the sandwich composition, which appeared to have too much flexibility for the roof structure. Tests and analysis had resulted in the introduction of these stringers to lead away the shear forces in the construction package. Due to results of the performed accelerated long time tests delamination could occur at the most critical points: at the supports of the columns, between the internal spans and the cantilevers. A similar problem and loading occurs at the point of attachment of an airplane wing to the fuselage. The core foam blocks were subsequently covered with the lower set of glass fibre weaves to form the bottom skin of the segments and an enveloping foil for the next vacuum injection. The polyester resin that was consequently injected between the blocks, forming the GRP glass fibre strips stringers, thus creates a structural connection between the upper and the lower skins.

In doing so, the function of the core blocks had changed dramatically. From the original shear layer, they were now only functioning as 'lost internal moulds' for the lower surface of the wings. Their function was also foreseen as a stiffener of the upper surface to ensure that a solid backing is available behind the upper skin if an unfavourable local load was to occur on the outside of the upper roof skin. Local buckling of the GRP sandwich is prevented in this setup. After production of the first three roof segments of the library, a mock-up was installed at the premises of Holland Composites. The segments were placed on a temporary supporting jig structure in order to fit all the segments, to connect them structurally, and to smoothen the final layers in order to prove to the manufacturing team, the engineers, the architect and the client respectively that the wing-shape would have the desired fluent shape without any irregularities. This mock-up was built in March 2005. After a site visit by the architect, and with his approval, the full go-ahead for the production was issued. The remaining segments of the library wings were produced in the above described production sequence. In May 2005, around the time of the first congress of Delft Science in Design, the two wings of the 'Library' were shipped to Israel in specially designed super-crates, sized 3.5 m x 3.5 m x 15 m to contain as many segments possible in a stacked position and a specifically designed order. Transport was planned in 5 lots of the 5 different wings via regular freight ships to the harbour of Ash Dod and from there on to the site by inland trucking transport.

Parallel to the production of GRP segments in Lelystad, the production of the steel columns and the rotating column heads had commenced in Delft. Next to the load bearing function towards the roof, these columns also bear the deadweight and wind load of the frameless

glass façade. Production of the columns appeared to be a routine job, the only difficulty being the connection between the columns and the roof. All columns had different 3D angles and the sandwich construction was quite weak at the positions of the supporting columns so that the danger of the column supports piercing through the sandwich was analysed. Hence, during the production of the GRP segments at Holland Composites, steel plate inserts parallel to the lower surface of the wings were placed within the sandwich to be able to connect the upper steel plates of the ball joint column tops to the sandwich construction without perforating the wing. Specially developed ball-and-socket connections on top of the columns were designed to accommodate the very different corners of the supporting points under the lower skins of the wings. The ball joints had to be bolted to the inserts.



FIG. 147 Milling machine at Marin, scale model of upper wing of 'The Library' and production of the roof segments at Holland Composites. Vacuum injection of the top layer on foam block milled by Marin. Insert to be placed in the GRP sandwich roofs in order to make a connection between the roofs and the columns (34 & 36). Placement of foam blocks and glass fibre mats, which will become stringers. Vacuum injection of the bottom layer. Final result, in this case an early prototype. Discarded foam moulds

The central part of the 'Great Hall' was a steel challenge. Due to the high forces, a tubular steel space frame was the only solution to make this span under this loading possible. The result was a complex space frame structure of tubular steel, later to be fitted with thin GRP panels at the top (roof surface) and bottom (ceiling surface). Because accurate

3D rolling of tubular elements is a rather complex procedure, the entire composition was made of 2D rolled tubular segments, which possessed a greater accuracy. The 3D tubes, mainly situated in the length of the central body, at best approaching the desired shape, therefore had to be connected to the accurately shaped 2D tubes. At the premises of Holland Composites, the entire central body was assembled in order to fit the panels. The structure appeared to be as high as 8 m, which was very labour-intensive for the erectors. So after the trial assembly in Lelystad, it was decided to erect the final assembly onsite in Tel Aviv in two halves, which would result in a building height of only 3 m. After the panels were trial fitted on the particularly engineered and positioned steel supports, the structure was disassembled and shipped. After the production of the roof segments of the lower wing of the library, discrepancies between the theoretical drawings and the practical distortions and tolerances from shrinking of the polyester resin in the enveloping vacuum bags were measured. Tolerances because of warping of the negative moulds resulted in unforeseen deformations of the produced GRP components. These components together had to ultimately form the perfectly smooth surface of the complete wing. All aspects were approached in an engineering manner: measuring, analysing problems and deducting solutions. Analytical engineering in the best traditions of the TU Delft made the initial amazing, improbable design solution finally a reality. The resulting design is a combination of structural design with a strong architectural flavour, incorporating the technologies from aeronautics, ship building, industrial design and geodetic surveying. It poses an example of multiple innovation of technology.



FIG. 148 The central body of the Great Hall (spanning ca. 30 m)



FIG. 149 Detail



FIG. 150 Roof segment



FIG. 151 Fitting of all the roof segments at Lelystad

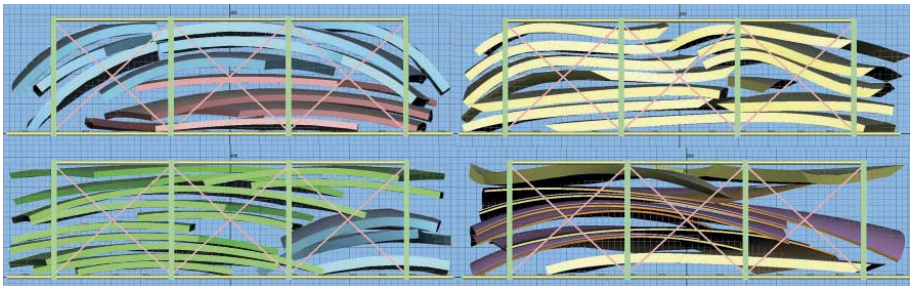


FIG. 152 3D drawings of the roof segments in 4 special transport containers



FIG. 153 Open container at Holland Composites with the roof segments ready for shipment in April 2005

06.13 ASSEMBLY, TOLERANCES AND THE NEUTRALIZATION REGIME

Due to the experimental character of the production process and the initial unfamiliarity with the consequences of vacuum deformation, it was decided to perform a test-assembly or pre-assemblage of all the wing segments on the premises of Holland Composites in Lelystad. The fitting took place on a positive steel frame; the shell would therefore be curved upward. One of the conclusions was that we would assemble the wings inversely, so the downward curve would face upward. If a technician would fall, he would fall into the

shell, instead of falling off of it. Subsequently, the shell was turned over with a mobile crane, by means of three temporary hoisting fixtures in the shell. Pre-assembly proved helpful for drawing conclusions regarding the theoretical versus the practical measurements of the individual segments. All segments were produced on individual foam moulds and they all had their own shrinkage and shrink-direction. Yet together, these segments were required to form the perfectly smooth surface desired by the client and architect.

It was noted that the total fitting of the individual deformed segments would still form a smooth surface when the entire shell was assembled. In order to achieve this smooth surface a solid frame was needed with clamps in order to force the segments into the desired position. In general, the segments proved to be somewhat smaller than intended. They had shrunk because of the vacuum injection, causing the seams to be 20-25 mm, instead of the anticipated 12-15 mm. When filling up the seams during assembly, a bigger seam meant more fibre and more resin (due to the required ratio between fibre and resin) and thus causing a larger weight of the shell.

The connections between the individual segments can be divided in connections in the length and connections in the width of the segments. Both have a structural function. On the side of the segments, a rabbet was made, 220 mm wide and 15 mm deep. In this rabbet, a prefabricated reinforcement strip of 200 mm width and 10 mm depth was placed (made of high density glass fibre weave layers that had been vacuum injected with resin). This reinforcement is glued and clamped by screws for curing purposes only. After the segments of the two wings in Lelystad were fitted on the steel frame, controlled and approved, the segments were dismantled and shipped in the special containers. The assembly on site had to take place on the south side of a tall wall on ground level. The segments were assembled inversely, measured, connected with the prefabricated reinforced strips, measured again, touched-up and finished with the structural reinforcement meshes and filler. The lower side with a fire retarding layer, the upper side with an infrared light resistant layer. Next, the shells were turned over and finished identically on the other side. After hoisting them onto the library, the first shell wing was positioned on a flat steel truss sub-structure, which in turn rested on a concrete wall with a much larger tolerance difference.

Positioning directly from the crane onto the column heads, or wing-connectors with their adjustable shaft and connection plates, could only take place accurately by following the theoretical drawings. Until the end of the assembly and erection, theoretical drawings remained the decisive factor. In all phases of engineering, production, assemblage up until the hoisting and positioning, theoretical drawings were always present and compared, as this was the only assurance that at the end the wings would fit into position. Neutralizing different components is an adventure in itself. Building parts were simultaneously produced in locations all over the world. In this project, the steel was manufactured in Delft, the glass in Luxembourg and Belgium, the polyester segments in Lelystad and the concrete works in Tel Aviv. The concrete had the biggest tolerances, up to 100 mm. The seams of the roof segments theoretic measurement 12 mm – came to 25 to 30 mm in reality, and the seams between the glass panels to a more accurate value of 8 to 12, average 10 mm. And all

these different tolerances have to be neutralized in their principle detail design (allowing neutralizing at all). Tolerances in the different stages from design, through engineering to prototyping, production and building onsite govern the success of each prototypical free form project. The geodetic supervision during the process of production and installation has grown in importance since Blob structures for free form architecture had to be realized.



1



2

FIG. 154 Preparation and hoisting of the upper and lower wing of the Library in August 2005



FIG. 155 Assembly of the roof segments by gluing



FIG. 156 Bolting glass fibre polyester plates on the seams before applying the finishing layer

Having arrived at this point, one has to remember that the success of Henry Ford in the automotive industry was not the production line. *"Ford's 1908 Model T was his 20th design over a five year period that began with the production the original model A in 1903. With his model T he finally achieved two objectives. He had a car that was designed for manufacture, as we would say today, and also was, in today's terms, user-friendly. Almost anyone could drive and repair the car without a chauffeur or a mechanic. These two achievements laid the groundwork for the revolutionary change in direction for the entire motor-vehicle industry. The key to mass production was not – as many people then and now believe – the moving or continuous assembly line. Rather it was the complete and consistent interchangeability of parts and the simplicity of attaching them to each other. These were the manufacturing innovations that made the assembly line possible"* [Ref. 06.05].

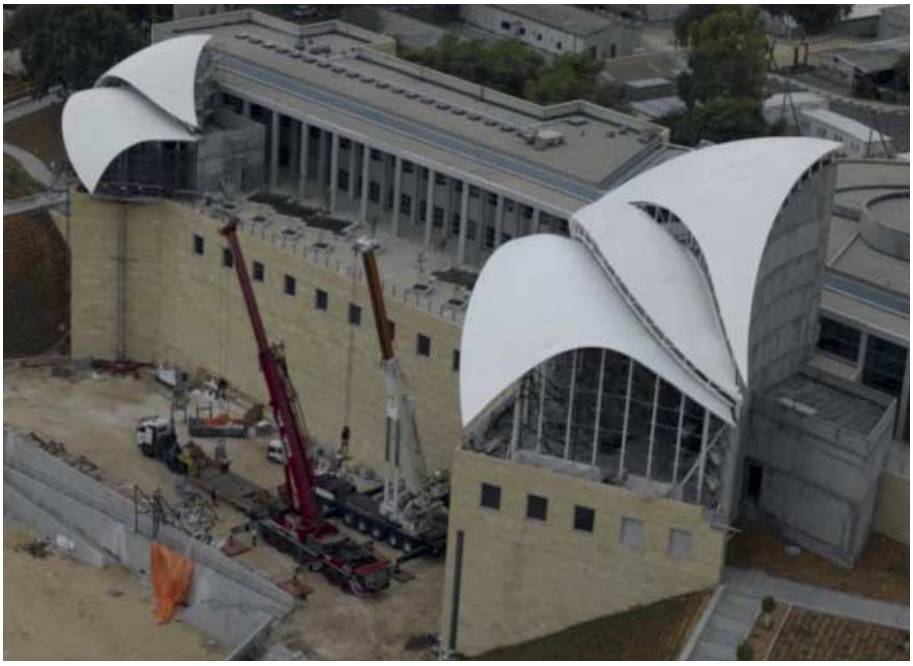


FIG. 157 View of the building site on 6th of November 2005, photographed by Ardon Bar Hama

In similar projects where buildings with free form design had to be realized (for example: Town Hall, Alphen aan den Rijn, see www.mickeekhout.nl), the total costs involving geometrical surveying from prototyping and productions up to assembly and installation came to as much as 3% of the contractual turnover: a serious amount of man hours. The building industry has finally arrived at the international industrial level of 3D design of components, boosted by the inevitability of the technical compositions of free form architecture. From now on the different ingredients or components of free form architecture that are made in lots by different co-makers / subcontractors, sometimes

in many countries all over the world for just one project, put the building industry in line with the automotive industry; only 100 years later. This is helped by the transition from the concrete and brick technology where joints can always be adapted locally, to the more industrial (factory manufacturing) metal and mid/high-technology where all components have to be fitted specifically in an industrial mode; so with confirmed and very accurate tolerances only. Once Henry Ford could force his components suppliers to produce and supply components with fine and accurate (and only negative) tolerances, he could avoid the adaptation of components on the assembly floor (in the building industry: on the building site). This made the difference between the former automobile ateliers where cars were hand-fitted after most of the time was lost in refitting the components and an industrial and almost 'blind' assembly solely focussed on the assembly activities and no longer on component care. From that moment on, Ford could even employ a conveyor belt as the basis for continuous production of assembly-only.

The glass facades were developed separately from the roof wings. They were based on more than a decade of experience of designing and realizing frameless glazing. The original design was a standard mullion façade, which was redesigned as a frameless glazing façade. The architect required a specially fitted glass in order to influence the daylight penetration and solar incidence. Scientifically, this part of the building was not as interesting.



FIG. 158 Overview of the building site after completion



FIG. 159 The Library – Interior view



FIG. 160 The Library – Exterior view



FIG. 161 Finishing of the top layer of the roof by "air-borne builders"



FIG. 162 The ´Great Hall´ interior view

06.14 CARBON FIBRE BLOB SHELLS, AS YET ONE BRIDGE TOO FAR

The above described sandwich construction shells of the Rabin Centre form a renaissance of the shell structures of the 1960s. In those days, based on simple mathematical manual calculations shells were thin, and followed the ideal spherical, conical, cylindrical or hyperboloidal forms. Results were mostly 50 mm thin concrete shells with only one central reinforcement layer of steel bars. Many shells had a Hispanic origin: Eduardo Torroja, Spain, and Felix Candela, Mexico were the prominent pioneers. The shells were built in countries with high material and low labour costs. In the 1970s, the pioneers retired and the concrete shell fashion stopped. Crafted carpenters retired after that, and making a concrete shell today would again be an experiment. Heinz Isler from Switzerland built his concrete shells with re-usable timber moulding on scaffolding in the 1980s. He also retired and closed his company. These concrete shells have now to be designed in open en direct collaboration between architect and engineer.

Blob architecture emerging in the late 1990's (Guggenheim Museum Frank O. Gehry, 1998) changed these conditions, as the architect designs either directly in models or on the computer in the manner of a sculptor. The dramatic 3D effect dominates architectural thinking. The structural designer does not have an equal position, but is rather conferred with after the architect has created a model or geometry, which suits him due to visual design considerations. Alas, there is usually no direct feedback, no improvement feedback loop from structure to architecture. That is to say the engineer has to translate the sculptural whims of the architect into a trustworthy architectural structure, safe in use. As a consequence, the forms of the new generation of shells are much more arbitrary in a structural sense and hence have a more unfavourable structural behaviour.

Many of these new shells are now governed by bending moments due to their unfavourable form and supports, rather than by normal forces and shear forces in the plane of the shell as in the first generation of shells. The constructional solution of the new generation of composite shells is in principle the one developed for the Rabin project and now the system solution: a double stressed skin sandwich composite construction in free form with a structural core. The two skins enable bending moments to be accommodated that are caused by unfavourable loading conditions, column or support positions and, structurally speaking, arbitrary or rare shell forms. We would still call these roof forms 'shells' as a reminiscence of the thin-walled shells from the 1960's, but mathematicians and methodologists suggest to invent and publish a new name. The answer is: Blob-shells of Free Form shells.

The next step in development is caused by the differences in loading behaviour between conventional structures in steel of concrete and glass fibre reinforced polyester shells. Blob shells, made of glass fibre reinforced polyester are usually much more flexible, and cannot reach the stiffness and rigidity of conventional structures. For sailing yachts, often

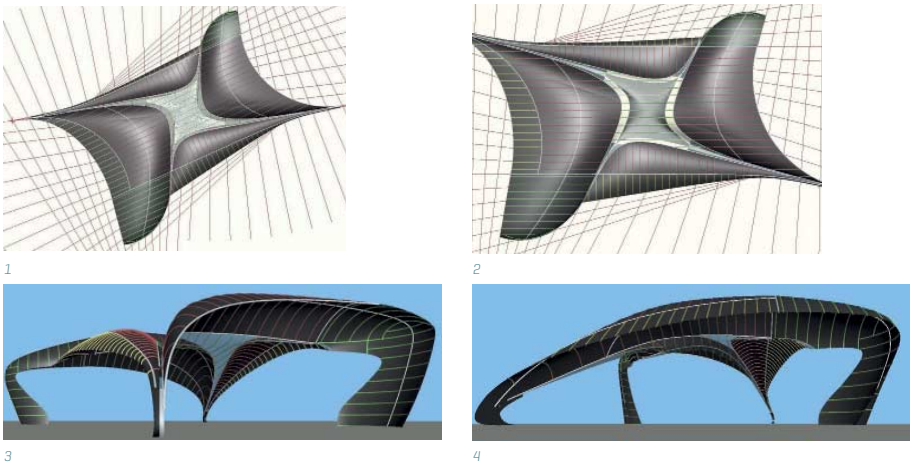
pre-stressed by masts and riggings, rigidity is a relative connotation. As long as the doors and cupboard doors still close and open, only a few sailors would mind the distortion in the hulls of their yachts. The consequences and joys of trimming in speed are more important. However, building components like windows and doors, often have vulnerable, annealed glass components directly attached to the roof structure. These are influenced by the stiffness of the load bearing structure. Depending of the details, this requires the engineer's attention. Cantilevering blob-shells are more flexible than those in conventional structure. The cantilever of the tip of the largest wing at Rabin was analyzed as 100 mm upwards and 210 mm downwards. The total sandwich thickness was 314 mm. This fits in the general shell theory of Thimoshenko, so that this composite shell still behaves as a shell. Alternatives in steel and in concrete were analyzed to show deformations of 200 respectively 100 mm only. The engineering line-of-thought was that, as long as the movements of the roof under loading do not cause brittle fracture, de-lamination or other handicaps in the blob-shells internally, and as long as the flexibility of the blob-shell does not lead to problems in the technical composition of the building around the blob-shells, for example by crushing glass panels or causing leakages due to too much movements in the silicone joints, a larger movement would be acceptable. So no rules yet, but intelligent and responsible building technical engineering, characterizing the experimentation phase. The standardization and normalization phase of newly developed technologies will only follow after 5 to 10 years. But new projects involving blob-shells in the future will appear with undoubtedly stricter requirements with regards to the anticipated deformations in GRP.



FIG. 163 Guggenheim Museum Bilbao, architect: Frank Gehry

Other materials are interesting in this respect as well. Epoxy and carbon fibre is the alternative usually employed in the production of high-tech sail yachts. The next generation will probably be blob-shells in carbon fibre reinforced epoxy. This material is much more rigid, hardly expands as the modulus of elasticity of carbon fibre reinforced epoxy is much lower than that of glass fibre polyester. However, these advantages are accompanied by a much stricter production process including curing in a tempering oven, which limits the sizes of

the components. For transfer of technology from the yacht building industry (for example used in the black and white ABN AMRO yachts of the Volvo Ocean Race 2005/2006 that were built in Lelystad NL using this technology in vacuum injection), the costs play an important role. As the thresholds in the building industry are quite low and the price of carbon fibre reinforced epoxy shells are high, clients could prefer to go back to reinforced concrete after studying the price of carbon fibre epoxy shells. Yet, amongst architects a strange mechanism works: the 'first-of-the-block' effect. The first guy on the block who buys a pink Cadillac is celebrated, the second one is a looser. So at least he has to buy himself a Cadillac of a different colour. Moshe Safdie designed shells that were realized as white shells in original material. The next architect would prefer a black shell to distinguish him or herself. In this case the famous London-based architect Zaha Hadid designed a Free Form Mediateque in Pau, France, near the Pyrenees. Her initial design images show the 'Mediateque' in white, but the tender documents of 2005 show a black design with carbon fibre as the basic material.



1 2 3 4

FIG. 164 Preliminary engineering drawings of the Mediatheque in Pau by Octatube

In the development of the Mediatheque tender design in the proposal of the author, accompanied by co-makers in the Netherlands and England, the idea was to produce the segments of the carbon fibre epoxy blob shell segments locally in a temporary factory shed, a re-assembled curing oven, next to the site. The process of tendering did not allow for any prototyping on the side of the client or architect. Rather, this extremely experimental project was tendered as a standard building project. The resulting tender price was 4 times that of the client's budget and, maybe as a blessing in disguise for this extremely experimental, giant scale project, the project champion, Pau's mayor André Labarrère, who wanted to realize his '8ième Grande Project' died the day before the tender date. The project was cancelled. The design drawings indicate the design proposals in carbon fibre epoxy blob shells, which will probably be illustrated in a next Delft Science in Design conference at TU Delft if the experimentation path could be continued.

06.15 THE FUTURE OF COMPOSITE SHELLS

The resulting design in this contribution shows that building technical design can lead to an integrated and innovative process. In such processes many disciplines are collaborating and have to be co-ordinated throughout the entire process including all of its unforeseen and experimental stages. The results of this process have to be integrated into one technical artefact that satisfies all requirements and provides efficient answers or compromises in all of its life phases, be it conceptual design, material design, detail design, engineering, productions, assembly, installation, loading behaviour, functional use as a building, meaning of the artefact as a building, (even as architecture) and in its (global) context/surroundings, in its meaning as an integral part of the building. Society expects perfect solutions from scientific designers. These solutions are not only the functional and technical solutions. It may be true that the well-known restrictions in the volume prices of the building industry, as posed by the clients in the building industry, lead to traditional and well-known technologies. Yet the thresholds to enter the building industry are low and competition is fierce. Sometimes experiments are persistent, initiated by technical designers who are willing to wander through the entire experimental development process and are able to analyse and solve all foreseen and unforeseen problems. It requires an experimental mind set. In this case the interdisciplinary collaboration of Architecture and Industrial Design Engineering, the Maritime Engineering and Aeronautical Engineering proved to be essential and an enrichment in the field of architecture in order to introduce the renaissance of the shell as 'Blob shells' of 'free form shells' for the world. One warning after this adventure has to be given as well: the entire process was extremely innovative. In fact, there were too many layers of innovation on top of each other, interfering with one another, making the entire process hardly manageable. Too many innovations make the process extremely fluent too many innovations make the process creep all over the place and it needs ultimate engineering skills to steer through such processes. Needless to say that the necessary energy to complete the process was more than the sums available in the project's budget – called an investment in company language. This is not a problem as long as the gained knowledge is used for further projects with similar technology. (In 2012, a GRP outside wall system would be made for the A2 Hotel in Amsterdam with the same co-makers.)

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07 SINGLE-LAYERED SPACE FRAME DOME FOR THE FRIESLAND BANK

Original lecture: the 5th international conference on Space Structures in Guilford, Surrey, August 2002. Reference: G. Parke, P. Disney, 'Space Structures, Thomas Telford, London 2002, ISBN 0727731734, pp. 1327-1336

07.01 INTRODUCTION

Leeuwarden is the capital of one of the northern provinces of the Netherlands. Its townscape has an average height of 3 to 4 stories, with a business centre of 10 stories and an occasional solitary 100 m high office tower. A glazed dome was build on top of an existing building complex of the headquarters of the Friesland bank, consisting of three existing and 1 new office buildings built in different decades, covering an internal atrium, and clearly visibly in the skyline of Leeuwarden town. The dome is composed of a single-layered space frame in network geometry, fixed between three triangular space frame trusses.



FIG. 165 View of the dome under construction

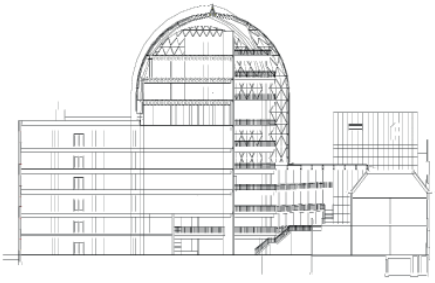

FIG. 166 Cross section through dome and lower glazed roof

The horizontal diameter of the dome is 28 metres. The main frames of the three trusses intersect at the top of the dome. From these three delta frames, the three space frame parts are suspended and stabilized. In vertical cross-section, the height of the spherical space frame structure is slightly over 14 metres. See Fig. 167 One of the three space frame parts is downward elongated (12 metres) as a suspended curtain. Furthermore, the lower side of this suspended façade structure supports the dead load and live load of the adjacent flat glazed roof, which is approximately 28 m x 28 m. This enabled the architect to realise an atrium without internal columns, which is clearly seen in the photograph taken from the ground floor looking upward.



FIG. 167 Looking upward in the atrium void

This additional dead load, not the wind, proved the governing load combination, in spite of the 26 metres height of the dome. The delta trusses are necessary, as the existing buildings could not support the dome structure. Thus, this jacket skeleton stands with 20 metres high concrete legs on the foundation. All three legs are stabilized sideward at the bottom of the dome by the adjacent buildings. Triangulated delta frames of welded tubular construction are positioned on top of the prefabricated concrete legs. All are connected together at the summit. The single-layered space frame is connected to the central lines of the delta trusses, so that these seem to form a unity with the space frame. In fact, the dome is suspended between the trusses. The building complex realized in the centre of Leeuwarden dominates the sky like St. Peter's in Rome, Italy and the dome of the Reichstag in Berlin, Germany, freely towering above the silhouette of the city.

07.02 DESIGN HISTORY

From the very first conversation between architect Aad van Tilburg and structural designer Mick Eekhout on, it was clear that building a dome on an existing building complex, with no appreciable reserves for extra load, could only be done by special transfer of the loads. Basically, the project structural engineer Stoel Partners had thought up the three high legs, along which the vertical load would be transferred to the foundation. This schedule led from a dome design to three scales that would be suspended between the delta trusses. The suspension of the adjacent horizontal glass roof (28 m x 28 m) proved an immediate complication and clearly determined the structural effects of the dome construction from that moment on. Due to the presence of the three delta trusses, a double-layered space frame was not an obvious option. The architect saw too many bars in this scheme and thought the graphic design to be confusing. Furthermore, the structural version would take up too much depth. The dead weight would have been less, however. Therefore, there was nothing left for the space frame but a single-layered realization. This was represented as a choice between a network realization with horizontal rings, with diagonal bars in-between, see Fig. 168, and an orthogonal realization with horizontal rings, made from ellipse-shaped tubes and vertical bars, without any diagonals. The architect preferred the latter alternative. However, in the first structural analysis it soon became clear that, by the heavy hitched on load of the suspended roof, this heavy vertical load would dominate and cause the dome part of the structure (the 'forehead') to be pushed inside too far. The consequence of this would be an unacceptable large vertical transformation, in the vertical sense of the lower side of the vertical screen (the 'dome face'): 60 mm in the middle between the two delta trusses. Despite the large share of dead load, for which an arch might have been a possible structural solution, against which the architect objected however, the share of snow load at the low roof was so great, that this structural "Schwedler" scheme was considered not suitable for the proper detailing of a structure with large glass panels.

07.03 FINAL STRUCTURE SCHEME

The most logical and inevitable final structural engineering solution was to connect the horizontal rings of tubes with diagonal bracers in CHS at 45°. This network geometry produced far more rigidity, so the same roof load resulted in a maximum vertical deflection of only 15 mm. See Fig. 168. This deflection has been settled over 15 seams between glass panels, resulting in 2 mm per glass panel. This was acceptable and could be accommodated in the glazing system. Still, the dome part of the structure suffers from inward pressure on the skull and horizontal compression forces in the rings, but these could be accommodated by the choice of a system for continuous CHS horizontal tubular rings of 150 mm diameter and discrete CHS diagonals of 80 mm diameter.

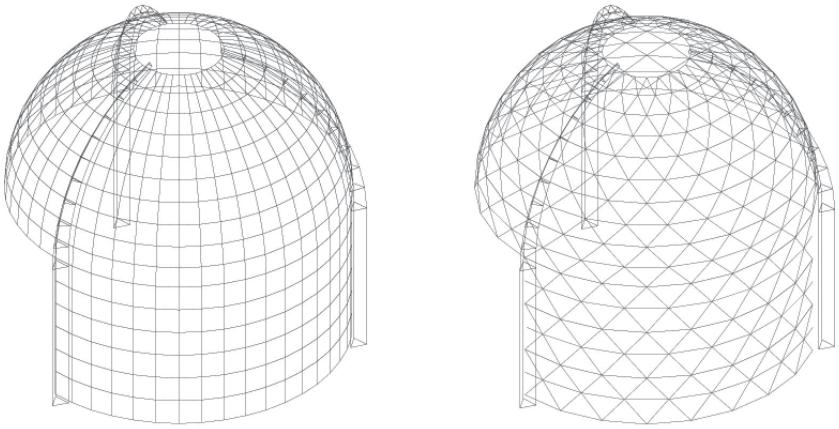

FIG. 168 Axonometric projection with a structure of horizontal ellipse-shaped tubes and vertical bars (left). Axonometric projection of the dome with a structure of horizontal rings and diagonal bracers (right)

07.04 WIND LOAD

With this scheme settled and agreed upon, a definite switch was made to a network geometry with horizontal tubes that would be put under compression and bending. Diagonal round tubes in-between would be put alternating under compression and tension, depending on their position towards the delta trusses, depending on the load cases and their combinations. See Fig. 169. To make the calculation of the wind load possible, building advisor Bureau Peutz Associés in Mook, the Netherlands, carried out a wind analysis in which the entire building, including the surrounding buildings, was taken into account as disturbing factors.

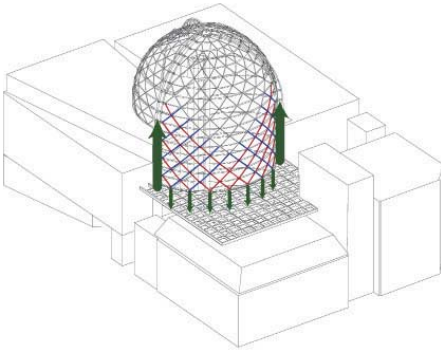

FIG. 169 Axonometric projection of the constructional functions of the dome and three delta-trusses

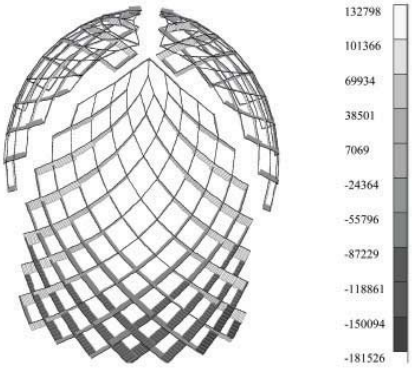

FIG. 170 Diagram with axial forces in members in north part of the dome an cylinder. (Tension members dark colored, compression members are light coloured

07.05 VERTICAL LOADS

Next to the usual loads, the load from the horizontal roof deserves particular attention. Particularly, the load of the horizontal roof is of great influence on the structural behaviour of the apron. The roof of the atrium transfers a load of 800 kN to the 'apron'. The wind load of a dome is very different from the wind load on a more orthogonal building. Bureau Peutz determined the wind load on the dome by wind tunnel tests. These test showed, according to the literature, that chiefly wind suction occurs and only limited wind pressure. Above ring 6, only wind suction can be expected. Looking at the floor plan proves that approximately one sixth part of the floor plan is subjected to wind load and five sixth is subjected to wind suction. This picture is the same for all wind directions.

07.06 MEMBER STRESSES

The loads are transferred to the bearings particularly via the diagonals. The rings provide extra rigidity and stability. The diagonals that run up from the bearings are usually loaded under compression and the diagonals that run down are tension diagonals. Therefore, the structure looks more like a triangulated truss in a spherical form than a traditional dome, where all vertical and diagonal bars are loaded under compression and the horizontal tubes under tension, when the external loading is directed downwards. The strongest bar forces

in the diagonals are the tensile forces at the bottom of the apron (cylinder), caused by the vertical loads from the atrium roof. The maximum bar force is well over 180 kN. The bar forces in the other two dome parts remain under 100 kN and great pressure forces exist particularly in the diagonals at the bottom of the dome, nearby the bearings. The bar forces in the dome part above the apron show many similarities with those of the other two dome parts. Here from, the conclusion can be drawn that the apron in particular absorbs the load from the atrium roof, while the apron serves as a spherical truss.

07.07 CONSTRAINT FORCES

In Fig. 169, displaying the constraint forces, the vertical reaction forces which apply to the arch trusses and the columns (as a result of dead weight and snow) are measured out. At the horizontal axis, the origins of the reaction forces are arranged from low to high, so from the lower side of the apron to the top of the dome. Logically, the reaction forces upwards diminish. The reaction forces are subdivided into two groups, namely a group where the diagonal endings are close to the arch truss (the supports of the odd numbered rings) and a group in which this is not the case (the supports of the even numbered rings).

The chart clearly shows that the groups of bars at the endings of the diagonals close to the delta trusses supply much more reaction forces. Most of the load is transferred to these origins. The other bearings, particular those in the apron, are almost zero supports.

The reaction forces from the snow load are normative. If a storm would occur, the atrium roof suffers from wind suction but the load thereof on the atrium roof is less than half of the snow load.

07.08 DEFLECTIONS

The deflections of the dome are subdivided into vertical and horizontal deflections. There are a number of design considerations that have a relatively large influence on deflection, i.e. the load from the horizontal roof, but also the position of the diagonals. The normative vertical deflection is caused, for a considerable part, by the load from the atrium roof and measures maximally 15 mm at the bottom of the apron. Wind loads causes deflections in the horizontal surface, but also vertical loads may cause horizontal deflections. The reason lies in the fact that the diagonals form an angle with the rings. This causes deflections in the horizontal direction, even when only vertical loads exist. The component which is perpendicular to the tube, is approximately 129,4/1850 = 0,07*Faxial. Therefore, if there is

a diagonal in the apron with a tensile force of 180 kN, this will supply a force of 0.07*180 = 13 kN perpendicular to the apron. This force is stronger than the member compression or suction caused by wind. The maximum horizontal movement is 10 mm.

The horizontal wind bearings at the bottom of the two higher spherical surfaces are connections between the horizontal network rings and the internal office floors, covering two thirds of the jacket surface. The connection points have vertical sleeve holes, so that there are no deformations in the vertical plane from the inner reinforced concrete structure to be accommodated by the dome and vice versa.

07.09 STRUCTURAL DETAILS

The diagonals have a length of 2300 mm and come in two variants: a diameter of 82,5 x 4 mm with M20 12,9 bolts and a diameter of 82,5 x 6,3 mm with M24 12,9 bolts. At the upper and lower side of the diagonal, slotted holes near the end of the tubes have been made for assembly reasons. Via these slots, the axial bolts (M20/M24 type Allen bolts) had to be inserted, tightened and pre-stressed.



FIG. 171 Installation of a diagonal tube to the horizontal ring nr. 18

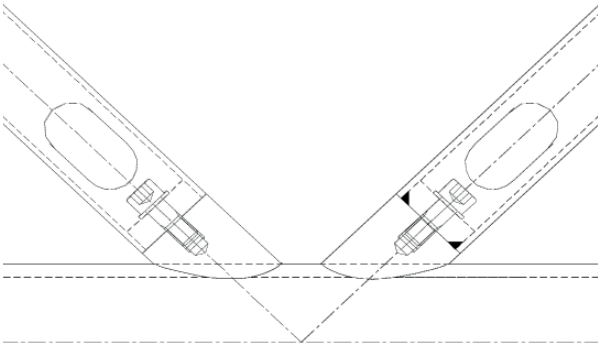

FIG. 172 Detail of the connection between horizontal rings and diagonal bracers

In fact, these holes strongly reduced and determined the loading capacity of the diagonal. The hole reduces the face of the diameter, and thus the maximum tensile force, by 25%. Since the holes are located at the endings of the tubes, however, they do not influence the buckling behaviour of the bars. With a pre-stressed bolt connection, these moments will lead to reduced contact pressure and not to a moment loading on the bolt itself.
To create a safe collapse mechanism, the connection was engineered so to that the

capacity of the tubes would be normative. During the installation the high quality pre-stress bolts appeared to have production faults, which made two of the bolts break after tightening. Material investigation showed that casting faults were the cause of this. With the tougher 10,9 and 8,8 quality bolts, these faults are not likely to occur. Moreover, after tightening, the gained space inside of the tubular end of the 12,9 bolt compared with the 10,9 bolt left room for a larger bolt. A lesson to be learned for the next 'Streamline' structure. The connection of the rings to the adjacent structure of the vertical, concrete delta columns and the higher up placed steel delta trusses is a moment fixed connection. Because of the eccentricity between the endings of the diagonals and the connection with the truss (chosen for architectonical considerations), the bending moments that have to be absorbed by the connection may become rather large. The distance between the intersection of the centre lines of the diagonals and the centre line of the delta truss tube, where the connection is located, is measured to be approximately 480 mm. The bending moments in the supports are obtained by multiplying the vertical reaction forces with a moment arm of 400 to 450 mm. Therefore, the arm is almost of the same length as the distance between the centre lines. The connection of the apron to the atrium roof is an overloaded one. The atrium roof transfers vertical forces to the connection, and the bottom tube of the apron loads the connection with a horizontal force. It is important that this connection has some degree of freedom. The atrium roof has to be suspended from the apron, but the apron should not form a moment tight structural unity with the atrium roof. Therefore, the connection between the ring and the bent IPE500 girder of the atrium roof had to be sliding (4 mm) lengthwise with regards to the profiles and be hinged around the axis of the profiles.

07.10 CLADDING COMPOSITION

The function of the dome is partly purely functional, partly symbolic in an architectural sense. Built inside the volume of the dome there are three office floors with a top floor for the Board of Directors. The symbolic enlightens the Friesland bank, as one of the crown jewels of the town. One part of the dome functions as a void, connecting the new upper floors with the lower and existing buildings. The office floors have a splendid free view over Leeuwarden, a provincial town with buildings of three to five stories height.

Only recently, one 105 metre high-rise building was realized: the Achmea tower. Because of that situation, the envelope of the dome had to be transparent. However, in its full transparency, the dome would absorb too much solar energy. For the office spaces, a dual façade had to be realised, with the insulated glass skin of the dome as the outer skin; and a vertical internal single glass skin and sun blinds possibilities in between. The glass dome envelope around the atrium void has a single-layered skin made of insulated glazing. The glass panels are composed of two fully tempered glass panels, maximum 1900 mm x 1850 mm, tapering towards the summit of the dome down to 1100 mm.

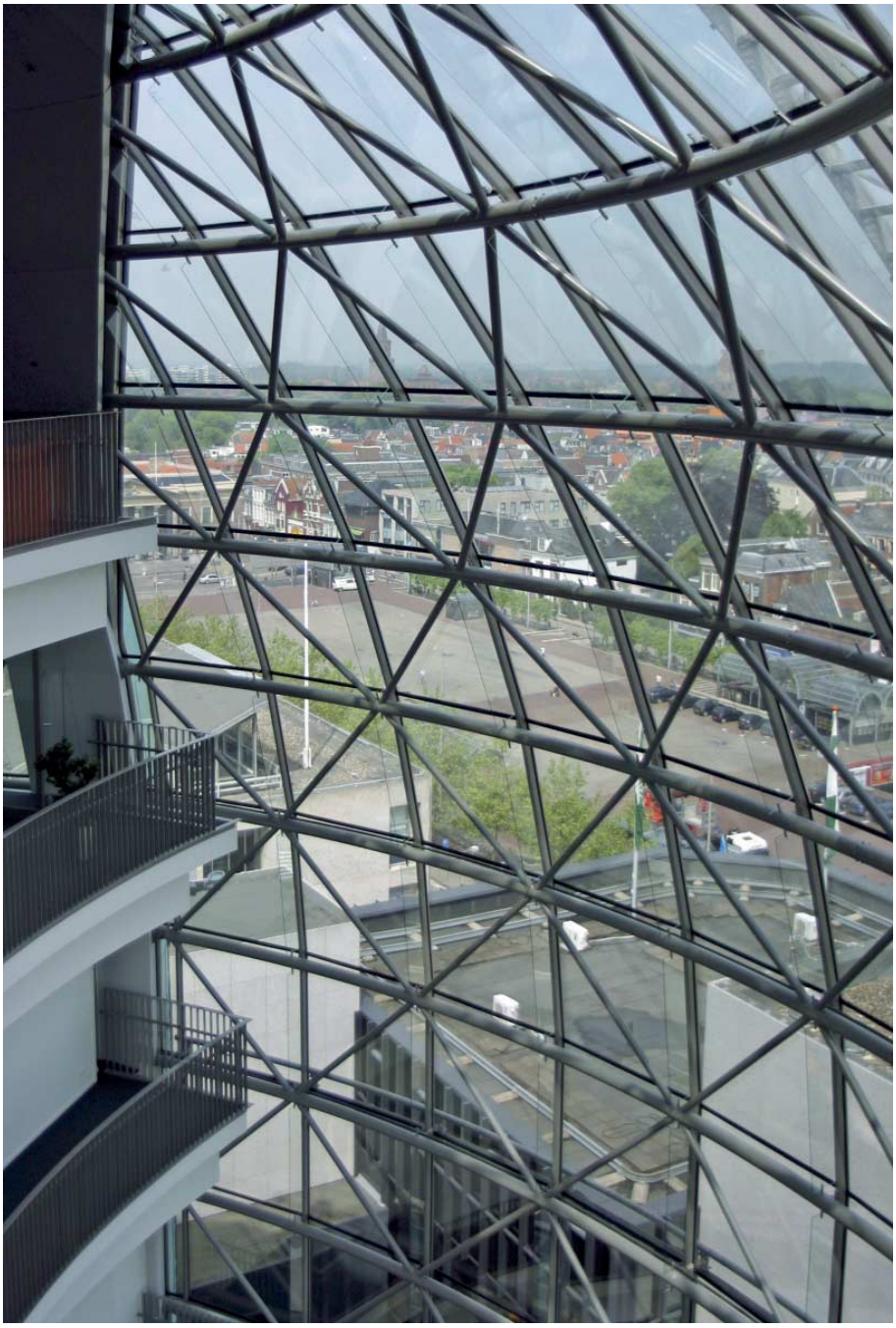

FIG. 173 View from the top floor



FIG. 174 Connection of an elliptical hollow aluminium glass-profile to the streamlined space frame

The glass panels, with a slope less than 80°, have laminated inner panes. The glass panels have a soft coating to reduce bright daylight transmission (54%) and a low solar transmission (27%) on side two. External panes: 10 mm, internal panes: 8,10 and 10,10 mm. In spite of these two transmission values the glass panes look rather transparent. The glass panels are fixed in aluminium hollow section profiles with a parabolic cross sectional form. They have sufficient wall thickness to be able to weld the corners of this profile, so that the many polygonal corners of these profiles could be made watertight against water leaking inside the profiles downward. Leakage water is drained outward at the bottom gutter. This parabolic aluminium profile is only used in vertical position. Horizontally, the joints between the glass panels are butt silicone sealed joints. This system was more economical than the completely frameless glazing with Quattro joints. For acoustical reasons, it also provided the opportunity to accommodate the 8 mm thick anti-flutter glass panels of 300 mm depth on the inside, in a continuous recess in the parabolic profile. The outside skin of the dome is made of insulated glass panels, composed from an outside plate of 10 mm fully tempered glass, and a lower panel of laminated fully tempered glass plates of a different thickness, as a result of the wind tunnel tests. These prefabricated glass panels are clamped in vertical aluminium mullions in parabolic form, while the horizontal seams have been fully sealed with silicone sealant. This enables rainwater to drain off efficiently, while the vertical aluminium caps do not receive much water loading as the rainwater neatly falls down parallel to the aluminium caps. An earlier alternative of frameless glazing was architecturally more exciting, as it was completely transparent, but it was neglected in favour of a less expensive variation

on the steel frame system. A horizontal aluminium frame would also be possible, allowing less visual obstruction from the interior, but its water tightness would cause considerably more problems as these horizontal caps are continuously under 'attack of rain water' and hence very vulnerable to leakage. This bold idea will be worked out in an alternative idea detail for a leakage free dome in Belfast, currently (end 2003) under quotation. The top part of the dome has been clad with pre-oxidized copper panels. Instead of glass, plywood sandwich panels were used, covered by the metal panels. This copper clothing has been extended over the delta trusses as well, so that the glass elevation has three partitions, divided by the copper clad delta trusses.



FIG. 175 Exterior of the dome, the insulated glass-panels and their transparency towards the interior of the dome



FIG. 176 Installation of the glass panels with usage of the maintenance bridges

07.11 MAINTENANCE BRIDGES

On the top part, the dome will be kept in good order by three rotating maintenance bridges. The vertical cylinder can be cleaned from an extra vertically caged ladder (a ladder with rings on the outside so that one cannot fall off). The design of the ladders has been developed in agreement with the graphic design of the dome. In the month of October 2002, almost near completion of the glazing works, a storm of wind force 11 to 12 Beauford caused considerable damage to the ladders. No damage was observed in the dome of the glass surface itself. This lead to a rethinking of the wind forces acting sideward on the 15 m long maintenance bridges, which caused considerable torsion in the bridges and deformation of its rolling feet around the CHS rails. The ladders are dimensioned for torsion stresses, bending and compression.

07.12 PRODUCTION AND INSTALLATION

The production of the elements and components of the dome started in February 2002 after one year of engineering and was finalised in May 2002. The co-design and engineering period took as long as the complete production and installation. This is often the case in pre-fabrication processes.

In the production phase the production of the space frame components was our main concern. The solid props, cut from solid bars of 80 mm diameter steel, were welded and checked in cross section several times by making samples and real cutting. The 'Streamline' has smoothened connections, which means that the structural welds had to be grinded, which is dangerous for the structural strength. In this way, architecture and structural design are at war with each other. The tubular members consist of tubes with steel saucers in the end, welded from the inside, also an invisible weld. Extra care had to be taken to ensure a good welding connection between the tube and the welding material. The steel bolts of 12,9 quality proved to be very vulnerable for production flaws. Two of the bolts showed cracks and broke. For reason of overall safety of the dome all bolts were replaced by new bolts, which were all pre-stressed and certified. The deflection of the installed dome with the suspended heavyweight roof was 6 mm, less than the 10 mm deflection anticipated in the structural analyses. Installation started in May 2002 and was completed in November 2002. The building was inaugurated in spring 2003.



FIG. 177 The roof of the courtyard is suspended from the dome

07.13 CLASSICAL DOME OR SUSPENDED BELL

This dome structure looks like a normal dome but actually is a giant bell suspended from 3 triangulated trusses. The three trusses stand on the only three available positions where foundations could be made in the subsoil between the existing buildings over which the dome would be hovering. From the entrance and the lobby, looking upward one can see the effects of the suspended dome: the lower side is almost entirely free of supports. In fact, the flat roof aside the dome envelope is also suspended from the dome. This started as a movement to monopolize the engineering design: *"You can even suspend the flat glass roof from the dome"*. But it did come as a surprise after the engineering process was actually transferred into built reality. So a surprising design scheme and a bit of bluff at the start; and as always ingenious engineering and determined processing need to be done to steer it towards a surprising result. The dome of Leeuwarden has a visual secret of which we, as designers, are quite proud.



FIG. 178 The final result of the completion of the dome contributing to skyline of Leeuwarden



FIG. 179 Northern side of the dome with the lower roof. In the back the 114 metre high Achmea tower

08 MUNICIPAL FLORIADE PAVILION, HOOFDDORP

Article written for Top Tech lectures TU Delft:

08.01 INTRODUCTION

After a limited design competition with four competitors, in early 2001, the municipality of Haarlemmermeer chose to realize the design of Asymptote Architects from New York (the architects Hani Rashid and Lise-Anne Couture): a pavilion for the Dutch Floriade 2002, to be opened on April 6th 2002. For six months, the building had to be the information pavilion of the municipality Haarlemmermeer and after that it had to be used as a café/ restaurant in the park. The competition design was located on the shore of the lake, but the realized building is on an artificial peninsula in the Haarlemmermeer (*'Haarlem lake'*) on which a building with two sloped roofs is situated. The big roof that covers the building volume harbours the entrance, exposition space and servicing spaces. The smaller roof is a freestanding canopy oriented sideward toward a dike. A continuous stream of water flows from the top of both sloped roofs, filling the glass pond and finally flows into two gutters on both sides of the entrance. The water streams visibly and tangibly, on the inner side of two glass walls, to the level of the lake. In several pavilions of the World Exhibit in Sevilla 1992, streaming water on facades was used as a climatic cooling system. But here it is only used as a symbol for the 'land of water'. Therefore, the theme of the pavilion was something like "Nederland Waterland" ("The Netherlands: Country of Water"). Not surprisingly; seen from the eyes of Egyptian-American Rashid with his 'desert background'. In the pavilion there are no references to the Floriade to be found, but the reference to the Dutch water landscape is excellent. For Asymptote this was the first building they ever realized in their 15-year-old careers as architects and a premiere in world architecture. The world-famous and often published 'Blob-designs' of Asymptote always remained platonic, up until then. Until January 8th 2004, the works of Asymptote Architects are exhibited at the NAi.

The architect's office of Anton Bronsvoort from Amerongen functioned as local materialising architect. The project management was, also on behalf of the client, in hands of Infocus Bouwmanagement from Nieuwegein. The main structural engineer was Smit/ Westerman from Waddinxveen and the main contractor Nijhuis from Houten. In contrast to this typical traditional cooperative building team there were the co-makers who proved to

be quite essential in this 'Blob' design: co-maker steel structure Smulders Duscon BV from Bladel, co-maker ceiling and façade elements Van Dam from Ridderkerk (who unfortunately went bankrupt several weeks before completion) and co-maker frameless glazing and roof panels Octatube from Delft. Apart from the co-makers there were approximately 30 subcontractors, directly under the supervision of the main contractor.

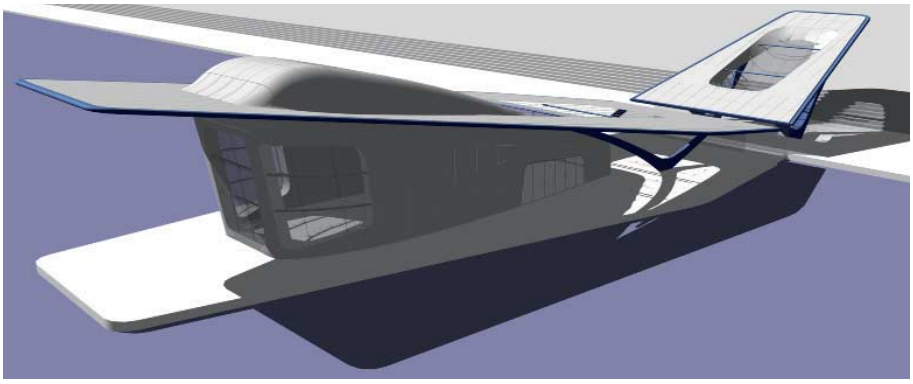

FIG. 180 Design by Asymptote

08.02 DESIGN AND ENGINEERING

Initially, there were high expectations of Asymptote's 'virtual office'. The idea consisted of a central location on the Internet where participators in the project could acquire the most recent drawings of the architect with the help of an access code. At the faculty of Architecture we already tested the system three years ago during the 2nd year module "Productie & Uitvoering" (Production and Realisation): and now it had already become reality! However, because of the lack of regular communication and exchangeability of the computer drawings due to the use of different software programs, the system did not work. The architect used Micostation/Bentley, the engineer X-Steel, Octatube and Van Dam worked with different versions of AutoCAD. During the process it became evident that there was no party in the design and engineering process that checked, or was able to check the measurements of the drawings of the other parties. All parties felt powerless, raised their hands to the sky and simply felt overwhelmed. During the short period of an actual building project it became clear that there is no time to start up a general and good communication system between parties (to work with compatible computer programs) and at the same time to realize the actual shop drawings, engineering, productions and execution on the construction site. This 'firstborn' of realized 'Blob' designs in the Netherlands showed the defects of the traditional infrastructure of preparation and execution of classical

orthogonal designs. With the help of (forthcoming) publications like these (but also lectures) conclusions can be drawn and strategies can be planned about managing the future design and engineering process of 'Blob' projects.

Asymptote drew with non-communicative software and had no possibility to transfer to AutoCAD, being the most popular software among co-makers and sub-contractors. During the transfer between instruction (architect) and execution (co-maker) a lot of information was lost due to the necessity to export all files to DXF format. The accuracy of the computer drawings was lost and it was up to the co-makers to estimate the measurements of their assigned parts on the basis of those drawings. AutoCAD is a software program purely for drawing, and is not suited for structural analysis. The steel structure companies in the Netherlands work with five different analysis and drawing software packages. In each of those packages it is possible to describe the geometry and the initial dimensions of the steel structures. This enables to analyse the influences of internal and external loads. These software packages are optimised for structural calculations and the production drawings for the resulting elements. Uniform engineering software is an absolute necessity to come to a feasible 'collaborative engineering'. In this case one could only speak about 'concurrent engineering'. – The difference is that in the first case there is cooperation, while in the other there is only simultaneous labour. – Collaboration on this project only took place by oral explanation and a fountain pen. But, being the 'firstborn Blob', the Floriade pavilion also had a guiding role. Despite the set boundaries of ICT [[what is ICT]], the partially very experimental high-tech nature of the building and the often very traditional partners in the building team, this eventually resulted in a remarkable accomplishment due to an open collaboration under high pressure. As stated before, the design is composed of two sloped roofs; one slicing the building volumes and the other containing a glass pond. Streaming water continuously covers both roofs. The design is the epitome of 'Blob' design. The volumes of the building were not determined mathematically, but by geometry. Consequently the glass pond couldn't be described by means of regular mathematical equations. The co-makers (working parallel to each other and exchanging DXF drawings) tried to estimate the geometry of Asymptote's Microstation drawings as accurately as they could. Yet the glass panels of co-maker Octatube and the panels of co-maker Van Dam had a deficiency in positioning on site of over 125 mm! It would be highly recommendable to force the architect to draw in 3D AutoCAD/Inventor so all co-makers can work with the same 3D model, which the architect certifies and safeguards. Just like in the petrochemical industry, the idea is to have several co-makers taking turns in filling in their part of the drawing in agreed slot times (periods of time in which only one co-maker is working on the 3D model).

The software package Catia (developed by French airplane manufacturer Dassault) appears to be extremely more comprehensive, since several modules can both draw and analyse, but it is very expensive (USD 100.000 = for one workstation) and nobody in the Netherlands is willing to invest in this kind of software. Students of the faculty of Aerospace Engineering are probably working with pirated versions of this software. But the building industry is an 'easy access industry' with a high level of competition, low volume and square metre prices. Consequently technology from the aerospace or marine industry can be adopted, but they

need to be adapted to cheap component prices for the building industry. A transition of technologies between different industries is obvious; the TU Delft with its open faculties offers a lot of good opportunities, which are gratefully used. The design and engineering process management for Blobs should be separately developed, a task that Sieds de Jong of the Blob research group (department Building Technology TU Delft) took up as a subject for his dissertation. Over 30% of the cost price is invested in design and engineering of all parties when it comes to Blobs. A good management of similar processes is absolutely necessary to accomplish efficiency in the process of preparation and realisation of Blob designs. Octatube manufactured and installed the aluminium roof, the glass pond and the glazing in the facades. Mick Eekhout functioned as head designer in this component process and ensured that one of the three very experimental facets ended up at the Chair of Product Development as a research project (third party funding) and was executed in its experimental status.

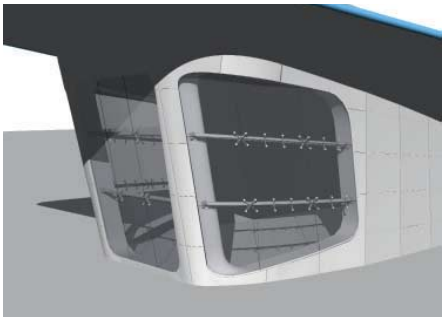

FIG. 181 Southern façade with bent glass

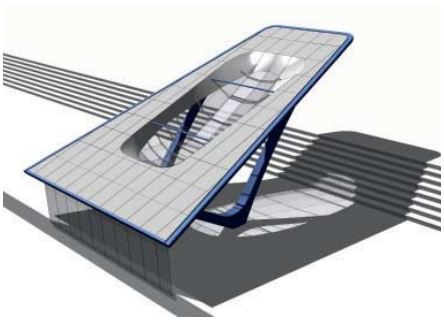

FIG. 182 Glass pond

08.03 EXPLOSION PANELS

The 1st innovation are the 3D corners of the aluminium panel roof which were developed under supervision of Dr. Karel Vollers (Chair of Product Development) as third party funding. Vollers received his doctoral degree in 2001 with his dissertation on twisted facades: "Twist and Build" [ISBN 90645O4105] and can be considered a specialist in the field of twisted glazing and façade panels of buildings. He assembled a task force for the 3D panels with Dominique Timmerman of Octatube for the overall geometry, with Ernst Janssen Groesbeek of the Chair TOI for drawing the components, with Haiko Drachsta's computer controlled machined foam moulds, with Hugo Groenendijk's Exploform for the aluminium panels and for the assembly, fitting, sawing, welding, filling, spraying, installing and waterproofing with Octatube again. A goal-oriented team for a small (18 m^2) but experimental part of the building, which resulted in a renewal of production technology for buildings. The usual tension between time and

finance on one hand opposed to experiments (trial and error) and not knowing whether you will attain your set goal was tangible in this project. But the task force stuck together and presented a technique never realized before in the building industry. Computer models had been made that subsequently were used to machine polystyrene foam blocks. The curved surfaces of those moulds were hardened with epoxy-resin glass. By pouring integral concrete (with short fibre reinforcement), an inverted mould was created. This mould was used as a sub mould for the explosion process. Hugo Groeneveld has a small company named Exploform that is located on the terrain of TNO Delft. He develops several production methods to transform metal panels in 3D. Initially we considered the idea to place the positive moulds in water and freeze the water in order to use the ice to explode the panels on. Yet, due to the high pressure the ice changes back to water, and the mould disappears too soon. On top of that it would require a gigantic freezer. The idea was beautiful, but not feasible in the short term, since Explofrom is not able to manufacture a huge freezer for the occasion. Aluminium panels were placed on the mould, vacuum deflated and with the help of a water basin with a small TNT ring an explosion was generated that transformed the 5 mm thick aluminium plate with radial yet liquid pressure into the shape of the concrete mould. The explosions caused the water and the plastic edges to be launched high up into the air. As a production method very experimental and far from industrial, but it proved that the desired accuracy could be attained. The panels had marks from the glass fibre on the epoxy skin of the negative moulds and had to be filled before they could be coated. In the factory of Octatube, a wooden 1:1 mould was created in which all panels were fitted and equipped with aluminium edges, sawn, welded and grinded into complete panel components.

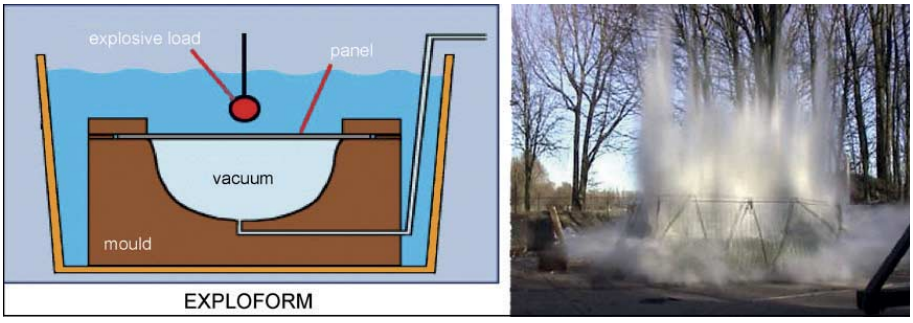

FIG. 183 Exploform process (courtesy: www.exploform.com)

In the future Karel Vollers will publish information about the accomplished production technology and in which manner eventual improvements can be added. Super inventor Haiko Dragsta recently developed a professional method to make cylindrical façade panels: With a CAD/CAM machine mould, as described earlier; aluminium panels are directly vacuum deflated and strengthened with a small foam layer and epoxy-resin so the shape does not pull anymore and can be regarded as stiff. This is the method he used to manufacture the corner pieces of the façade panels after the bankruptcy of Van Dam in the Floriade building.



FIG. 184 Mould for shaping the aluminium panels



FIG. 185 Completion of all bent panels for one side



FIG. 186 Opening for the bent panels



FIG. 187 Completion of the roof

08.04 GLASS WATER POND

The 2nd innovation in the Floriade pavilion is the hanging glass pond that is developed to accommodate the weight of 1,14 m water depth: 1,140 kg/m^2, which is 12 times as much as the average roof or wall load! As far as we know this has never been done before, not even in a James Bond movie. The original tender design indicated a water depth of 300 mm that gradually increased to 600 mm, 840 mm and finally in the definitive drawings, 1,410 mm. The weight load on the glass was reaching its definitive height. It was able to take the load; just a matter of analysis. Normal frameless glazing has a surface area of 2 m x 2 m, but in this case the panels were reduced to 1 m x 1 m; resulting in a quarter of the bending moment. The heavy load caused the dot-shaped suspension (desire of the architect) to be transformed into a sort of dotted line support in a structural sense; a number of node-shaped suspensions with a distance of 300 cm between each other. The shape of the pond was ideally designed by Octatube as a composition of fluent 3D shaped glass panels, 2 x 12 mm thick. The current state of affairs is so advanced (also because of the earlier described 3D aluminium panels) that it should be possible to machine foam blocks from CAD/CAM files and utilize epoxy and glass fibre mats to

strengthen the surface and pour reinforced concrete over it to create a mould. When the mould has dried, it is covered with an isolating glass fibre blanket and you can gently lower glass panels on it in duos of 2 x 12 mm at a temperature between 600°C and 700°C.



FIG. 188 Node-shaped suspensions



FIG. 189 Assembly of the ode-shaped suspensions

After cooling down, the pre-cut 3D shaped panels with polished edges were shipped in wooden crates to the factory were the chemical bath is. There are only two factories with this kind of chemical bath in Europe: one of them is Glaverbel in Switzerland. Chemical pre-tension: the sodium ions in the outer surface of the panels are replaced by potassium ions, which are bigger and subsequently cause a very thin pressure zone on the outer surface. This technology is highly developed for laboratory glass and produces guaranteed high tensions, usually twice as high in comparison to thermal pre-stressed glass.
The chemical baths should be enlarged since chemical pre-stressed laboratory glass is usually much smaller. After the chemical pre-tensioning, the nested panels are shipped back to the Netherlands where transparent tape is applied in the spacing of 1 to 2 mm that can be filled with epoxy or acrylic resin in order to acquire a stiff lamination between the panels. Subsequently there is the problem of transportation to the construction site. This described production order is not used, since it is very expensive, labour intensive and transportation intensive. The danger of fractures is always present. In the case of the Municipal Floriade Pavilion, considering a possible replacement could take up to several months, this would have been a disaster. Therefore a simpler solution, namely a polygonal variety, was chosen and realized. The fluent transformed and chemically pre-stressed laminated structural frameless glass ultimately was too great of a step for the client, but remains to be a persisting challenge for experimental product developers. With the help of 2 x 12 mm completely pre-stressed glass, without holes, frameless due to elliptical dishes connected by seams; the first problem was deflection under the continuous weight of the water. The second was waterproofing the pond, and the third corrosion or the water on the laminate in the glass panels in a moist environment. Eventually a liquid acid silicon by Tremco was used on the top to close off the upper laminates. For the bottom, a grey prefab silicon profile was used (grey is the colour of all the other silicon on the construction site), enabling ventilation; important with the regards to the ventilation that the laminate requires. If the laminate – considering the waterproofing properties of silicon – is under constant water pressure, the humidity could be sucked into the laminate due

to capillarity and cause a white colouring of the laminate layer. The seams are kept wide since the glass opening on the top is 15 mm; the shape of the basin is round so the outer seams are much bigger.

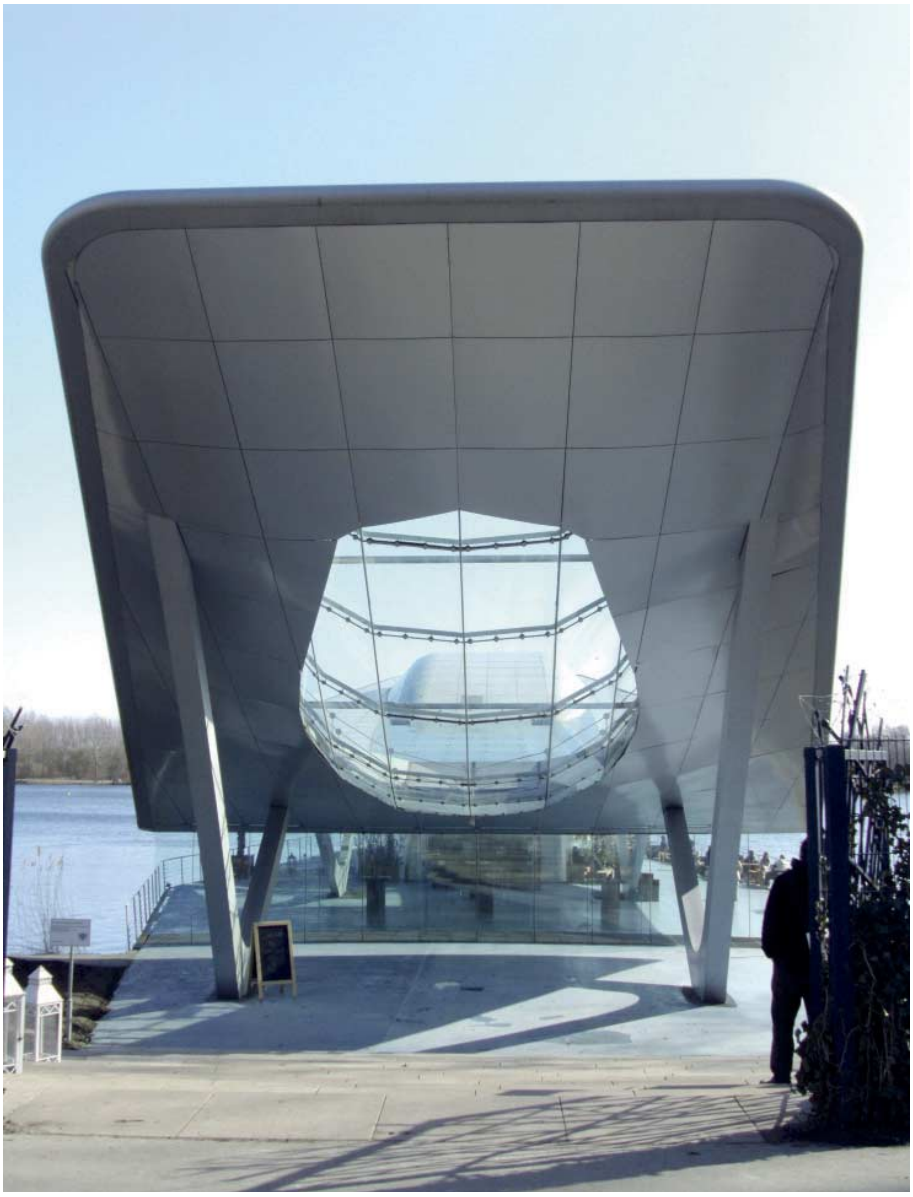

FIG. 190 Completed pond without water



FIG. 191 Completed pond with water

08.05 COLD BENT FRAMELESS GLASS PANELS

The 3rd innovation is executed in the south façade. This façade consists of three glass surfaces of approximately 6 m x 6 m, each divided in 3 x 3 panels of maximally 2 m x 2 m. The central glass surface is flat and consists of 9 flat panels of monolithic 12 mm completely pre-stressed glass. Both surfaces on the side are bent 2,5D. The original design included a conical and a cylindrical part. Making the conical mould was possible, but confronted the producing parties in Spain and England with big problems. That is why the architect was convinced to alter the conical shape into a smaller cylindrical shape. The three stacked corner panels were manufactured as 12 mm thick monolithic thermal pre-stressed glass panels (pre-stressed by Interglass, GB). In addition 2 x 6 non-orthogonal panels, each 2 m x 2 m of laminated, completely pre-stressed glass were cold bent on the construction site. From the beginning these glass surfaces were offered as polygonal. The architect changed his mind however and desired bent glass. Thus, an alternative in Plexiglas was calculated. Since the elasticity modulus of glass and acrylic differs by a factor of 30, the distance of the supports became 1 m instead of 2 m and the number of nodes needed to be multiplied by 4. In addition, all the corners had to be bent and the thickness of the acrylic was increased up to 20 mm: everything in relation to the maximum wind load. Acrylic, suggested during a dinner, proved to be no solution. The next suggestion was to make a distinction between the warm bent corner panels and the other cold bent panels. Cold bending of glass panels is highly exceptional; and usually avoided. Cold bending took place at the construction site by pressing two points of the horizontal sides downwards with a camber of 80 mm over 2 m. The bending

stress is calculated as maximally 50% of the total used stresses of 50 N/mm^2. The rest of the acceptable work tension (50%) is reserved for the wind load. The laminated structure of these cold bent panels was chosen because of the danger of fracture during assembly.



FIG. 192 Southern façade with curved glass panels.



FIG. 193 Interior view.



FIG. 194 Exterior view of the *southern façade*

Cold bending naturally caused the phenomenon of too tall windows, which could only be shortened to the right length by pre-tension (in horizontal direction). It also causes a deficiency in the vertical seams (which want to curl upwards) so a number of nodes on the vertical seams had to be applied. It must be possible to bend weak and cold laminated completely pre-stressed panels into cylindrical panels with a sufficiently low bending stress to take on wind loads. In this case, a short span pays off to reduce wind moment; several supports are used in order to make the glass thinner and easier to bend. (The experiments of this project on laminated glass were awarded with a nomination for the DuPont-Benedictus Award of 2003.)

08.06 EXPERIMENTING IN A RUNNING PROJECT

This prototype process showed that it is not easy to combine experimental and innovative production processes with the velocity and efficiency of a running building project, especially when HM The Queen will perform the opening. The velocity of product development and project processing are completely different. Yet they become entangled in each other. As the experimentation only concerns a smaller part of the project, its conditions are established by the tuning of the engineering of the project. On top of this, there is always the ghost of competition. Only if the overall price is right, orders are given. Pre-engineering is only done by the very experimental and smart architect offices. Thanks to much professional effort in this case the building was completed just-in-time. But next time I will pass on such an experimental project with so much time pressure. If we had had more time on our hands the technical results would have been far superior.



FIG. 195 Overview of the pavilion seen from the Haarlemmermeer

09 TENSEGRITY BRIDGE, PURMEREND

First published in the Dutch magazine 'Aluminium', 'Een vlijmscherpe brug'; afterwards translated.

09.01 INTRODUCTION

The 'Bridge of Masts' in Purmerend is designed according to an old principle in the sense that it derives its name from the Norwegian word 'Brygge': a pier, a platform built over water. This bridge spans 3 water levels with different dikes and polders along its full length.

Jord den Hollander is the architect of the bridge. Next to architectural design, he was primarily occupied with architectural criticism, films and architectural documentaries, but always from his viewpoint as designer. He designed a sort of a pier of 144 m length for walking, cycling and fishing, between the new town part (VINEX) Weidevenne and the polder 'De Wijde Wormer', southwest of the municipality of Purmerend, which is located north of Amsterdam. The assignment, as stated by the city council and the municipal building commission, was based on minimal use of materials and the use of aluminium as the least corroding off all structural metals, thus having the least effects on the ecological system. After the building process only one city in the Netherlands proved to be so fanatic in monitoring durability with regards to the choice of materials: the city of Purmerend. Octatube's assignment for engineering, production and realisation came through Vermeer Wegenbouw as main contractor and Van Campen Lelystad as the aluminium contractor. These companies considered the bridge a side-job, since it was part of a package deal with the big noise screen that was built in the neighbourhood, next to the motorway A7. Octatube, as a specialist contractor, would develop the sketches of the hybrid bridge by architect Den Hollander into engineering drawings, shop drawings and they would also take care of production and assembly of the metal parts of the bridge. During the development, the construction of the aluminium bridge deck was subcontracted to Bayards from Nieuw-Lekkerland. Octatube engineered it all and produced the steel components. The bridge was entirely assembled and installed by Octatube on the concrete canoe foundations of Vermeer. All together a somewhat complicated form of collaboration, which is comprehensible if one knows how fragmented the building industry is, based on a hierarchic ad-hoc system of collaboration and fragmented by all sorts of specialisations. The practise of sub-tendering parts is not an option but a rule. The building industry

produces excellent and unique designs in a rather industrial time frame, thanks to wayward concepts of architects and the presence of engineering offices and specialist producers who are used to the production of prototypes. This bridge is also designed as a unique design – a 'one-off' similar to the yacht industry – with no plans for duplication.

09.02 THE DESIGN PROCESS FROM THE FIRST IDEA TO ENGINEERING

The idea the architect perceived since the beginning (autumn of 1998) was 'a fine maze web with a bridge deck in between'. He created a model with small sticks, tensioned wires and a suspended bridge deck in between. The deck and the structure should have a fine, ephemeral expression; "a bridge that floats above the landscape" as poet Martinus Nijhof once wrote. The first sketch of the architect was a fantasy of a deck that was suspended from balloons: 'air anchors' as construction workers tend to refer to them. The bridge had to 'float' above protected nature. In this landscape with water and reed the influences of humanity over time are wonderfully visible: dikes, polders, water regulation, reclamation for agriculture and finally city development and newly built houses. Along with the urbanisation, the landscape was also intensified to become an ecologically balanced area, consequently expressing the early culture of polders and modern culture of the city at a respectable distance.



FIG. 196 Tensegrity Bridge in Purmerend



FIG. 197 Tensegrity Bridge in Purmerend

In October 1998, Van Campen sent a scheme made by the architect to a German company for a materialised proposal. But according to the architect the German proposal was too rigid, and massive and heavy space structures were applied in order to span the bridge. Visually, the proposal was way off the design concept. After the first facsimile to Octatube, the reply was immediately returned: "But this will be a tensegrity bridge! We would be glad to develop it." Immediately we made a proposal for a 144 m floating deck that was held up by outward diagonal, guyed masts spaced every 8 m, which was principally accepted. Jord den Hollander and structural designer Mick Eekhout clicked immediately. Discussions started about the designs of Richard Buckminster Fuller and artist Kenneth Snelson, who invented the notion of 'tensegrity' and used it in buildings, publications and expositions ever since.

A tensegrity structure is an autonomous and spatial whole of compressed and pre-stressed elements, whereas the compressed elements never touch each other directly, but are only indirectly connected by pre-stressed elements. The deck was considered as a long pressured plate (stiffened with longitudinal and cross-beams), which was to be suspended indirectly between 36 columns with tensile rods, cables or solid guys. The deck had to be visually independent of the masts in order to attain the floating effect.

In November 1998, Octatube materialised the design concept and preliminary dimensioned the elements after a structural analysis, while sketches were made in order to find the

most logical shape for the composing elements. The masts were conceived as circular tubes and the stressed elements as solid tensile rods, directed in both the upward and the downward direction. The deck, suspended between the freestanding masts would contain compression forces in both the longitudinal as well as crosswise direction and a fair share of deflection. After a first structural analysis, the masts were considered as galvanized steel, the rods in solid steel to minimize the need for pre-tensioning and to make the bridge as stiff as possible. The complete aluminium deck was thought of as a frame of lens-shaped beams spaced 4 m apart, connected to 2 longitudinal beams and finished by punched aluminium plates for the surface of the deck.

Preceding realisation, a partial assignment was issued for co-design and pre-engineering based on the total design and build quotation. The work initially concentrated on the design and realisation of the deck, being the only experimental building part. In the considerations concerning the design, the thermal dilatation of the aluminium deck played an important role. In an early stage we decided to use the smallest stable unit; a bridge module of 16 metres length, suspended between a total of 2 x 2 = 4 masts with 2 x 4 guy positions (the smallest autonomous structural tensegrity module). It was possible to fix each module independently from the other. Within a dilatation zone of 16 metres each, a sort of thorn connection in the curved edges was assured. The thermal expansion in the summer and contraction in the winter (calculated at 200 mm over 144 m length and 60°C temperature difference) would be reduced to 25 mm per dilatation seam. The guys that were thought as a hinge on both ends could easily cope with such a change in length. During pre-engineering, the concept to give the deck a lens-shaped section was changed to extruding 16 m long triangular aluminium profiles, to weld these lengthwise and thus create great longitudinal stiffness to a flat plane of 3 m wide and 16 m length; a smooth surface to walk on. Every 4 m, at the guys, extra bracing would be mounted underneath the upper surface.

Punching the flat aluminium panels was initially conceived in order to acquire sufficient grip on the surface, but was abandoned at a later stage due to the expectation that the bridge, which would undoubtedly be used quite intensively, should not get a surface that could easily injure people. Indeed, people linger and chat on the bridge enjoying the magnificent views, and boys, sitting on the deck, are hoping to catch a fish. An epoxy finish would reduce the risk of injuries considerably in case of a fall. Unfortunately, the budget was insufficient to make a ceiling of curved aluminium panels underneath the deck, in which case a perfect linear airplane wing would be achieved. Looking back, a large number of starting points were estimated correctly, the engineering was therefore only the further development of this concept. The concept remained unchanged, but was further analysed, dimensioned and detailed. In general, the most important decisions concerning the efficiency of the design were made in the design phase.



FIG. 198 Connection detail

09.03 THE ENGINEERING

The engineering consisted of a structural part, a technical drawing part and a management part. The structural part treated the structural analysis of the deck in several cyclic rounds, subsequently the pendulum masts (with hinging connections to the foundation) and the tensile rods, combined with the reaction forces on the foundation. The analysis was executed with SAP90, software to analyse defined elements. The dimensions of the steel masts could be minimized to 139,7 mm x 7,1 mm in St 370, the rods have a diameter of 24 mm St37-2K. The aluminium edge tube of the deck remained at 140 mm x 9,5 mm and was strengthened with a wall thickening of 16 mm at the location of the welded nose plate connections. The architect considered a holistic approach of the design as extremely essential; the whole should breathe lightness, the chosen materials and the (slender) dimensions of the components should support this, but the craftsmanship would primarily show in the details. The details should also reflect the super lightness of the overall design. This is why the details were carefully developed by the engineers in a dialogue with the architect. The slenderness is now located in the structural scheme, the dimensions of the components, and is consequently carried through in the details.

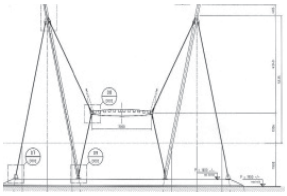

FIG. 199 Principle of tensegrity

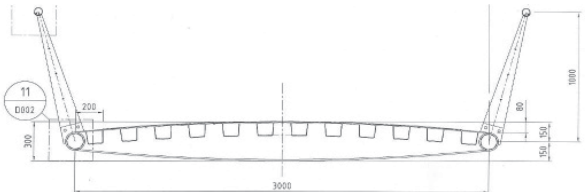

FIG. 200 Deck of the bridge with supports

The engineering department worked out the principle that the top of the masts had to be aligned in one single line, about 6 m above the assumed standard level. The deck, however, would get an asymmetric camber of 1000 mm in the lengthwise direction in order to cross the three different water levels. The base of the mast, however, would be located on different depths, since the concrete canoe foundation beams had to be constructed at different levels. The definitive heights, measured by the municipality, were supplied quite late, which resulted in redrawing our earlier drawings.

Cambering the deck in the lengthwise direction was initially not a demand or desire, but was proposed by the architect in February 1999: a just correction considering the visual aspects. The straight bridge acquired a slowly inclining jump to become a better design. After a lot of internal deliberations it was assumed that every tensegrity module could be cambered up to the desired height with the 4 rods on the left and right side of the

bridge. This also proved the advantage of the dilatation in the lengthwise direction that could take on deformation, which was also realised. The deck modules were cambered and bent upwards under tension with the help of the rods, thus proving that a tensegrity construction could have structural benefits.

09.04 PRODUCTION

A lot of attention was given to the deck. After it was decided to use extruded profiles, at first a tube extrusion with a section of 250 mm wide and 130 mm high was used, composed of three triangles. The average thickness of the profiles is 7 mm for the upper and lower walls, and 3,5 mm for the inner walls. The deck profile had profiles in the cross section in order to make welding easier while connecting the elements. These kinds of profiles are used for helicopter decks on off-shore platforms. These profiles can be connected by welding the upper and lower side when structural action in two directions is required, or just on the upper side. In the long wait between engineering and the definitive shop drawings the profiles turned out not to be available and after a structural analysis we changed to a reversed box profile: also 250 mm upper width and a tube-shaped strengthening, changing in width from 125 to 105 mm across a height of 110 mm and a thickness of 5 mm. The weight of this profile eventually came down to 6,5 kg/m^2.

This final version of the reversed box profile was extruded in a double-version of 500 mm width, so 50% of the seams could be welded in the lengthwise direction. This was accompanied by a careful decrease in cost for this part of the work. In this case, only the upper seams were welded with a mobile welding robot and the welding seams were mechanically brushed in order to acquire an even surface. Aluminium quality of the extrusion profiles is AlMg Si 0.7 / AA 6005. The four crossbeams underneath the profiles are manufactured from a flat plate: 5 mm vertical and a rib of 10 x 200 mm. The upper side of the cross ribs were cut in the contra-profile compared to the welded deck profiles with a camber of 100 mm in the width-wise direction and subsequently welded under the deck. The edge profile is manufactured from a tube, also welded in the ensemble of the deck in Al Mg Si 1,0 / AA 6082, the vertical profiles of the crossbeams in AlMg 4,5 MnW 28 / AA 5083 H1 16, while the lower strips are manufactured from Al Mg Si 0.7 / AA 6005.

During the development of the structural analysis, the commercial availability and the production process of the deck, it became clear that the agreed production price was tight. Because of the subcontracting to new parties and the final price that had been agreed upon a long time ago, the internal budgets came under great pressure. The 'design and build' method that was applied in this case is a good method when experience with the demanded realisation techniques and dimensions are available. Post-calculation is directly linked to pre-calculation. If the post-calculations are missing, every price is wrong. In this case, the design concept was right on, but the internal costs structure had to prove

accurate during the engineering process. Of all parts, the deck was the biggest question mark. Eventually these matters were reasonably solved thanks to the flexibility of Bayards. The deck elements were welded on the construction site and at the start of the assembly transported to Purmerend by trailer.

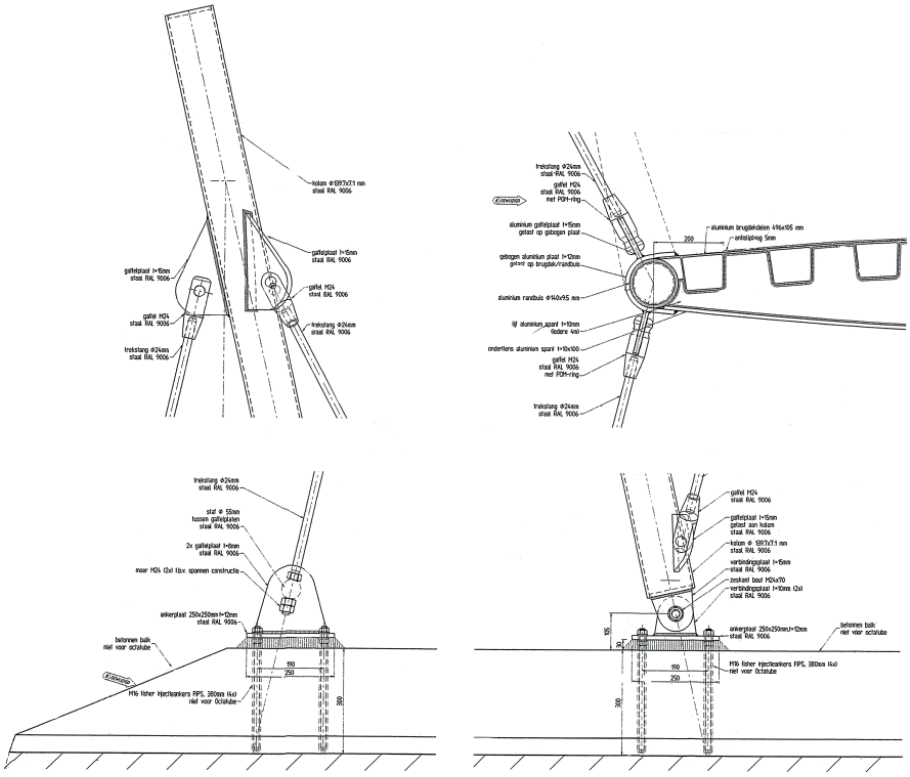

FIG. 201 Details of the mast, tensile rods and deck

The aluminium parapet bearers in strips with round feet plates, fitting on the edge tubes and the aluminium parapet were separately produced and transported to the construction site. Even in the beginning it was evident that it would not be logical to make the masts from aluminium. The buckling vulnerability, the required outer diameter and the large amount of welding to the aluminium mast for the nose-shaped connection plates made these components a lot more expensive in aluminium than the alternative in galvanized steel. Although the municipality preferred untreated aluminium and galvanized steel, the columns were additionally powder coated in order to durably protect the galvanized layer.

09.05 ASSEMBLY AT THE CONSTRUCTION SITE

Assembly was one of the main issues at the start of the design and engineering process. The main considerations were the three waterscapes, the dike bodies and the reed lands in between. Those did not constitute a very useful construction site seen through the eyes of the building industry. A civil constructor (in this case Vermeer) sees this differently. A simple sand body parallel to the bridge is created, except in the reservoir; where boats were used. This temporary construction element was used to pile the foundation, and the prefab concrete beams were adjusted on the pile heads. These beams were located across the width of the bridge and had sufficient length to connect the rods and the feet of the masts.

The second problem concerned the tolerances. Piling gives large deflections. The lower side of the prefab concrete beams had notches that enabled an off-set of 100 mm of the pile head. From the start it was determined that the tolerance for the upper elements was a maximum of 10 mm in all directions. Thus the decision was taken to reduce big piling tolerances to 10 mm in two stages: by the space around the pile head that had to be poured, and by locally drilling mechanical anchors at the upper side of the concrete canoe-shaped beams. Thus, in the preparation phase sufficient measures were taken to prevent problems during construction.

The steel columns and guys were adjusted on temporary derricks of 3 m width, fitting the foundation beams. The trucks with the deck modules were unloaded with a crane, which was located a little bit further on the temporary sand body. The modules were placed one by one on the derricks and guyed. After several were placed, the camber of 1000 mm was applied. Initially by feeling, and then with the help of laser-driven water levelling. The 26 mm wide rubber seam sealant was applied, followed by parapet bearers, the parapet and the cable elements in the parapet. After adjusting all metal components of the bridge, the surface was finished at the construction site with a granulated epoxy layer. In general, this project is an example of a 'one-off' design, which was not obstructed by any problems during realisation and production worth mentioning, due to addressing and solving all considerations of production and assembly in advance. In this case it illustrates the benefits of the 'design & build' approach, whereas all knowledge, ability and insight in the different departments of the company were constantly influencing each other to realistic and sometimes daring undertakings. If the preparation was based on the classical execution of an architect's design, the structural analysis, the tender and the productions and assemblies were realized by different, independent parties; the process would definitely be a lot more rigid and the result would be the direct consequence of this. The only hick-ups in this process lied with the financing and the step-for-step assignments of the municipality as a client, something out of the control of the designers and contractors. The bridge was completed in the fall of 2000.

09.06 MEANING OF THE TENSEGRITY BRIDGE AS A STRUCTURE

This floating and practical airplane wing in a reed- and waterscape, suspended from slim masts results in a V-shaped profile in the cross direction, focuses on the openness of the air. In the lengthwise direction the slightly cambered deck, suspended with flimsy rods, steals the show. The heads of the masts are perfectly aligned, making the camber visually present. Bridges in the Netherlands are increasingly designed from architectural considerations. Our country is only benefiting from this. Apart from the usually down-to-earth functional-technical considerations of civil engineers, suddenly considerations focussing on design, culture, society and environment come into being. Every architecturally designed bridge is a feast to the eye. Bridges are often solitary objects in the landscape that are highly visible and stay there for a prolonged period of time. Through public use, they participate in the social debate. They are financed from communal money after all. Quite different from the over-designed bridges designed by Santiago Calatrava in Hoofddorp and the Enneüs Heerma bridge to IJburg, Amsterdam designed by Nicholas Grimshaw that does not even allow low ships to pass underneath, the architectural design in this case is in a harmonic balance with its modest slow traffic function, the spatial surrounding, the environment and the polder.

Seen the hybrid build up of this ultra light bridge and the functional use of steel and aluminium, it was nominated for the 'Steelprize 2002'. Quotation from the jury report:

"This tensegrity bridge is wonderfully adjusted to its environment. The composition of the slender masts and a thin bridge deck, floatingly suspended between tensile rods, increases the experience of the surrounding landscape. The light, almost fragile structure does not force itself but is characteristic at the same time. From a distance the bridge reveals itself as a natural fine maze network. Looking closer, the minimal use of materials is clearly visible. The exciting vertical camber in the deck is achieved by adjusting the pre-tension in the steel rods underneath. Clever thinking. The harmony of colour and detail strengthen the image of the bridge as one structure".



FIG. 202 Overview of the bridge

10 ALUMINIUM SPACE FRAME FOR DUTCH ALUMINIUM CENTRE

Article for: Dutch magazine 'aluminium' (originally written in Dutch)

10.01 INTRODUCTION

Architect Micha de Haas, as the result of winning a design competition, has designed the Dutch Aluminium Centre in Houten, the Netherlands. The concept was a rectangular, all aluminium single storey building with an aluminium structure, floors and claddings, resting on more than 600 aluminium piles. This contribution deals with the design and development of a special aluminium space frame system with customized cast aluminium joints and glued tubular member ends. The eight main features of interest in this project are:

- The all aluminium 'streamline' space frame, fitting in an all aluminium building;
- The curved form of the space frame trusses and the individualization of the joints;
- The essential form of the designed components in a 'Streamline' system;
- The problems of an axial screwing method with diagonal bracings in assembly;
- The use of glued connections between tubes and tube ends;
- The individualized, yet industrialized aluminium cast joints;
- The transfer of the aeronautical/automotive industry technology to the building industry;
- The different process speeds of experiments in an actual building project.

During the first phase of the building design, the intention was to create a standard space frame. Then, the actual building started with a further commitment of Dutch industrial aluminium parties. Instead of the Tuball space truss system, already developed in 1984, Octatube proposed to add a new development to the building process. Whereas the Aluminium Centre, being the client, was more interested in an entire building and all its commitments to that, Octatube thought it more interesting to take on new technical challenges. From the very beginning, it was agreed that Octatube would maintain the leading position in the project. The choice for a new development consisted of the introduction of customized cast joints and the aeronautical gluing technology. Parties in the Netherlands were willing to contribute to

both techniques. Furthermore, the aluminium would be supplied by an aluminium extrusion company. By the nature of the development process, the chair Product Development of the Delft University of Technology would support and publish the process, so that the general message of product development would become public knowledge.

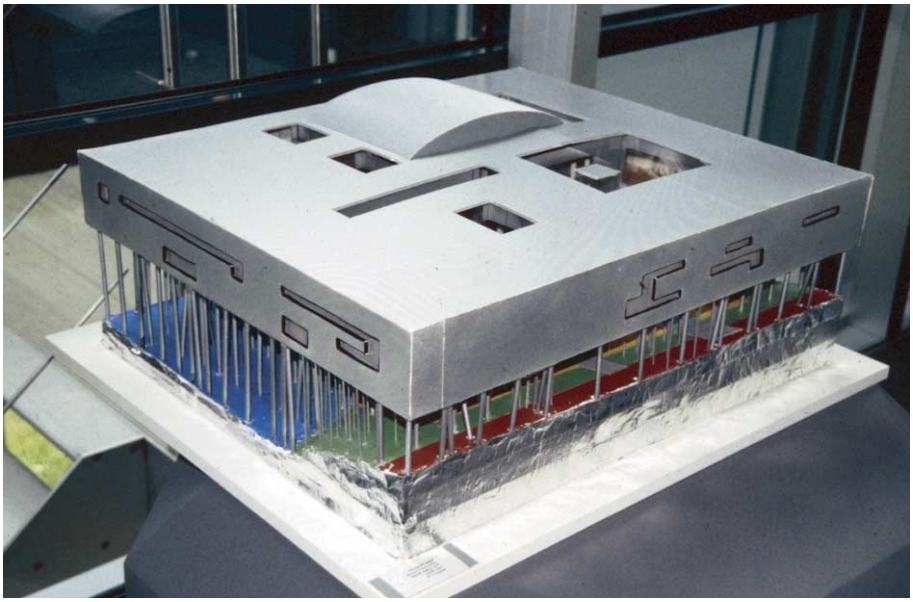

FIG. 203 Model of the aluminium centre



FIG. 204 *Exterior of the Aluminium Centre*



FIG. 205 *Patio*

10.02 PRODUCT DEVELOPMENT IN GENERAL

During the product development process of the space aluminium roof structure for the Aluminium Centre in Houten, it became clear that fundamental research, directed at product development, could only be fitted into a current building project with the greatest caution. Basically, the product development process and the building process are two independent routines. They are not compatible in the aspect of time, but they often need one another in the sense of stimulation, or for source and cause. It is a good thing to deal with this contradictory dependence.

10.03 ASPECTS OF TIME

The following aspects are of importance. When a development process is started, there is a rough indication of the direction in which the process will move, but only the actual making of the design clarifies what it will actually look like, and how it will be assembled. This applies to the design of an entire building, as well as to the design of a building component, such as in this project. The designers give the design a very personal interpretation by their specific choice of composition. Insight, concerning the possible realization of the solutions, arises gradually during the product development process. In the initial stage, relatively little knowledge and experience of the actual experimental material application will be available, but the most important design decisions must be made. At that time, feedback is not yet possible and consequently there is no experience yet. (Therefore, it is tempting to bring a composition of well-known techniques to the task). It often occurs that the design process manifests itself iteratively. First, a concept has to be made, then a prototype that has to be tested, and subsequently improvements to the original concept are made. This cycle may have to be passed through for several times to come to a permanent useable product that complies with all the requirements of the basic principles. These are considerations or unfamiliarities and insecurities that accompany each new process of product development.

On the other hand there is the process of the building project. Working against the clock, as is usual with current larger building projects, there is only a limited period of time for each part. This means that for engineering, sub production and assembly at the factory, as well as for the assembly of the various components of the building, limited passing-through times are inevitable. These time limits are usually specified on time sheets of the project's planning scheme. The architect must identify the components that will require much development work in their processing, and assess duration and complexity. It is sensible to set the starting point of development for the most crucial components as early as possible. For an example, particular aluminium project façades are often supplied before the architectural tendering. Particularly experimental building components, like the delta trusses in this case, require sufficient (quiet) time to consider broad scope decisions. Some

aspects need to pass through one or more iterative rounds before the final consequences for building can be established, especially for the other building parts (i.e. in the form of reactive forces, fastenings or connections of a building component). Especially for the sake of reliable product development processes, continuous feedback and reconsiderations are a necessity to achieve high quality projects. Furthermore, new prototypes are often needed after the design has been changed due to testing results, which means repeatedly new production and assembly cycles for the prototype.

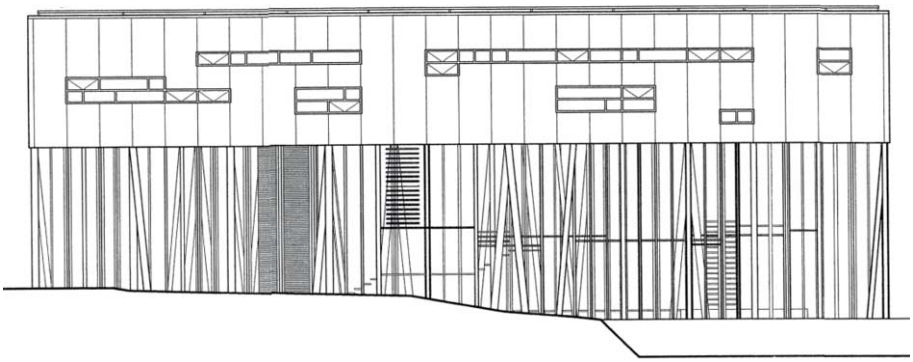

FIG. 206 Cross section aluminium centre

Unfortunately, in the case of the Aluminium Centre, the time gain as a result of delays in the preparation and production of other building components and their assembly at the building site could not or hardly be used for the important design and development process of the delta trusses. The process already had a kind of 'just-in-time' character, due to its free of charge nature. This 'just-in-time' character in particular takes away all possible elbowroom for setbacks in experiments. Therefore, the building preparation and realization ran parallel with the development process of the newly glued aluminium construction with cast joints. These increasing arrears in the preparation, production and realization of the remaining building components had nothing to do with the product development of these components, but with the ordering of materials and the starting up of their production, after the dimensions were established and the detail drawings were made. This could be called the engineering of building parts, building engineering or building development.

10.04 ASPECTS OF BUDGET

The Aluminium Centre took on various parties from the aluminium industry, to collectively bring about a basically gratuitous realization of their new accommodation. Led by the 'pilot' company Octatube Space Structures, each of the parties bore its own expenses and ran its own risks in return for a share in the intellectual ownership of the final product. This principle had both a bright side and a drawback for the development process. A positive result was that the companies were receptive to acquire new knowledge, expertise and insights. Octatube stated only to be interested in a contribution for the Aluminium Centre if actual experimental steps forward could be taken. The casting company had developed a casting method that, in principle, could be suitable for very small series. They would gladly examine and test this method. Sergem, an engineering office, manned with former Fokker employees, was specialized in aircraft construction and interested to take the step to the building industry by giving advice on gluing technologies. Because a development budget in this 'free of charge' project was lacking, the participants wanted to try to realize their own share in the strive for a new industrial product with minimal means only, within a set period. This restricted effort caused parties to wait for the other parties to make their contribution and subsequently react, rather than participate in a collaborative engineering process and anticipate the results of team members. Only to discover later that much energy was spent in vain, because successive activities could not be realized. Therefore, the consequence was that this 'free of charge' project was not carried out with full labour force. Waiting for each other's results extended the total development process in such a way that the profits from building delays could not be cashed.

To make the entire process run effectively and efficiently, a cooperation of the five participating parties was set up. It was agreed to respect each other's contribution in terms of copyrights, but also to communicate openly with one another. The proceeds of each participating company had to be from the offspring of the company products, and/or the company services in a later stage, and the copyrights for every own contribution by means of an individual or mutual patent application.



FIG. 207 Space frame in the Aluminium Centre



FIG. 208 Node of the space fame

In general, it can be stated that many models and variants need to be made for the development of modernizing products and their industrial constructing processes. Like the products, time to think and do is expensive too, but is necessary if the result is to be a good product. Project independent product development is an expensive undertaking for a company, but it has its function within the framework of the continuation of the company's future, as a long-term investment and in the quest for more benefit for the company. This also shows the difference between the functioning of contracting or producing companies. In particular, now that the customer, as compared to some decades ago, dominates the current market it is important for companies to strive for a considerable amount of individuality, identity or possible benefit, by which they distinguish themselves on the market and thus obtain commissions.

However, many companies mainly follow the route of short-term investments of applications, tendering and cashing the commissions. Basically, the present process has passed through only one cycle of design, engineering, production, assembly and tests. The series of tests was restricted to the testing of individual components. There was no time left for the full scale mechanical testing of an entire truss, as was planned, due to having to fit it into the assembly of the building schedule. One last attempt for full scale testing of the building itself level failed after calculation of the necessary water load and its consequences for the floor and foundation of the building.

10.05 DESIGN

OBJECTIVE

The design of the lenticular aluminium delta trusses should lead to a new aluminium building system (the development of a new type of aluminium truss girder with a triangular diameter for medium-sized free spans). Furthermore, the introduction of the transfer of the gluing technology from aeronautics to commercial and industrial building, as well as the introduction of the technology of singular aluminium casting. In addition, the experimental product development team was a prototype of the cooperation of companies in co-makership for a building component.

CONFIGURATIVE DELTA TRUSSES

Initially, the design of the architect showed one delta truss and two half-delta trusses. Because of the triple division in the functional programme of the exhibition room, this quickly changed into two large delta trusses with two half trusses (so, three interspaces). Subsequently, Octatube turned the truss around, so that the basis became the top and a nicer, logical architectonical arrangement of the space was established. The roofing sheet span was hereby reduced (from 3600 mm to 1800 mm) and thus became realizable in

simple aluminium profiled sheeting. The delta girders would each be built from two plane trusses, with bent upper members and straight lower members, consisting of aluminium tubes, aluminium cast joints and structural glued joints. The roof girders were used as stabilizing cross bracings for the 'spatial girder'. Octatube drastically reduced the number of diagonals by choosing a larger modulus size (from 1200 mm to 1800 mm). The advantage was the reduction of the number of joints and therefore time and money. All connections had to be designed in a 'Streamline' shape. Yet, this basic principle should be set aside if the multiplicity of the joint would become an issue.

10.06 ENGINEERING

CONFIGURATION OF JOINTS AND BARS

Industrial production considerations resulted in an important change. Initially, Octatube thought of a fixed joint distance, through which a variable triangulation would occur. From this, a fixed triangulation (all equilateral triangles with 60° angles) with more different joint distances was developed. The advantage was that a more regular joint geometry in the lower member was achieved. Placing all diagonals in 60° angles reduced the tension in the bars. The reduction of the tension proved to be an additional advantage. Initially, the upper and lower members were separately divided in equal bar lengths (therefore, two types of lengths). The change to a fixed triangulation resulted in the small disadvantage of an increasing number of bar lengths, but this was nothing compared to the advantages of a reduction in the number of cast joint types.

INTRODUCTION OF SCREWED JOINT

A direct structural glued joint between aluminium bar and cast joint resulted in too much tension concentrations in the glued joint. This was caused by the wall thickness of the bar, which was too thin. In addition to this problem, the tolerances of the cast joints, the dimensions of the truss and the chosen triangulation turned out to be so big that they could not be measured up to the much smaller tolerances (0,2-0,3 mm.) which were required for the glued joint. The solution was a screwed joint at the ends of the cast joints. This way, the tolerances of the triangulation could be absorbed. Subsequently, the development group chose for the direct absorption of screw threads in the lost foam model and not for making threads afterwards. This was done to do as much justice as possible to the industrial production. Only a minimum number of actions resulted in an optimal high quality product. One consequence of this choice was that two types of foam models would be necessary, one with a left-hand screw thread and one with right-hand thread. Tensile tests showed that the screw thread, which was cast along (left and right), would meet the required strength to a large extent.

INTRODUCTION OF GLUE RING

The above resulted in the introduction of an aluminium 'glue ring' on both sides of the aluminium bars. The structural glued joint shifted to the bar glue ring connection. Initially, a glue ring, with an internal screw thread, was entirely glued in on the inside of the bar. Thus, the glue ring remained invisible and only one seam between bar and cast joint could be seen.

Tensile tests showed that the aluminium member wall was too thin at the joint. Consequently, a second visible seam occurred and the glue ring became not just the physical, but also the optical connecting element. The wall thickness of the aluminium member could be reduced from 10 mm to 5 mm, while the bar ends were narrowed internally to keep the tension concentrations in the glue line to a minimum. The bar was pushed over the glue ring. For the sake of safeguarding the glue thickness, the member butts against the glue ring. Therefore, the narrowing is not carried through entirely, but stops at a thickness of 1 mm. This prevented the glue from squeezing out of the joint.



FIG. 209 Space frame node

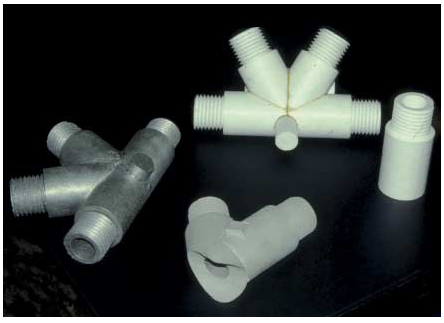

FIG. 210 Polystyrene moulds, on the left an aluminium node



FIG. 211 Space frame node with (lower) glued connection



FIG. 212 Polystyrene moulds with an aluminium node

10.07 PRODUCTION

MEMBERS

The quality of the aluminium was 6060 T6 AlMgSi-0.5. The total number of members was 186. The outsides were anodized with a matt surface. Calculations showed that all occurring (normal) forces should be absorbed by tubes with an external diameter of 60 mm and a wall thickness of 5 mm. The accuracy of the internal diameter at the point of narrowing was important, because the narrowing at the outside of the glue ring should not entirely be completed, so that the member could butt against an edge of 1 mm height. All this was necessary for the safeguarding of the thickness of the glue line. The narrowed surfaces had to be blasted thoroughly with aluminium oxide to improve the bond of the glue. The tolerance for the linear measurement of the members was set to approximately 0,1mm, but was basically of marginal importance. It was safe, because the screwed assembly could absorb the tolerance for the entire truss length. At this point, a not exactly fitting connection with a margin of one turn per member was already considered.

CAST JOINTS

The casting process was carried out according to the principle of the lost foam model. This technique is often employed for the production of small series, in this case 102 pieces, divided over 6 types. The choice for the type of expanded polystyrene affected the surface condition of the joint (globule appearance). The assembly of foam model components into a complete model was done by hand. The resulting tolerances could not be united into a glued joint. The introduction of a screw thread proved to be necessary. By employing a high quality aluminium cast alloy (A356-T6), the required strength of the screw thread could be guaranteed. The metric screw thread M48 was chosen to go along with the foam model, instead of the making of screw threads afterwards. On the one hand, two moulds would have to be made (right- and left-handed screw thread), which would involve considerable extra costs. On the other hand, an additional treatment of the product would not help the total industrial character of the product. Tensile tests of the screw thread which was cast along showed that the required strength could be achieved to a large extent. By the triangulation of the delta girders, during the assembly phase, it showed that more tolerance in the screw thread was needed. Therefore, the thread needed additional rotation to make a good fit.

GLUE RINGS

Firstly, the glue ring as a whole was inserted into the member. The sudden material transition from 5 mm to 10 mm caused too much tension in the glued connection. As mentioned earlier, the glue ring now inevitably became visible (thus, two seams), to keep the material thickness at the point of the glued connection constant. One half was externally narrowed under an angle of 5,7° with an edge against which the bar would butt. The other half was internally equipped with metrical screw thread M48. The accuracy of

the external diameter at the point of the narrowing again was of great importance (see 'Members'). The narrowed surfaces had to be blasted thoroughly with aluminium oxide to improve the bond of the glue.

GLUED CONNECTION

Cold setting glue was chosen over warm-tempered glue, so that no additional production step of heating was needed. It could be applied to large elements that do not fit into an autoclave. It will be fully tempered after seven days at room temperature. Subsequently, nine tensile tests were carried out with epoxy glue 'Scotch-Weld 2216 B/A' (3 x 12,5, 25 and 50 mm) with singular lap joint test pieces and six with bevelled lap joints (50 mm; 5,7°). All test pieces were 5 mm thick and 30 mm. wide. The average shear strain was 12,5N/mm² ± 1,7. With this, approximately four times the required (calculated) force can be resisted. Greater length of overlap of over 15 – 20 mm would hardly have an effect, because tension concentrations at the edges are the determining factor. However, by employing bevelled components, an increasing length of overlap proves to be sensible, because tension concentrations are then partly balanced out. Surface treatment also proves to be of great influence, datasheets show an average shear strain of 17,0 N/mm². In a phase already too late, it was discovered that a roof strip of 2 metres width had to be supported by the 'half' delta girders. The glue joints would collapse. Therefore, additional structural arrangements had to be made outside the roof construction.

10.08 ASSEMBLY

THEORY

Beforehand, it was established that the assembly of the triangular trusses by means of screw joints would not be possible in theory, and in practice should be based upon broad tolerances. The assembly should be carried out as follows: after spreading out all cast joints and members with glue rings, all bars would be tightened simultaneously. In theory, it was recognized that it would be impossible to form the triangular trusses from axially turning tubes. Yet, it was expected that the members would yield sufficiently. It was also recognized that the maximum 'tightening difference' between the various screw connections could amount to one rotation per joint. To minimize this tolerance, the production process would have to become far more accurate, more time-consuming and cost increasing. Some examples are that both glue rings at the ends of the bars should be better adjusted to one another. Furthermore, during the composition of the separate foam models to a joint, the screw thread on each expanded polystyrene foam model should be precisely determined. Because the foam models were assembled by hand, this proposed quality-increasing measure would be impossible.

PRACTICAL PROBLEMS

Yet, some greater problems arose. The simultaneous tightening of the members failed. They soon got stuck. This was caused by defects in the angles of the cast joints that could not entirely be absorbed by tolerance. This could have made the members bend slightly. However, due to their tremendous rigidity, they did not bend and therefore caused immense tensile forces perpendicular to the glued connections which, in turn (three of them), caused delaminating. Time was short. New joints could not be cast and the bar heads could not be finish-turned wider anymore. It was an unexpected detail that the glue line apparently could not bear the tensions. Subsequently, it was doubted to what extent the glue lines in the not collapsed joints could still be trusted. Firstly, a design was drawn up in which only glued connections were used. By the triangulation of the truss, the members and joints would all have to be connected in one go. Since there are no autoclaves in which a truss of such dimensions would fit and also because it would not come to a general structural system, it seemed necessary to apply a cold setting glue epoxy glue type 'Scotch-Weld 2216 B/A' by 3M (seven days at room temperature). A disadvantage of cold setting glue types, as opposed to warm setting ones, is the lower quality.

PRACTICAL SOLUTIONS

The screw threads of all cast joints were cut once again. This was a lot of unnecessary work. The assembly, however, was much easier and the tensions in the glue connections were minimized during the assembly process. A safety locking system was installed in the members, because of the suspicion regarding the non-delaminated glued connections. A stainless steel cable with screw-threaded end (M20) with a diameter of 10 mm was fed trough the lower bar and anchored this in the ends of the castings. To this purpose, the joints had to be bored! For the upper side, a lead-through was made for the bearing cams of the girders. Here as well, the stainless steel cables were anchored in the in the ends of the castings. Because the tolerances, with regard to casting and glued connection, were not in proportion, the glued connection was shifted. A glue ring was introduced by which the structural glue line was relocated between the bar end and the glue rings. These smaller elements were suitable for a warm setting epoxy glue type.

DELTA GIRDER AS A WHOLE

In their factory, Octatube assembled the cast joints and the members with glue rings to six flat lenticular truss girders. Subsequently, two whole delta girders were formed from these, by the connection of the straight lower members by means of a rotated aluminium connecting ring at the point of the cast joints, and an M6 securing bolt. It was important for this connection that the joints were accurately put next to each other in the linear direction of both truss halves, to make the aluminium connection ring fit. To realize this, the bars were tightened equally as much as possible.

ASSEMBLY OF COMPONENTS

To guarantee the 60° positions of the two whole delta girders during transportation, strips served temporarily as the third side. These two whole delta girders, together with the 'halves' were transported to the building site at Houten. The following types of connection for these elements were used.

CONNECTION DELTA GIRDER – I– EDGE BEAM

For the endings of the delta girders, special cast joints were made, to which an L-profile was cast. To absorb changes in the length of the truss because of temperature differences, a roller support at one side of the delta girder was realized by a slotted hole in the mentioned L-profile in the linear direction of the girder. This connection was made at the point of the bottom flange of the I-edge beam. A hinging connection was fitted at the other side, by means of one single bolt connection in the linear direction of the truss. At first, it was considered to connect the delta girders to the body, but then the truss would not be capable of moving freely and unwanted moments in the body of the I-edge beam might occur. Fastening them crosswise with two bolts in the mentioned L-profiles prevented toppling over of the whole delta girders. This crosswise stability idea proved to be sufficient during the assembly.

CONNECTION 'HALF' DELTA GIRDER – C-EDGE BEAM

To prevent buckling of the lenticular 'half' delta girder, it was hinged-connected to the body of a C-profile at every joint in the lower member. Again, this was done by a (longer) turned aluminium distance block, locked with an M6 securing bolt and fastened with an M12 bolt. Changes in the length of the truss, as a result of temperature fluctuations were absorbed in the C-profile by applied horizontal slotted holes at the point of the cast joint C-girder connection.

CONNECTION DELTA GIRDER – ROOF PURLIN

The temporarily applied strips at the basis of the delta girders were replaced by roof purlins. The cast joints of the upper members have an aluminium block that was cast along, the upper surface is 30 mm x 50 mm, in it is a hole with a tapped screw thread. The aluminium extrusion C-profiles (50 mm x 100 mm x 50 mm x 2 mm) were already equipped with holes at the point of connection with the cast joint in Octatube's factory. Only at the building site, delta girders and roof purlins were connected to each other. For this connection as well, it was of importance that the cast joints were nicely placed on one surface, crosswise in the separate (half) delta girders. This was done to stop transformations in the roof purlins as much as possible, casu quo to prevent them.

10.09 INDUSTRIALISATION IN LOTS OF ONE

It is possible to design and develop an aluminium space frame system with customized cast aluminium joints if an appropriate node design is maintained. In theory, all joints can be different, with regard to the development of digital baroque architecture with its irregular a-systematic composition. It is also possible to use glued tubular endings. Due to the nature of the triangulated space frame geometry, it is not advisable to design axially screwed connections in a triangulated space frame. It would be better to develop cross pin connections. The development of such structural systems is best done independently from ongoing building projects.



FIG. 213 Exterior of the Aluminium Centre

11 ALTERNATIVE DESIGN FOR GLASS ROOF FOR THE DG BANK, BERLIN

Lecture given for Bout students at Berlin excursion, 2002

11.01 FROM SHELLS TO FLUID DESIGN ARCHITECTURE

State-of-the-art computer programs enable architects to produce free-form designs for buildings. In contrast to orthogonal architecture, free-form envelopes are not easily developed. Cones, cylinders and spheres are counted as old-fashioned developable bodies. They are, in our current view, highly regular bodies. But in the last century in the eyes of the people of those days the same highly irregular bodies were introduced on top of the century old domes and cylinders: saddle-shaped hyper (in full: "hyperbolic parabaloidal") surfaces, as these were easily to be calculated and realised by hand. They were based on straight rules lines and hence moulding surfaces were not hard to build by specialised concrete form carpenters. The world master in this field before computers was the Spanish Mexican Felix Candela (1910-1999), who took the Spanish technology of reinforced concrete shells as developed by Eduardo Torroja (1899-1961) at the time of the Spanish Civil War (1936-1939) and fled to Mexico, where he designed and built his master pieces. Usually they were extremely thin (50 mm) reinforced concrete shells made in an on-site timber mould. His mathematical and mechanical knowledge and insight assisted him in realising extremely thin concrete structures. After he had collaborated with space frame expert Castano (Triodetic space frame systems) for the roof of the main stadium at the 1968 Olympic Games in Mexico, he withdrew from the building industry and went to live on an island in Greece. The ratio between labour costs and material costs had changed, also in Mexico; his structures needed little material and lots of labour. Candela realised beautiful shells as big, extremely thin cantilevering roofs. His Chapel of San Vincente de Paul in Monterry is very elegant. The pioneer came and started a generation of buildings. With his retirement the shell era seemed to have vanished.

His works were, as it were, continued by Julius Natterer in Germany/Switzerland and Heinz Isler in Switzerland. They focussed on efficient mouldings and timber shell structures respectively. Isler (1935) recently closed shop, while Natterer is the timber professor and known for his "Holzbau Atlas", that was translated into Dutch in the 70s. Also ABT (Pestman and Oosterhoff) built timber hypar shell structures in the 60s. Not long after that, the prices of mould carpentry these became too high. The joint forces of economy and architecture killed the interest in shells. How comes that fluid design architecture with its extremely high geometrical complexity, higher even than the 20th century shell structures, came into the spotlight for the last 5 years?

11.02 THE GUGGENHEIM MUSEUM OF FRANK O'GEHRY IN BILBAO

In 1998 I was asked to give a series of lectures in Spain after the publication of my book 'Las Structuras Tubulares en la Arquitectura'. [Ref. 11.01.] The tour brought me to Seville, Barcelona, Valencia, Madrid, Vigo and Bilbao. Just after landing and before lecture time I went to visit the Guggenheim Museum. After seeing it and being impressed by this architectural bomb, I dramatically changed my slide show by drawing mini pictures on translucent paper for the slides. Yes, it had been realised in Spanish technology, but the signature of the master had not been tampered with.

The building was a sculpture! It was a building so interesting sculpturally and spatially dominant that it needed no sculptures to draw visitors. Overshooting? Of course! A museum should house art and should accommodate it modestly, abstractly and neutrally. This building was brutality! But the building was also one of the first fluid design buildings of the last decade. The town of Bilbao never was the same after Gehry. The mayor was right. This museum, even more than hosting art, was a sign of a brand new architecture; it was also a true cultural deed and a social manifestation. A visual bomb had been planted on the river border. This 19th century town all of a sudden became middle aged. Even the congress building, under construction down the river, had the looks of a sixties building hopelessly out of date, even before it was completed. The form of the building was extremely expressive, a flowering explosion. One could question the Spanish building method: crude and with easy details, making it far from perfect. But Gehry's first European building loosened the tongues. As far as in Tel Aviv, I noticed, it was the talk of the day. Architects were jealous of the first use of titanium panels, probably acquired via the new Russian business channels from one of the previous Soviet republics, one said. They could only afford aluminium panels.

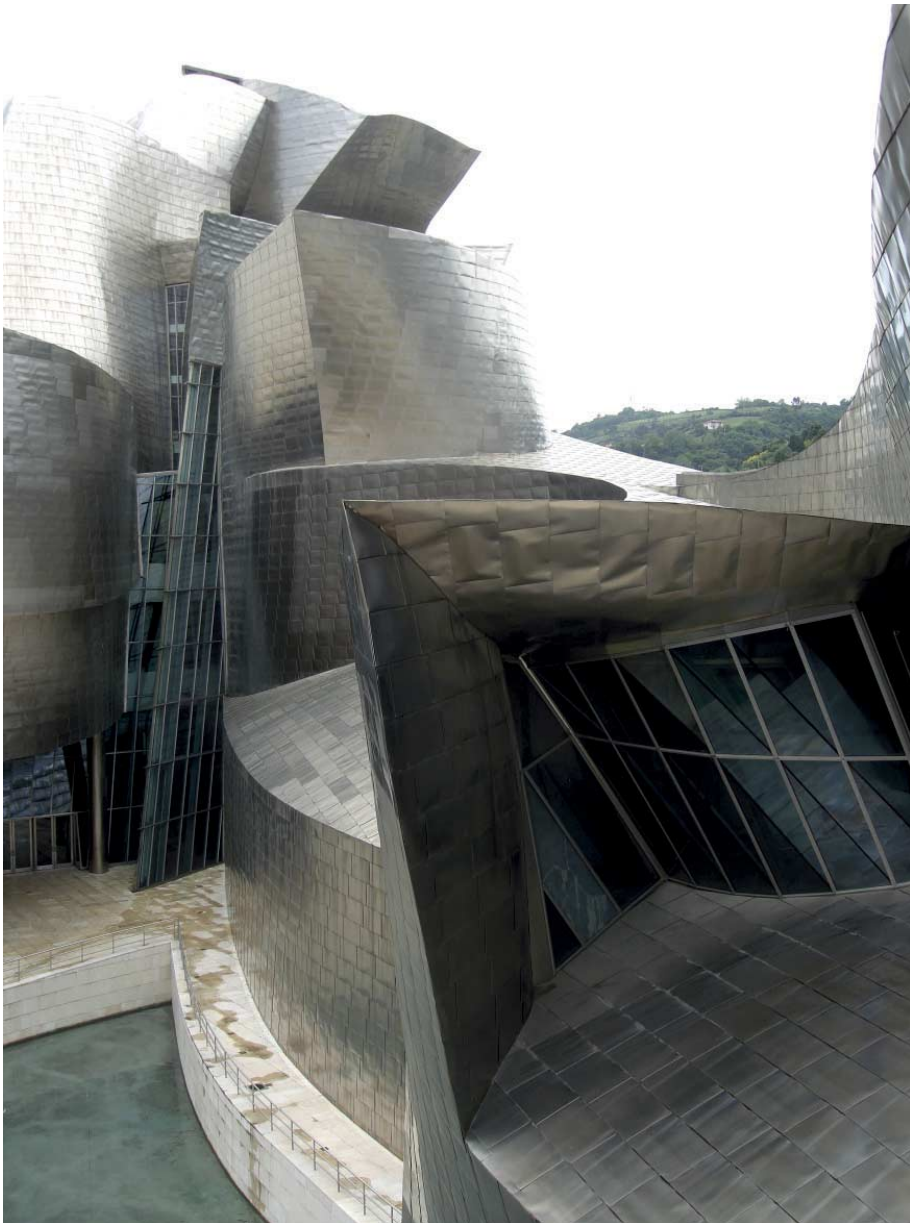

FIG. 214 Guggenheim Bilbao, Frank Gehry

11.03 THE TENDER OF APRIL 1996 OF THE DG BANK

Octatube has realised a number of building parts in Germany in the 1990s. Just after 1990 we were the first who dared to load glass in a structural way. First in the Netherlands, and after a few years we built with structural glass in Germany as well. This was much to the liking of enterprising German façade advisors such as Klaus Glas (Wiesbaden) and Peter Reich (Frankfurt). Architect Gerkan, Marg & Partner. Ian Ritchie was involved. Klaus Glas was hired to prepare the Messe building in Leipzig in 1996-97, for which I proposed a connection detail of a sloped glass sun louver panel and a steel tensile rod perforating through this glass panel. The building in Leipzig was much too big for us. The cylindrical building was to be built by Seele and Mero, our main German competitors. During one of the discussions of that time, Klaus asked my opinion on Gehry's new design in Berlin. And he showed me the design drawings. Interesting and difficult, extremely difficult. Really something one leaves to his best competitor. Let him bite the bullet. But at the same time it seemed a challenge due to that complexity. I gave a price indication on the spot, based on the dimensions he mentioned: 9 million Guilders, ehem D-Mark. He said: "No Mick, better study this original in more depth. Maybe you will find alternatives, which will make it more economical. Take care, don't burn your fingers". He did not have to tell me twice. In Delft we sat around the table and my engineers were as impressed by the complexity of the design and by the individual character of the elements and components. It looked like clock makers' work. You have to be in Switzerland for this accuracy. But back in Delft the opportunity seemed too challenging to let it pass by. So one week after the previous discussion with Klaus I said that an eventual alternative would be based on my space frame system Tuball, this time with stainless steel cast nodes, connected by cut circular tubes as a basic system. The cost level was around 12 million D-Mark. He seemed still surprised and said that 2 big competitors were interested; each wanted to develop their own details. But in the mean time Gehry had told him to keep to his original design with the finger-formed details.

11.04 ANALYSIS OF GEHRY'S DESIGN

The roof design encompassed a whale-like volume with a high and narrow end and a flat and low end on the other side, with a fluent triangulated volume in between. In fact there was a single layered space frame made of solid rectangular bars, connected by solid stainless steel nodes with 6 fingers, covered by triangular double glass panels of a special composition. The relative high slenderness of the structure gave rise to the danger of local buckling in the space frame shell under high local loads, leading to progressive collapse and hence possible collapse of the entire structure. For this reason all connections in tube ends and connectors were provided with double bolts so that the bending moments could be absorbed over all connectors. For the purpose of stiffening the large shell surface, three

stabilisation trusses were designed, perpendicular under the shell surface, composed of tensile rods only, in the fashion of the stabilisers invented by the Russian structural engineer Schuchow and built in the GUM magazines in Moscow in early 1900. It was clear that the geometry of the whale only knew mirror symmetry, in fact all individual nodes, steel rods and triangular glass panels had to be engineered and produced as individual products. The entire job contained a number of more repetitive glass facades, roofs and floors. The design has been extensively documented in the *'Excursiegids Bout Berlin 2002'* as a reprint of an article from *Glaswelt Juni 1999* *[Ref. 11.02.]*. In this article a number of essential pictures have been repeated from the same source. In the original design the nodes had the form of a hand with 6 fingers, cut from a flat plate of 40 mm thick stainless steel, after which all 6 fingers had to be pressed into the designed vertical direction, which was different for each finger. Some fingers even needed twisting. Each finger-formed node was different, no: unique. The precision of the ends of the bars with the double-lipped connections with two bolts was exactly calculated as the maximum by engineering bureau Prof. Dr. Dipl.-Ing. Jörg Schlaich from Stuttgart. This implied that there was no allowance for production or installation inaccuracies. This exact engineering, too exact engineering, astonished me, which I also put on the table in discussions with engineers of Schlaich's office. Their accuracy would create immediate implications for the executing producer in case of overstressing. From that moment onwards I was not Schlaich's most favourite candidate for the job. The Dutch language has a special word for this: "instinker". Do your job exactly, but do not allow any inaccuracies from the makers. The expected problems were to be put entirely on the table of the producers. Not very social. After a few weeks of study and development it became more and more clear that I had to work out my own alternative, which was far easier to produce, had its own charm in design and would be much more economical in engineering and production.

11.05 LOGISTIC IMPLICATIONS OF AN EVENTUAL CONTRACT

First of all, a job of this complexity requires an extremely skilled team of engineers, because all problems need to be solved in the engineering process. The project turnover was twice as big as the yearly turnover of Octatube, so dangerously big, even if executed over 2 subsequent years. Because during these two years the regular customers of Octatube also has to be serviced. We decided to found a semi-independent engineering department for this project. In this team, Dingeman Korf with his experience independently running the construction of the glass facades of the Deutsche Bank / Guggenheim Museum Unter dem Linden in Berlin, would become the project leader. He would be assisted by two structural engineers, three 3D draftsmen, an aeronautical engineer and a geodetic engineer. The aeronautical engineer was needed because of his experience with Catia, the computer software that Gehry's office used and in which the design was described.

In the project specifications the Catia system was obligatory. It would cost $100.000 for one terminal station. So, care had to be taken. These high costs were the reason that the software was not popular in The Netherlands, apart from the pirate versions used by TU Delft aeronautical students, as the rumour went. It was said that the Catia system would contain 3D drawing modules, and compatible 3D static analysis modules, so that complicated geometrical forms could be fully described in overall drawings, detail connections, structural analysis and shop drawings from one house. In fact one would need at least 3 or 4 stations simultaneously. We did not work out clearly how to buy one licensed package and have 3 or 4 engineers working on them simultaneously. But the main idea was to reserve a separate part of the office space for this project. This idea is still the same for a following large and complex project, not interfering with the daily Octatube business. (Currently under evaluation: the renovation of the skin of the 9 spheres of the Atomium in Brussels, which is 1,5 x the yearly turnover.) In later projects, for example the town hall of Alphen aan de Rijn, and in the municipal Floriade pavilion it became apparent that each large or complicated project should have a senior 3D draftsman cum building technical designer in the lead of the project at Octatube. The engineering of Blob buildings or Blob parts by a specialist producer takes place on the computers of his engineering department. The simultaneous co-operation on the 3D model on the same level by several engineers is not recommendable. There should be one main designer/3D computer model operator and the other engineers work on the 3D model in parts of a lower order, filling them in only later. The actual filling in of the main 3D framework will only be done after checking and approval by the main designer himself. This is all happening in front of the monitor, not on paper. A double check of all this work is hardly possible, as is the case in engineering of orthogonal buildings, which follow the shape of 2D drawings. But the obligatory unique position of the main designer makes the project very vulnerable. Occasional illness of the main designer/ engineer could result in a catastrophe.

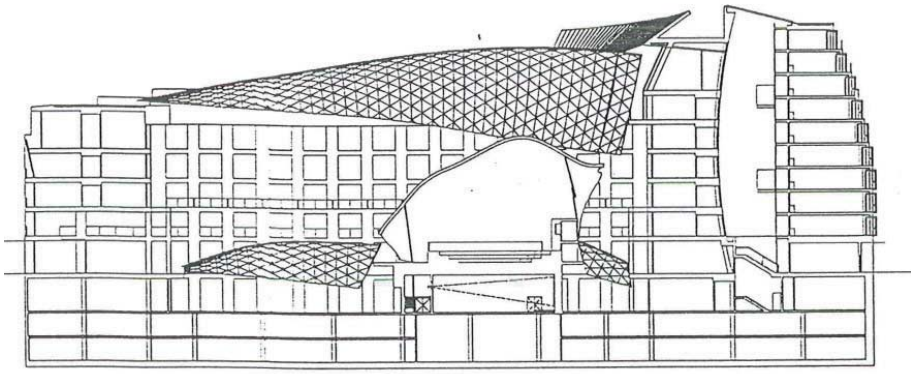

FIG. 215 Section of the DG Bank

The architect of a Blob design has to work in much the same manner with regards to the co-engineering contractors. The architect builds, checks and certifies the 3D model from a model of centre lines up to a fully materialised model, in progressive degree of minimal materials, material shapes in elements and components, connections between materials, elements and components towards the realistic sizes of all elements and components.
He can hand over the 3D model to the main engineer of only one engineering sub-contractor at a time. This works similar to the 'slot' times of aeroplanes. A pilot gets a slot time of a quarter or half an hour from the airport control tower during which he can start or land. If he does not use the allotted time period he has to ask for another slot time. The co-makers get their slot times from the co-ordinating architect in order to attach their pre-designed elements and components to the main 3D model of the architect. At that time, no one else is allowed access to the model. After installation of the co-maker the architect checks and certifies the updated 3D model and brings the model to the next co-maker, and so on.
Production would lead to a different type of approach in co-operation. Quite different from engineering, which essentially has to be controlled from one hand and one place only, the production could happen in a lot of different places, depending on the specialisation required for the different sub-productions. Compared to this the engineering of a Blob design is the core of the matter. Design is the cause of this troublesome route, but engineering is the core of success. An architect who neglects the co-ordination in the engineering process can hardly expect a perfect building according to the design in his mind. Actually it is my opinion that both the design process in his office as well as the engineering process with all the co-makers should be managed by the architect. Smart structural engineers of the office of Prof. Dr. Jörg Schlaich had included in the specifications that the 'lucky' sub-contractor to whom the steel and glass work was contracted, would also be completely responsible for the static analysis of the work. This part of engineering had to be redone by him.
At the same time, the Schlaich office would be discharged from its own responsibility with regards to the execution. This would lead to a contract where the sub-contractors would be handcuffed with laughing structural engineers on his back! I have made my astonishment on this situation clear several times during the discussions and negotiations with the local representatives of the architect and the structural engineer; however they pretended not to understand. That is to say, it was understood very well, but was considered as aside of the matter. I made a correcting note in this respect in my final offer. This all happened at the time of tender engineering, before drafting the final offer and the tendering. One can imagine that the tendering parties of the architect and engineer were not very eager to enter into a contract with Octatube! Some time ago I heard from a source in Jerusalem where Gehry is preparing his last project (he claims), that Gehry was not very enthusiastic about the possible participation of Octatube in his Jerusalem project. In my opinion every professional in the building industry should be responsible for his own deeds. The architect has to fix the geometry of the building, the principle material choice and the form of the components from which his building is composed. The structural engineer should make the static analysis of the building down to the behaviour of the different elements and components. If they take their rights but refrain from accepting their obligations and responsibilities, it does not seem correct to me. At the top of the pyramid of the project building 'team' rights (for profit and control) are accumulated, while the duties end up in the lowest layers of the pyramid (that is real execution and full responsibility for the final design and for realisation). I do not want to

use the word "outrageous", as these practices happen in The Netherlands more and more, and so Dutch parties doing business with my own company could make their conclusions of this statement of Professor Eekhout. In my own office I have always taken full responsibility for design, engineering, production and realisation. But in those cases it was me who decided, in co-operation with the architect, the shape and details of the final design.

The design has to be made by the designer, the structures will have to be designed by the structural engineer and the producing and building parties produce the designs fixed by architect and engineer only with their responsibility towards production and realisation. In case the sub-contractor / co-maker comes up with a design alternative of his own, based on his own experiences, that is more efficient than the original design, he has to show the structural consequences of this proposal and its compatibility. In such cases only the sub-contractor will join in into the game of the design. But certainly when the structural engineer wilfully positions the project details on the edge of the possible, showing off his eternal cleverness, while he deliberately neglects possible errors and tolerances in production and realisation, and he disappears when complaints are made, then one could speak about an unbalanced development in the responsibilities in the building process. This top-down shifting of responsibilities and the bottom up concentration of control can only take place under the umbrella of ad-hoc building teams with a strong protectionist character from the client and a non-present participation from the constructing parties in the game. This can happen a few times, until after a number of failures and bankruptcies there are no constructing parties left who fancy these sorts of projects with the underlying responsibilities. Then it is confirmed that the construction industry has not advanced that much or is incapable.

11.06 ALTERNATIVE DESIGN PROPOSAL BY OCTATUBE

As the complexity of the roof in the design of Gehry was high, and certainly was not allowed to be changed on the level of the overall geometry, this was only one type of alternative in order to approach an understandable, producible and economical alternative with acceptable risks for the company. The biggest problem was not formed by the glass panels or the rectangular metal bars, although all bars were twisted. The most complicated parts were the finger-formed knots with 6 fingers, each in a different direction vertically and horizontally, in order to follow the overall geometry. The root of the fingers in the hand would also give cause to a twist, a torsion. Without criticising the structural design too much: frankly, I did not understand the logic. Most probably the architect only discovered those twists in the nodal fingers and the bars at a late or even too late stage, and did not want to spoil his reputation by changing the technical concept.

For me there was only one clear alternative: spherical nodes and circular bars of the Tuball system which I invented back in 1984. From the many projects after that date I knew that all possible corners could be made by simply drilling cylindrical holes in the wall of the

hollow spheres. Also in terms of the glass support lines, over the years we had developed a clear solution to clamp the glass panels. During the development of our prototype, the German representative of the architect maintained Gehry's requirements of the rectangular stainless steel bars and the twisted stainless steel nodes in hand-and-finger form. Octatube developed their own proposal based on the Tuball system.

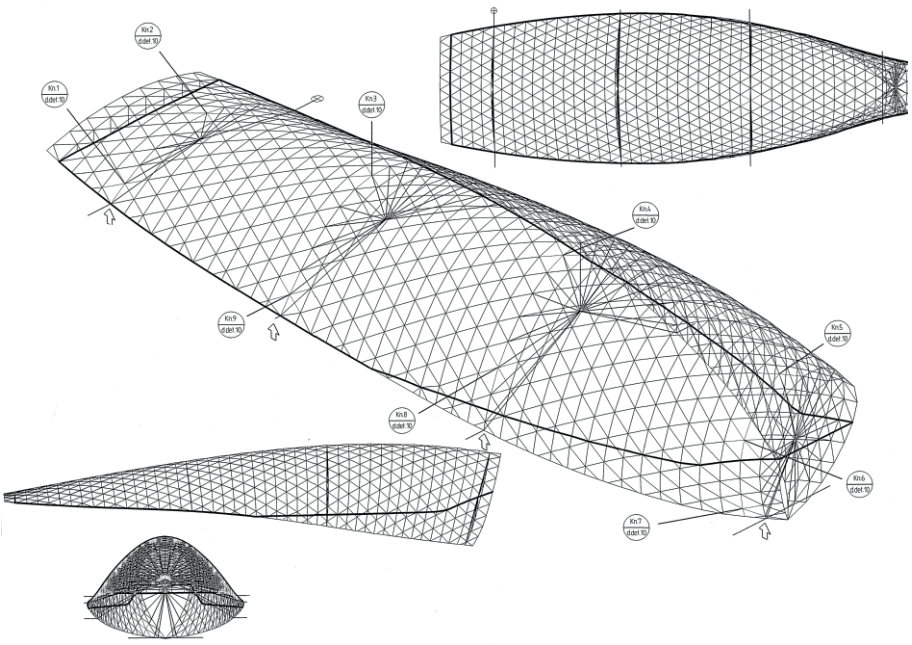

FIG. 216 Alternative geometry (Octatube) – isometric view

11.07 THE TENDERING, THE NEGOTIATIONS AND THE CONTRACTING

The negotiations took place in Berlin. We were invited by a manager from Hines, a German building management organisation. His goal was to close the contract for as low as possible a price, which he managed by playing competing parties off against each other. After the negotiations between the general contractors were over, Müller-Altvatter was the 'lucky' winner for a bid of 90 million D-Mark, while the first tendering prices were at 125 million D-Mark. I was told that the German frameless glazing company Seele had refrained

from bidding, and that the competition was between Mero (space frames), Gartner (curtain walling) and Octatube (space structures and frameless glazing). During the negotiations it became clear that Gartner wanted to get the job at all costs. Gartner had always been the best and biggest curtain wall manufacturer in Western Europe, with a good name and many export projects. But many weeks were lost by negotiations, making proposals, preparing models, all while the completion date did not change. Three months later I thought the time ripe to organise a discussion with my biggest competitor from Germany, Mero of Würzburg, in order to come with a communal bid with each half of the engineering and half of the production, and hopefully half the profit. The price Mero calculated on the base of my alternative was 16 million D-Mark, the price of Octatube was 14 million. Together we put in a bid of 15 million D-Mark for our alternative. Mero agreed this time: the original design was perfect but very complex and extremely more expensive to engineer and to produce.

Gehry's original design was put on the market for pricing via management cum financial costing bureau. Especially this management party was very successful in playing parties against each other. A bank, the DG Bank is an important customer in a low economy and hence parties would agree to a much lower price than usual. In order to keep the cash flow running, the personnel working free of charge until times would be improving. Selling under the market price happened a lot in Germany in those days and it has not changed much since then. The consequence of a bad economical situation since the 'tour de force' of the reunion of the two Germanys, the almighty position of the banks and the insurance companies were played out against companies. It is logical that the hunger for work made many companies buy projects literally far below their cost price. This harsh financial climate is not very attractive for German companies, let alone for smaller foreign companies. Slyness and mistrust dominate the games. And in my view, there is always somebody prepared to put a knife in your back. At the same time bankruptcies are regular occurrences in the German building industry. No week without the bankruptcy of one of the German curtain wall builders. Until none are left. This project also added to this downward economical spiral. Read and shiver.

When writing this essay I presume that Hines played the game that they sort of leaked the quotation of Mero/Octatube of 15 million D-Mark as if it was a quotation on the original design. Gartner panicked, reduced the offer dramatically. The original price of Gartner was well above 20 million D-Mark, presumably even 25 million; it now went down to 18 million and with one last stroke was made a deal for 16 million D-Mark. The exact figures were never known to me, but my guesses have been deducted from analysis my marketing manager in Germany, Rolf Evers, made. On the basis of this outcome the decision was easy for Gehry: 16 million for the original and 15 million D-Mark for an alternative unwanted by the architect and the structural engineer. Gartner received the order on the basis of the last negotiations, ehem price reductions. It was only later that Gartner heard that Octatube had always offered to the client on the basis of an alternative design and never quoted for the original. But at that time, it was too late for Gartner and it was too late for us, too, unfortunately. My impressions were confirmed when in October 2000 I visited Gartner's exhibition stand at the Glastech Exhibition in Düsseldorf and gave a huge compliment to

the original mock-up of the DG Bank on display. After I introduced myself to the staff, they exclaimed their despair.

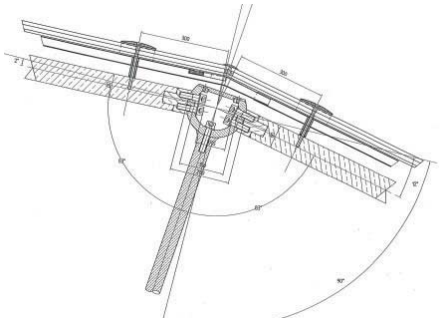

FIG. 217 Alternative detailing (Octatube)

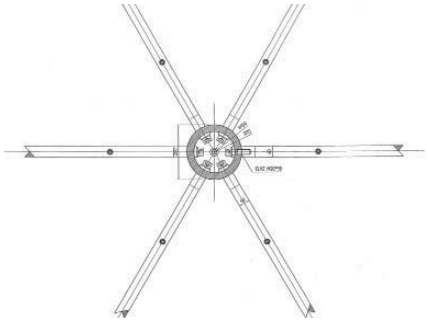

FIG. 218 Alternative detailing (Octatube)

After Gartner closed the deal we were in contact for a few months with their Gundelfingen office, trying to get a part of the job as a sub-contractor for them. We had co-operated to the satisfaction of both of us in the double facades of the Guggenheim project in Berlin. But project leader Mr. Merinda of Gartner judged that this time we were way too expensive. May be he was right. He decided to engineer and produce all elements and components himself. When I think of the financial results of this project, actually it is astonishing that he reacted like this. It must have been harsh for them, after they learned of Hines foul play, when I showed our alternative. Both Gartner and Octatube felt taken in.

11.08 IMPACT ON THE STATE OF THE ART

The DG Bank offers only limited occasions for visitors: only on Monday mornings, with a guide. During the Bout excursion, this visit, around which the entire Bout travel programme was organised, was refused at a very late date because of cleaning activities. Not very elegant at all. I never knew whether the name of the young organiser, my son Nils Eekhout, had something to do with it and other powers pulled the strings. But the photographs give a result that entirely matches with the original design of Gehry: super-ingenious watchmakers' work for the price of a bicycle maker.

Once bitten, twice shy is a common saying. The reason that the original design of Gehry has been realised was not due to the intelligent design of Gehry, nor the almost too perfect engineering of Schlaich, blaming all possible problems up front to the 'lucky' contractor, but because of the cunning actions of the project manipulator. I wonder whether Gartner would

have made the same jump twice. Shortly after my visit to the Glastech Exhibition I learned that the famous Gartner company, the pride of Fritz Gartner for decades, had been sold to Permasteelisa of Italy, also with the manipulations of a German bank to make profit, ruining the national industrial pride in its wake.



FIG. 219 Interior of the DG Bank in Berlin

But the very completion of the original design of Gerhy for the DG Bank was an immense boost for complex spatial structures of steel and glass in building technology. The financial balancing act that was involved is not mentioned in the official publications. (Most probably this paper here is published only for Bout and hence for a limited audience). That is logical. The technology attained is something Gartner can be really proud. In line of the behaviour of architects it is likely that architects will copy Gehry's technical vocabulary, although his fishes and whales are clearly his own brand mark. Architects will copy Gehry even though they rather say: "we cite Gehry". The fear for the next step forward in the deep and whirling sea of the future building technology has disappeared. It is good to know that more economical alternatives can alqyas be developed producing the same effect in a more efficient way. But the realised transparent roof is an astonishing example of the art in engineering, art in the highest degree, for which the engineers of Gartner are highly praised.

While writing this lecture (end of December 2002) it was announced that the old architect Gehry wishes to make two more buildings: one in Jerusalem and one in Warsaw, where he is

said to be born. The process of prequalification has been started. Who will take part in the tender? Eiffel from France, Gartner and Mero from Germany and maybe Octatube. We shall see. In Israel, Octatube has realised more than 20 projects. The Israelis know Octatube and are not afraid to show their architect the reality of their economy.

When I travelled with my son Nils to Jeddah in the spring of 2002 we met an old friend of mine, Bodo Rasch in the aeroplane. I knew him from my working days in 1970 at Frei Otto's Institute for Lightweight Structures in Stuttgart. He had been designing and building big folding umbrellas and travelled to Saudi Arabia to sell the biggest he ever designed: over 100 m x 100 m. He also told me that one of his companies, a ship hull building company in Malaysia went into liquidation as they had received a multimillion job for the horse's head in the DG Bank (below the glass roof) and could not finish it for this money. Actually it would have cost them triple the contract amount. This company was based on `hand-lay-up' techniques of epoxy shells. It was another story of victims along the road of experimental architecture. Experimentation should go hand in hand both with courage and with prudence to last long.

REFERENCES

REF. 11.01 Mick Eekhout, *`Las Structuras Tubulares en la Arquitectura'* (title of the Dutch version: 'Buisconstructies in de architectuur') ISBN 90-75095-29-5.

REF. 11.02 Gartner, *`Glas Architektur und Technik´,* Glaswelt, Juni 1999, reprint in Bout Excursiegids page 202 to 218, june 2002 (hand out, 30 copies only).

12 SPACE FRAME FOR FLORIADE PAVILION, HOOFDDORP

Article written for 3rd year students of the Prototype Laboratory at TU Delft.

12.01 INTRODUCTION

The current architectural tendency towards 'fluid designs' produces a new type of buildings with a remarkable influence on thinking about spatial structures. An obstinate example of such a 'fluid ' or 'Blob' building is the design of Kas Oosterhuis, Rotterdam, of a pavilion for the province Noord-Holland, the Netherlands, meant for the Floriade, which was realized in April 2002. In the design stage, the architect Kas Oosterhuis and structural designer Mick Eekhout developed the structural design, up to a point where the architectural and structural ideas and finances showed unbridgeable differences. This contribution is mainly concerned with the various design considerations, which strongly steered the development process. After all, the most radical decisions are made in the earliest design phases. Design decisions in the final phases of design and engineering have much less impact.

12.02 THE EARLY DESIGN STAGES

The preliminary drawing of the architect looked like a collapsed Gouda cheese: a round building with rounded sides and a somewhat dented roof. The estimated dimensions in the floor plan were approximately 24 metres, the height of the edge was 7,5 metres and the centre height 5,5 metres. Although this was an obstinate draft with regard to designing, it was still very much related to the long years of experiences of building dome structures due to its rotational symmetry. The negative curving in the roof would be a reason for a double-layered realization, while the rest of the dome would basically be single-layered and three directional.

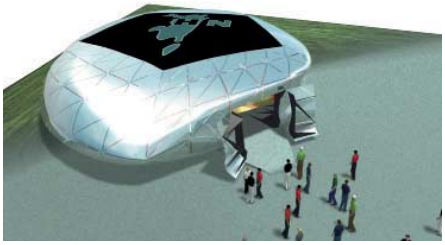

FIG. 220 Initial design of the pavilion (design: Oosterhuis.nl)

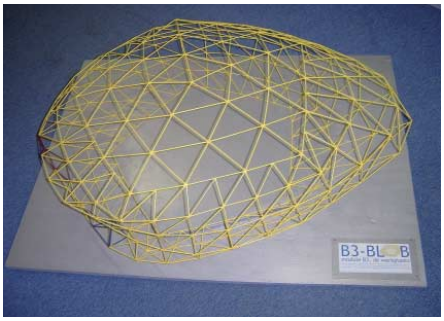

FIG. 221 First scale model created by students

The second version of the architect's design showed a rounded triangular shape, much like a Brie cheese wedge. Other shape associations use the terms 'cobble' or 'potato', or more respectfully, a spacecraft. The dimensions in the floor plan were 27 m x 20 m and 5.4 metres in structural height and 6,3 metres for the total height. From the dialogue between Oosterhuis and Eekhout arose a structural concept for a single-layered space frame with universal joints, connected to bars into three directions. This concept would be capable of handling the irregularity of the geometry, but was also based upon a record of accomplishment. The cladding and the space frame would be parallel. The second design did not have any rotational symmetry anymore. It was fully arbitrary in its shape and thus suddenly showed a serial size for the production of one piece for all components. Hereby, the industrialization factor between the two described models seemed backdated two centuries. The familiar dome models from the latest history of three-dimensional metal dome structures show the single-layered domes for smaller spans and double-layered domes for larger spans. Furthermore, the nineteenth century geometry is orthogonal, with radial ribs and horizontal rings, the Schwedler type. The twentieth century domes are all based on various domes of Fuller and look familiar: network models with horizontal rings and parallel lamella/delta girder models. The dome models that are composed of triangles all have a similar material efficiency, which is much greater than that of the orthogonal models. Usually, all these different dome models are half, or less, spherical, their height is less than half the diameter. Only rarely, domes are made ¾ spherical, i.e. radomes. In the eighties, Mick Eekhout did research into a 60 metres sphere in Rotterdam. The structural analysis and the soldered (1: 100) model proved that the greatest forces would occur in the bottom bars of the dome. Three-quarter domes suffer from weak knees. This phenomenon would clearly occur in the Floriade design. In the history of metal dome structures, the globular shape of the single-layered domes has always been fully synclastic. One of the few exceptions was the Multihalle by Frei Otto, Mannheim, Germany. There have been scientific analyses of the collapse of single-layered metal domes, where a small indentation in the synclastic surface, a local failure of bars and joints, had catastrophic consequences for the stability of the entire dome and resulted in a total collapse. The Floriade design had a hollow, an indentation in the upper part of the design, to which the architect, from design considerations, was much attached. A solution to this intrinsic problem could be two-fold.

– The local extension of the single-layered system to a double-layered system;
– The removal of the indentation and return to an entirely synclastic surface.

Overall, the above considerations illustrate that the architectural design was propelled by the possibilities of sculptural designing on the computer, as opposed to the acquired experiences and regularities of the design and building of domes over the last decades. Therefore, in the first discussions between the architect and the structural designer, these considerations came up extensively. For each experiment, the challenge to the designer is a motive of great importance. In this case, the challenge in a structural sense was to make the improbable possible and feasible. Architect and structural designer soon agreed on the following basic principles:

– consider the object as a shell;
– make the shell rigid by the triangulation of bars and joints;
– make the shell rigid for loads perpendicular to the surface;
– introduce either moment rigid connections;
– or introduce shape rigid spatial angles at the connecting points.

The necessity of shell effects and triangulation was agreed upon in the first telephone conversation. On the one hand, the dimensions of the triangles depended on long bars, rough angles and greater shape rigidity and on the other hand on the limit of the covering 'Hylite' panels: a propylene core between two ultra thin layers of aluminium, totalling in 2 mm thickness. These panels for this project would be supplied free of charge by Corus, their main facility being in IJmuiden, in the province Noord-Holland. The size of the trading plates was 3,0 m x 1,5 m. The number of panels was limited. Each triangulation causes much waste (up to 50%); therefore, the engineering had to make optimal use of the material. The structural concern was: the rougher the connecting angles perpendicularly to the shell, the greater the external loads resistance. Small angles around the joints often cause failure. Therefore, a triangular coarse-mesh netting was preferred over a fine-mesh one. The architect had in mind to project the model of an icosahedron on the envelope of the object, whereby the way of the subdivision of the primary axes of the icosahedron (five meridians) was characteristic of the dimension of the triangulation. Because of this optimization, four triangulation alternatives occurred, namely from a 5-piece to an 8-piece. With regard to the shell rigidity (per moment or per shape), it was decided to take the risk of applying a single-layered hinging space frame to these relatively small free spans, with maximal sized triangles. If the structural analysis would show that the shell would not be sufficiently rigid, possible additional actions would be taken. Which could lead to a moment rigid joint instead of a ball hinge, or to internal cross beams that were functionally useable in the floor plan, or to five short frame rigidities, diagonally on the outer walls, or to bow strings reinforcements.

It was well-considered not to choose the usual schedule of deep ribs perpendicular to the surface and in an orthogonal system, due to the expected large consumption of material, the relatively banal simplicity of such a schedule and the fact that the development of an internally ribbed structure is quite a common thing in aircraft construction and the ship

building industry. To create some new way of designing in architecture, the structural designer desired to develop at least a new and unique way of a lightweight structure. The architect on the other hand was interested in building the object, in whatever realization. The basic idea of the principal was to develop the design as 'economically feasible' as possible. Of course, in this phase the industrialization factor played a part too. The first design of the Gouda cheese was rotational symmetric. However, the architect already had made an arrangement of the icosahedrons, which had internally exploded against the envelope of the object and thus, the repetition factor was reduced. The result of these considerations is the pentagonal roof of the object. The wandering visitors of the Floriade cannot really see the roof. It was designed as a five-fold icosahedrons roof: the five constituent icosahedrons triangles were all equal, so that they offered a small serial advantage with the production of both the skeleton and the skin of the object. The structure of the object has lost somewhat in consequence, in a scientific manner of speaking, but has won economically.

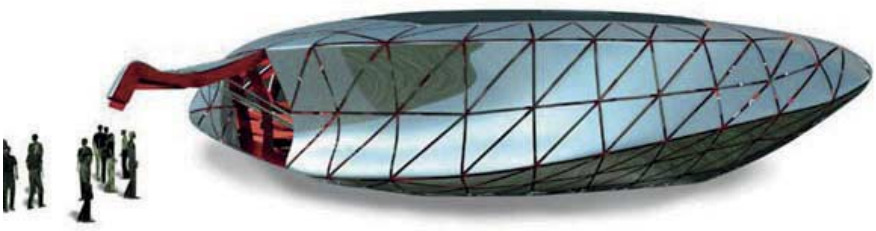

FIG. 222 Design of the provincial pavilion (design: Oosterhuis.nl)

A subsequent consideration was the cladding. This would be made from 1,5 mm thick panels. The initial considerations were:

- the triangulation in the shape of the panels;
- the cutting loss of the panels from rectangular trade plates;
- the individualization of the panels and the edges;
- the maximum size of the panels versus the thin material;
- the relative non-rigidity or flexibility of the panels;
- the necessary water tightness for the entire skin of the object.

The major concern was how to make the skin of the dome panels watertight. This was expected to be difficult, due to the high degree of individualization. The main task would be to create an envelope of fitting panels. As a second task, a waterproof membrane of PVC coated polyester fabric, suspended from the panels, would realize the water sealing. From that concept, the thoughts of the architect and the structural designer led in two different directions. The architect thought that, if there is a watertight suspended membrane, then the seams between the panels do not have to be waterproof, or accurately connected.

Moreover, in the space between the aluminium panels and the watertight skin, artificial lighting can be applied, so that the object would be linearly illuminated. The architect thought in terms of the object as an extravagant building with fanciful possibilities. To the structural designer, the aim of the development of the panels was to make them fit as accurately as possible in the side connections, so that a watertight seal could be applied. He considered the waterproof membrane as a second moisture barrier, not unusual for buildings. It should be possible to put the progressing insights into practice for further assignments. After all, 'Blob' designs have a rising popularity and are worthy of a sound development to bridge the increasing gap between designing, engineering and production. Meanwhile, the architect went on with the detailed design of the object. He found that, due to the largely visual character of the panels, the skin design could be semi-independent of the skeleton design. In terms derived from the car industry: the architect proposed to run the body independent of the chassis at the rear. This considerably complicated the individualizing of the panels. Initially, the panels would be parallel to the space frame. Now, suddenly spheres and hollows occurred in the cross-sections of the panels over the space frame, as a result of sculptural interventions in the architect's digital shape model. The image of the American cars from the Sixties came up. This new wish of the architect, which gradually became a demand, would eventually result in an unbridgeable difference of opinion between the architect and the structural designer.

12.03 COMPUTER AIDED ENGINEERING

The architect Kas Oosterhuis is famous for his digital designs. He has worked in this field for over ten years and did not build more than one design per year, but he published several colourful books. In the year 2000, the Delft University of Technology appointed him part-time professor for the duration of three years. Thanks to pioneers like him, new 'Blob' designs are published all over the world. In general, architects explore the bounds of possibilities by means of their CAD expertise and increasingly advanced computer programs in which 3D designs can be generated. However, these programs are not yet compatible enough to the usual engineering programs. For example, the number of bars, joints and panels had to be derived from a generation list. The drawings were not sufficient. The DXF file, which transferred the computer file that was certified by the architect for the use of co-designers showed many shortcomings. Only after many weeks of work, the geometric data became clearly readable in AutoCAD 2000/14, common for engineering; but only for the computer operator. By the time the geometric data could be read, the structural data were still not suitable for cost accounting. Because of the experimental nature of the draft design and the insecurity with regard to feasibility, the structural designer started work based on a commission for co-designing and pre-engineering. The gap between the accelerating architect on the one hand whose greatest focus was the design, and the carefully operating structural designer on the other hand whose greatest focus was on feasibility, became even greater. This gap cannot be bridged; because

the computer programs the architect uses are not compatible with those of engineers and producers. Therefore, a classic dilemma emerges: to act alone (keep everything in one hand, basically how Octatube started some twenty years ago), or communicate in collaboration with appropriate means. Maybe, the architect could have generated the entire project by means of his own computer programs, so that the sum of the architectural design, the structural analysis and the component breakdown could have been developed by one hand, while the structural designer only gave advice and the producer made his cost accounting as accurately as possible. In the course of the three months of cooperation (between the end of February 2002 and the end of May 2002), the choice for a parallel way of working was made: concurrent and sometimes collaborative. The architect worked out the design and tried his best at forming proposals for materializing. The structural designer and his engineers (Karel Vollers, Sieb Wiechers and Freek Bos) tried, already in an early stage, to get acquainted with the essence of the work, the rigidity of the structure, the composition of the elements and components and the full water tightening, parallel to the work of the architect. They reached different conclusions with regard to their possible future responsibility and liability for structure and water tightness than the architect.

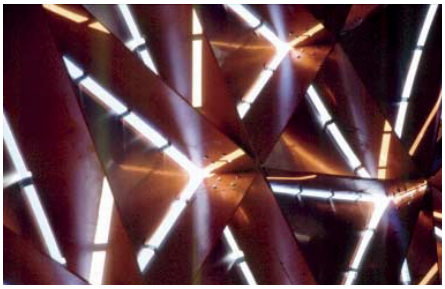

FIG. 223 Interior of the pavilion (under construction)



FIG. 224 Exterior of the pavilion (under construction)

The result was a continuous dialogue and discussion. The total budget of the project was of a very decisive influence. The first estimate of Octatube varied for two alternative realizations from € 430.000 to € 630.000. Only one month later, when the commission was handed out, the actually available budget for the engineering, production and assembly of the structure, cladding, membrane, floor and two doors emerged: € 240.000. Calculated on a skin surface of 600 m², this meant a price of € 400/m², including two complex doors. This square metre price was hardly a realistic budget for an experimental project. The commission for co-design and pre-engineering was estimated at approximately 5% of the realistic budget, but was only accepted as an obligation regarding the means, not the obligation regarding the result! The estimates were established as the sum of assessed individualized element component costs and the way of realizing the components.
The great difference between the first estimate and the available budget proved that it was necessary to be modest in terms of the degree of experimenting. Indeed, there is nothing wrong with a low budget, just as long as it is realistic. Nevertheless, in the current case, the estimate could only be verified after three months of design development, structural

engineering and the development of the skin. Only by the time the layout of the space frame was established and computer analysis showed that the structure was sufficiently strong, rigid and stabile, the cost accounting of the space frame provided insight. Unit prices and the number of elements and components established this. Basically, there was no discussion on the economy of the space frame (56% of the budget), but all the more on the economy of the cladding.

12.04 STRUCTURAL ANALYSIS

The second half of April was used to make the structural analysis. The 'Blob' Graduation Building Technology student Freek Bos did this. Splines do not transfer correctly from Maya to AutoCAD. Therefore, much work was done by both parties to come to a proper computer communication. Via the pre-processing in FemGen, the structural analysis in DIANA and post processing in FemView, insight was obtained in the behaviour of the frame shell.
The indentation in the roof (with the possible local snap through as a result) was already removed in the network development. The introduced bars had the following dimensions: 82.5 mm x 5,0 mm, 101,6 mm x 7,1 mm and 203,0 mm x 8,0 mm, the heavy bars on the five main axes, the meridians.

Dead load, snow and wind loads were considered the main loads. As a result of the dead load and snow loads, the tail in the long diameter proved to flare up. Furthermore, the roof sagged by the deformation of the lower halves of the bars: the knees. This was confirmed in the material model of the students. The remedies were:

- to enlarge the structural height of the shell in all cases by maximal 1000 mm from 5,4 m to 6,4 m;
- to make the bottom bars of the frame shell considerably heavier;
- to flange couple a number of bars on the five meridians, moment rigidly over the joints by means of welded flanges, by which tubular interconnected beams would occur with a dimension of 203,0 mm x 8,0 mm;
- to place five internal slender cross bearers on the meridians with a dimension of 101,6 mm x 7,1 mm, by which the entire shell would be divided into a flat roof and a round 'doughnut' wall;
- to introduce five internal meridional trusses to give the shell a great rigidity and which were acceptable to the architect;
- to introduce a number of shell rings to master the horizontal lateral thrusts, but the two doors in the bottom edge would cut through these. This alternative was further neglected;
- to place five external outriggers at the sides of the meridians to strengthen the bottom sidewall. The architect did not appreciate this, though it very much resembled the landing gear of a space vehicle.

The conclusion from this phase of the structural analysis was that, by rising from 5,4 to 6,4 metres and the internal strengthening by means of welded beams with a diameter of 203 mm on the meridians, a reasonably rigid frame structure was the result, with a maximum vertical replacement of 20 mm in the middle over the shortest span of 20 metres, which means a 1/1000 of the span. In other words, with still some approach cycles ahead, the frame shell would not cause unexpected and insolvable problems.
The total of the estimated dead load of the frame shell with strengthening would amount to 600 m^2 over the skin surface, approximately 6.000 kg. (10 kg/m^2).

12.05 CLADDING DEVELOPMENT

Problems seemed to concentrate on the side of the cladding. On the one hand, there was the strongly reduced budget of the client, and on the other the architect who wanted a metal skin in its shape independent of the space frame. Already from the first internal estimate, it could be concluded that the budget was too low for an extended engineering of the skin, now that the skeleton was more or less roughly established. Though less desired by the architect, with the possibility of reaching a level of flat panels in the back of his mind, the quest for panels with a spatial curve began. After the architect had established the desired curves in the skin with regard to the centres of the joints and axes, by means of splines and nurb curves, it became clear that very complex 3D components had to be manufactured to fix the cladding to the required position in space, considering the space frame. Furthermore, a number of rather extreme cladding components had to be developed and manufactured. The required 3D nature of the cladding triangles was limited because the flat plates could only be folded or curved into one direction. Therefore, a triangle has a more or less flat centre and three points which can be curved upward or downward, independent of one another. The regularities of curving 2D panels into star-shaped 2.5D panels still have to be further exploited.

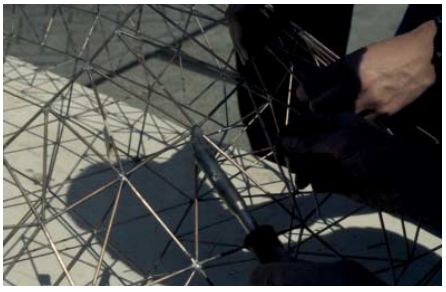

FIG. 225 Scale model made by students



FIG. 226 Scale model made by students

Based upon these results, the definite offer was made with the bulged plating, a number of flat alternatives for panels and a stressed membrane as alternatives. Based on this outline of the costs, an agreement to go on could not be reached and the activities of Octatube ended there. Half a year later, the structural designer developed 3D aluminium panels and they were realized for the council pavilion in the Dutch Floriade. The costs for that project proved to be even higher than those estimated above.

12.06 STUDENT PROTOTYPES

In May and June 2002, a group of ten third year Building Technology students was occupied in the framework of an obligatory study project, named 'the prototype', with two different parts. Half of the students had to develop a regular cladding component, as mentioned above, based on a box-shaped component of which the body would run independently of the chassis. The other half was commissioned to design a workable door, fitting in the system, with a minimum width of 2,2 metres, opening turnable, swivelling, twistable or slewing. They derived their principles from the double hinging doors of civil airplanes. To obtain the necessary insight, a thread model was built first on a scale of 1:20, of 3 mm soldered coppered welding wire. After all the virtual models on the computer, a material model existed at last. The students learned much in these eight weeks, but the results of their work were not satisfactory. Their work confirmed the assumption that, within the given preconditions of the required design of the cladding, the necessary engineering and production efforts and the available budgets: no satisfying compromise was possible.

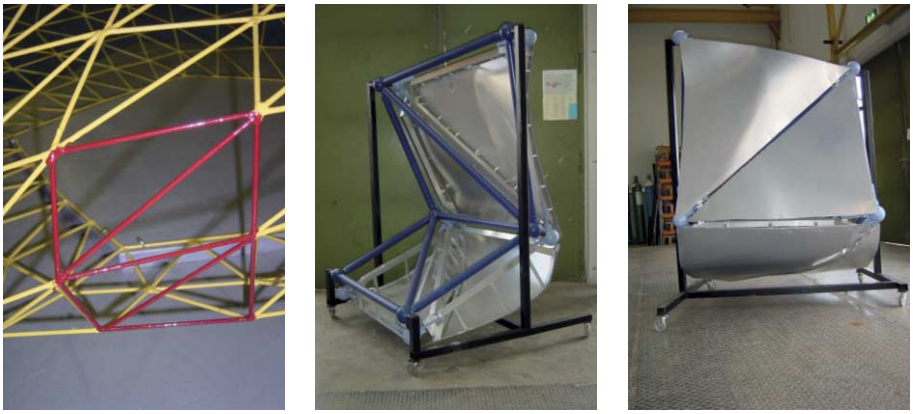

FIG. 227 Prototype of cladding, based on the tubular structure, made by students

12.07 FINAL REALIZATION

After the leave-taking of the architect and the structural designer Eekhout/producer Octatube, the architect had to take another route. Oosterhuis never specifically asked for double twisted façade elements because he thought it didn't fit in the budget. With the help of the consultancy D3BN, a load bearing structure was realized, based upon set steel strips of 20 to 30 mm thick and 100 to 400 mm high, in the familiar triangulated geometry. The strips functioned simultaneously as main support structure and as cladding fixation and were buckled to that purpose. The architect applied for a patent on this system.
The cladding still had slightly bent flat panels 'Hylite' in a flat shape, fastened by means of steel braces to the steel strips, not being waterproof. The waterproofing of the inner space was realized by making the projection screen waterproof. By this, the project had indeed become a fancy and extravagant building. Yet, the building was realized. The dead load of the steel structure, manufactured and assembled on the building site by steel structure producer Henk Meijers, Serooskerke, the Netherlands, is 100 tons of steel. The 'Hylite' skin weighs nearly nothing. The total costs for the construction and the 'Hylite' skin were € 250.000. The intention for the period after dismantling the pavilion when the Floriade exhibition has ended, is to erect it again with a new watertight skin as a 'Blob' laboratory at the Faculty of Architecture of the Delft University of Technology. The architect is developing a new watertight and insulating, fire- and burglar proof skin for this purpose.



FIG. 228 Pavilion after completition

12.08 LESSONS LEARNED

The lessons learned from the preliminary studies are fundamental and essential enough to put them before an international forum.

- The dramatic break in the development of systemized lightweight spatial structures, by geometrically unusual architectural 'Blob' structures;
- 'Blob' structures bring along a loss of systemizing and repetition in the material load bearing structure;
- The high degree of individualization in engineering and manufacturing of the individual space frame components requires further research;
- The shift of critical attention from spatial structures to spatial cladding calls for design energy;
- Computer Aided Design enables to architects to make 'Blob' designs. Computer Aided Engineering is vital for the establishment of the spatial complexity of the entire design and the individual establishment of the elements and components;
- In the near future, the digital bridge between Design and Engineering will determine a majority of the technical and financial feasibility of 'Blob' designs.

13 GLASS FAÇADES IN TOWN HALL OF ALPHEN AD RIJN

This case study is derived from the reader "Stadhuis Alphen aan den Rijn", published by the Faculty of Architecture, University of Technology, Eindhoven, 2002, ISBN 90-6814-146-5, chapter 5. Possible references to pictures that have not been included in this article can be found in the mentioned reader. The introduction to the 5th chapter describes the starting points of Octatube as a co-producer. These are thought to be sufficiently known to the professional community and left out of this publication.

13.01 INTRODUCTION

During the design phase, Octatube was invited to visit Erick van Egeraat Associates (EEA) several times, but Octatube was not under the impression that its recommendations were taken seriously. We discussed façade styles, distances and connections, and the twisted section of the façade was a topic during these talks in 1999. That part was the most attractive to Octatube because of its complexity and the experimental character. At that time, Mick Eekhout's Chair of Product Development at the University of Technology, Delft, did research into twisted facades, but this had not progressed sufficiently enough to be applied to this twisted façade regarding coated and screened double glazing. Dr. Karel Vollers was only to obtain his cum laude doctorate on this topic with the thesis *Twist & Build* [ISBN 090-6450-410-5] much later in February 2001. Because Octatube usually is extraordinarily interested in the challenges of complex structures, a commission with the theme of a twisted façade was awaited with great interest. In this phase, Octatube supplied EEA with budget estimates on a regular basis, in the form of m^2 prices.

13.02 CO-DESIGN PHASE

Because of the aloofness with which the orientation discussions were held and the fact that EEA clearly had other discussions with more parties at the same time, the responsibility of the façade design rested entirely with EEA. During the tendering, 'Spider' glass was

prescribed, a product of the competitor St. Roche. Furthermore, only a few companies, among which St. Roche, could produce the required glass width of 2,4 m. It was particularly the specification of a glass gauge that in Europe can only be produced by a few companies, that sent the purchasing contractor in the direction of St. Roche. However, the gauge of 8/6 mm with the given post distance of 2,4 m, as described in the tendering document, was as a combination in a class of its own. It is impossible to meet the Dutch or any EU criteria with the given column distance and glass gauges. Most probably, after the order, St. Roche would have come up with an additional charge or change order request for the necessary 15/10 mm gauge glass at 2,4 m width, or would have even further decreased the glass width. All this depending on the given designing responsibility of the executing parties, as described in the tendering plan. In any case, this topic had become an ever-present point of differences in interpretation. With this, no earlier design suggestions of Octatube were recognizable or blameworthy to herself. At times, it is an advantage when a producer has not yet been appointed at the tendering, since contractors will always look for an alternative, due to the habitual exercises in the Netherlands to economize after tendering. Tendering with more than one supplier usually causes a 'Wild West' situation of randomly scored prices, as compared to a procedure in which the parties of a building team spend their time together from the very beginning by means of subsequent estimates, all plausible and fitting into the budget. Apparently, the eventually offered price of St. Roche's was higher than Octatube's, because the quantity surveyor continued the definitive negotiations with Octatube.

In the spring of 2000, during the final tendering negotiations, there was a discussion with the architect on variants in the technical realizations and simultaneously with the quantity surveyor on prices and price reductions for variants. These tendering negotiations took place entirely based upon paper 2D drawings and a tendering document which was soon replaced by the written text in Octatube's quotation in which a few offer conditions were explicitly different from those laid down in the tendering document. Gradually, Octatube's suggestions, i.e. the ellipse-shaped façade columns and the smaller façade column distances, were adopted in the architect's drawings. Also, the size of the glass panels, a different layout for the glass panels in the façade and the shape of the support structures in the frameless glass façade were accepted by the architect and worked into the drawings. Initially, the façade was quoted in super neutral glass, after that in green-coated glass and then in clear glass with a decorative foil. The advantage of the foil was that, after a number of years and no doubt a change of fashion, this film could be removed. This would be convenient for a client who might become tired of the design, but the architect was adamantly against this proposal. From a technical point of view, a foil application would have a shorter life span than a screen print in the same design. Eventually, by the end of 2000, the result would be realization with super neutral coated glass with an internal branded screen print. The screen printing of glass or the application of foils was initially estimated as being a separate item, because of the unknown effects and the suspected gigantic negative consequences for production and logistics. The parties involved hoped that this cup would pass them by. It so happened that the architect's design provided for an utter individualization of the screen printing that would result in the 835 panels to all be individually engineered and produced.



FIG. 229 The front façade after completion



FIG. 230 Detail of the façade

Five graphical designs were successively worked out by the architect's office: firstly a very wild design with trees which would need uncountable screening masks?, then a design with bamboo which already had some restrictions, after that a design with letters and numbers, a kind of graphic travertine design, and eventually the final design of flower leaves and tree leaves. Octatube selected Lerobel, Hasselt, (Belgium) from the regular suppliers as the sub-contractor/co-producer of the glass panels, together with the company IGP, Hoogstraten (Belgium) as the producer of the silver-coloured screen print that would be branded into the glass. The definitive leaves design assumed a total of nine different parent moulds (see above) for the screening, upon which the layout of the various glass panels in changing positions and orientations could be established. IGP planned to realize this plan faultlessly, but, of course, errors lie in ambush everywhere with such logistics. In addition, such a task had not been realized before anywhere in the world, as far as we knew. If 'Murphy's Law' would apply to anything, it would apply here. Lerobel would assemble double glass panels from the IGP exterior panels and the low-E soft-coated interior panels of Luxguard, Luxemburg. Due to the scattered component productions and assemblies, internal transportion and the individual designs of the different glass panels, it was assessed at an early stage already that subsequent late delivery or omissions before completion would have rather drastic consequences on the time schedule. But also, damage to one single panel after regular production was expected to be a nightmare in terms of logistics and costs. All this was reported to the client before the contract was entered into. In the meantime, Octatube's prices were totalized, according to economic measures, and all parties involved knew them. The façade structure was offered based on a centre-to-centre distance between the elliptic façade columns of 1.800 mm. When the quotation clearly fitted the required overall picture on the 3rd of March 2000, Octatube moved on from quantity surveyor to the main contractor as the nominated façade subcontractor. The tendering of the façade was done separately, but simultaneously with that of the main tendering of the building. In consultation with the quantity surveyor of the project, Octatube came to a principle agreement, after which the project was handed over to HBG, being the main contractor. From the very start, HBG regarded Octatube's work as a mandatory management supply, but within the building team, Octatube was positively considered as co-producer with the corresponding design & build responsibilities of the specialist.

FROM PROVISIONAL TO DEFINITIVE DESIGN

From the start of the building team phase (April 2000), a considerable course of design development was necessary before there could be any well-organized engineering of all components of the building. This was caused by the geometric complexity of the building, the misinterpretation of principal details that were all drawn at right angles, while all intersections proved to be oblique in different angles; the architect's hesitation to provide the 3D data in a heart line model on CD-Rom, and the problems connected to the complexity of the geometrical measuring and controlling of the positions of components on site. Much time went by during the phase between tendering by the quantity surveyor, the transfer to HBG and the actual contract by HBG before Octatube considered the conditions under which all façade components of the particular building part 'glass façade' had to

be engineered and produced clear and definitive. Actually, eight months passed between invitation to sign and Octatube finally signing the contract. During that time, the building as a whole, as well as in her components, became increasingly complex. More and more incongruence was discovered, which caused more and more claims for supplement costs. Many discussions were held to clarify the interaction between the steel and concrete structure, as well as the façade structure, and to make the details mutually acceptable in terms of tolerances in the glass façade and deflections by distortions as caused by loadings on the main supporting structure, i.e. the 23 m long cantilever underneath the council chamber. On the 30th of May 2000, main contractor HBG sent Octatube a principal order confirmation. The reasons for signing an altered contract text only eight months later were strategic considerations. Immediate signing of the contract could have meant that Octatube would possibly be liable to a contract that would be impossible to realize, with all its legal complications. Since Octatube is basically a technically driven company and not a financial/legal driven company and does not want to spend much energy on that particular aspect, we chose for this simple solution, much to the concern of the contractor. In the meantime, without a signed contract, Octatube actually worked on the design development at its own risk. The choice for working without a contract was made because in the period between August and November 2000 ever increasing complications turned up from the engineering department, all of them having great financial consequences. All this while the client Burgomaster and Aldermen from Alphen aan den Rijn had made it quite clear not to fancy the idea of extra costs. In a common tendering route, the occurring technical problems would have been covered by the clarity of the technical description that goes along with an entirely worked out tendering design and its subsequent price. The façade parts of the Town Hall project, however, one could claim, had been put to the market too soon, so that a definitive follow-up designing and engineering round was necessary, although the client did not recognize this as such. They had the idea to have tendered a completely designed and engineered building. Obviously, the client had the advantage of a set price for the current design, which is connected to early price making and therefore the convenience of oversight of the total price of the entire design. Actually, Octatube wittingly takes a design & build risk in many of its 'design & build' projects: a double risk, but usually Octatube is the most important player in the game. In the current case, the design phase was influenced considerably by EEA project architect ir. Ralph van Mameren who, as an independent player in the game, followed his own (EEA) route towards a stunning building with inspiring details and materialization. Octatube faced the risk of committing itself to take on uncertain and increasingly complex engineering, for which the demand of individual screen printing of the glass panels could no longer be avoided. In this period-without-contract, Octatube took on the risk of carried out engineering (investment approximately Euro 50,000) versus the increasing complexity of the work in which nobody had sufficient insight, due to the fact that the company anticipated possible greater losses than the money invested in engineering.In August 2000, it became clear that the fully loaded steel structure of the council chamber would bend to an unacceptable degree with regard to the tolerances of the frameless façade. Frameless glazing has a maximum deformation of 1 to 2 mm per sealant seam. ABT performed an extended re-calculation and re-dimensioning, with considerable consequences for the steel weight and the price of the steel structure. It also demanded an adjusted design of the details of the façade's joints in order to

accommodate the required movability. In addition, the suspension of the façade posts from the roof, as initially agreed upon and permitted, proved not to be possible at all points, due to too low a rigidity of the roof structure. This period saw discussions on this topic in various design consultation meetings with the knives out!

13.03 FINAL PRICE-MAKING

After all technical problems were finally analyzed and solved, all complications for the engineering, production & realization were clear to the producer. One could say that between the time of the definitive offer/tendering (April 2000) and allotment/contract (November 2000), the technical design was made definite. On both sides, many harsh letters were sent with requests for information and recriminations of references to non-worked out aspects, which were of great influence on pricing and planning. Octatube did not accept the time consequences and penalty clause of the main contractor. In the mean time, Octatube's supplement costs were deemed correct and accepted by the HBG and by Burgomaster and Aldermen, and amounted to approximately 25% of the initial offer. In total, HBG claimed supplements on several fronts which were agreed upon by the commissioner, up to approximately 20% above HBG's allotment sum. From that time onward, a period of relative calm began in which the definitive engineering was worked out, guided by frequent consultation between engineer coordinator Harry Pasterkamp (EEA), engineering leader Bob Kleuters (Octatube) and planning engineer Margriet Müskens (HBG). The resulting engineering effort, which amounts to an average of 18% of Octatube's projects, increased in this project up to 30% of the costs, for the major part due to the individualization of the steel and glass components. Over 5.000 drawings were made, in addition to hundreds of study files. For a comparison: the Eiffel Tower was built with 15.000 handmade drawings, but then it was as high as 300 m!

13.04 CO-ORDINATION AND INTEGRATION IN THE OVERALL DESIGN

OVERALL GEOMETRY

The geometrical design of the Town Hall is characterized by a composition of geometrical systems, all of which lead to a higher level of complexity by their fragmentation.
The described geometry of the positions of the glass panels in the façade is no exception. It is a succession of circular systems with various radiuses, alternated with straight

lines. The total description of the frameless façade can be subdivided in seven different geometrical zones. Zone 1, 2, 6 and 7 are cone-shaped, zone 3 and 5 are straight-lined in development and only zone 4 describes a twisted surface. With the exception of zone 4, the described geometry of the façade cannot actually be considered a true, so-called 'Blob'; the term 'Quasi-Blob' would be in order here.

INTERSECTIONS

The vertical sections over the façade know two different profiles in the geometrical sense. The one profile starts off at the west side and slightly leans forwards. This profile is buckled at the second floor level. The other profile starts off from the east side and slightly leans backwards. Both profiles develop from a horizontal point of view over the circular systems and at their meeting point, an intermediate zone occurs. This zone describes the twisted surface, which fluently connects both systems to one another. The whole of the frameless façade has a strong geometrical foundation. Only locally, they arbitrarily deviate, i.e. the torsion façade and the entrance area. The edge of the roof describes a very arbitrary contour, so that all vertical sections over the façade columns are eventually unique.

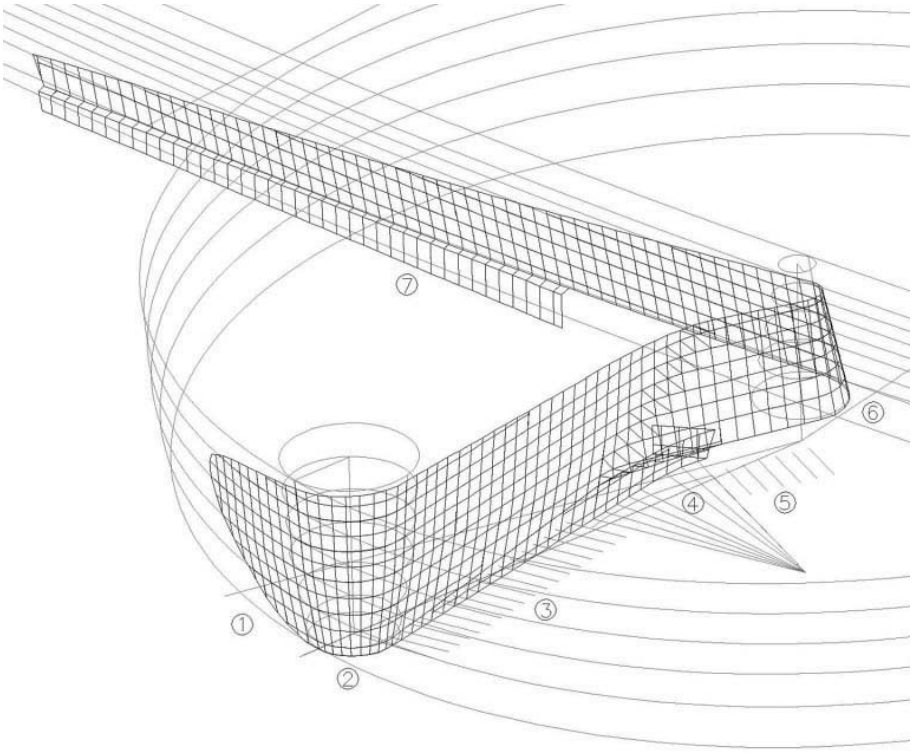

FIG. 231 Seven geometrical zones

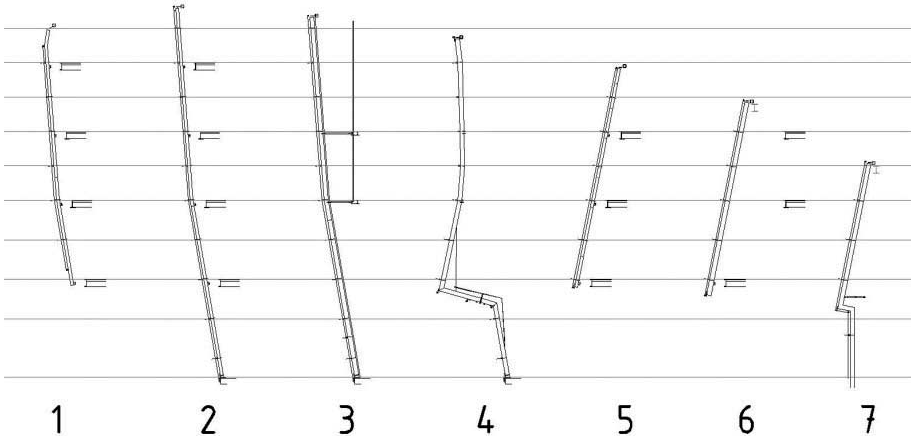

FIG. 232 Seven typical intersections

Seven types of ellipse profiles are distinguished:

SEVEN TYPES OF ELLIPSE PROFILES ARE DISTINGUISHED	
Type 1	'standing' ellipse of the west façade, leaning on the steel structure at the rear
Type 2	'standing' ellipse located at the southwest façade, leaning on the concrete floor (zone 2)
Type 3	'standing' ellipse, located at the atrium in the straight south façade (zone 3)
Type 4	'standing' ellipse, located at the torsion south façade (zone 4)
Type 5	'suspending' ellipse, located at the southeast façade (zone 5,6)
Type 6	'suspending' ellipse, located at the east façade, internally made rigid because of the large free span (zone 7)
Type 7	'standing' ellipse, located at the east façade with the trimming framework girder (zone 7)

TAB. 01 Various ellipse profiles

The entire façade is built up from 109 elliptical façade columns, all individually different. To these, 650 glass nodes in 75 different models have been applied which fixate a total of 835 glass panels as filling-in components between the façade columns.

13.05 THE 3D MODEL

The architect drafted a 3D model of heart lines and system lines to describe the architectonical design. The 3D model was drawn in AutoCAD with the use of the mechanical engineering extension 'Mechanical Desktop' and it describes the principle coordinates of the building components, to be engineered and produced by the various (sub)contractors.

Therefore, the 3D model ranked at a very important place with the mutual coordination of the co-engineering subcontractors and the integration of the building design as the total composition of technical building parts.

For the positioning of the façade, the following data from the 3D model were of special importance:

- position of the glass panels;
- position of the concrete floor at ground floor level;
- position of the concrete wall of the rear structure (east façade);
- position of the obliquely placed roof columns (east façade);
- position of the steel IPE façade column profiles (southwest and southeast façade);
- position of the steel roof edge profiles;
- position of the atrium bridges (south façade);
- position of the concrete stairway (south façade).

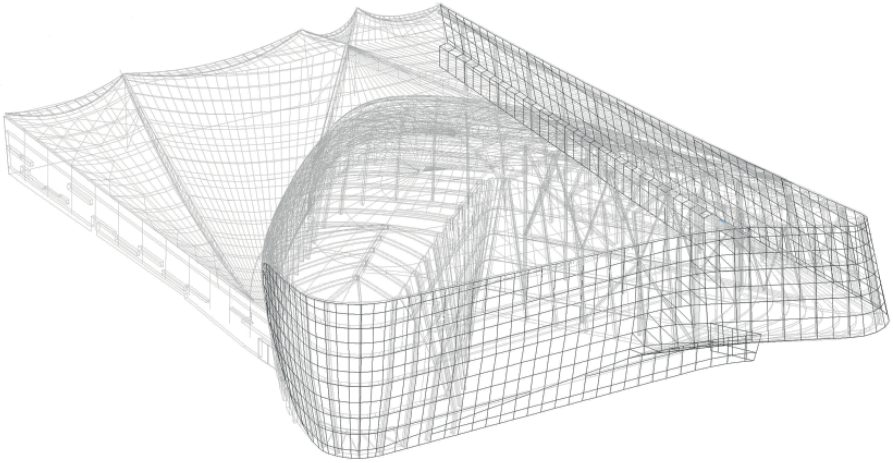

FIG. 233 The 3D-model of EEA with (in black) the frameless façade

13.06 DETAIL ANALYSES

The central question of Octatube's engineers was: Where is the work of the third parties and how do we link up with them? Armed with the 3D model based upon heart lines and the principal details of the architect, a large number of detail analyses were done. Furthermore, detail analyses were made of the supporting façade components (columns, framework

girders and pended posts). All this in relation to the various possible production techniques that were halfway the proposals by EEA required design and the functional structural characteristics. The position of the framework located at the east façade was meticulously prepared in 3D. The available space between the obliquely placed columns of the main supporting structure and the ellipses of the glass façade could only be determined with the help of 3D computer models.

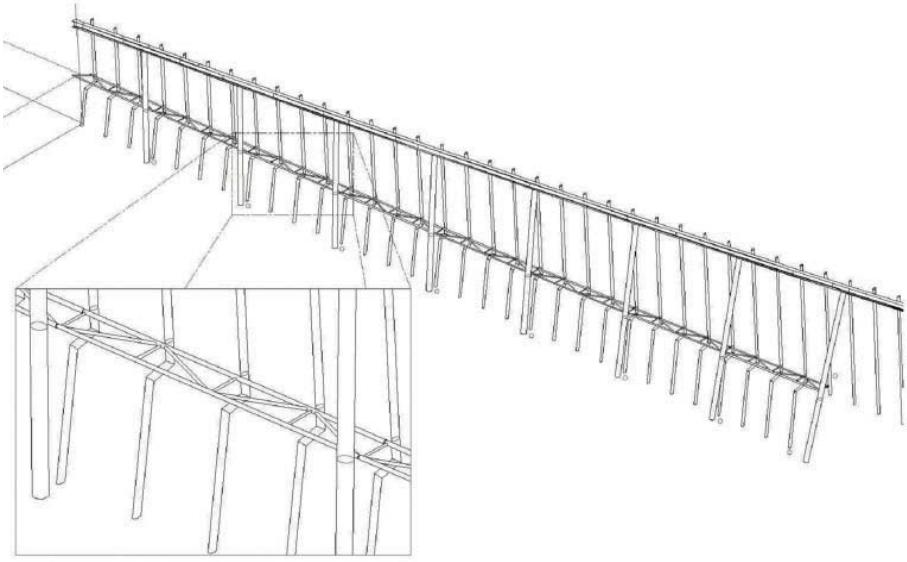

FIG. 234 The framework as located at the east façade

The roof edge detail was discussed extensively until it was developed to its final realization. The standing and suspending realization of this connection detail are visually hardly distinguishable. The standing version is equipped with a smooth stainless steel pen at the top side. The suspending version is equipped with a threaded end, completed with rings and nuts. They both form only one single point of connection between the glass façade and the main supporting structure. This is convenient for the many different dihedral angles of the columns in the horizontal intersections. In addition, it was decided to connect the edge setting, which envelopes the glass panels at the column foot details and the roof edge details to the ellipse columns by means of supporting strips or so-called 'little rulers'. By doing so, the façade, including all details after the placing and setting of the ellipses, could be completed almost autonomously. The alternative would have been to set the 'little rulers' at the rear structure, which would have been far more time-consuming. It would have caused the assembly process of the various contractors to become too much interdependent on each other.

13.07 THE 3D WORK MODEL

Based on the tendering documents of the plan, i.e. drawings and specifications, a subcontractor usually develops his own working model. A work model for a building part with a simple geometry consists of a set of 2D drawings, together with accompanying comments. A limited number of ground plans, intersections and details describe all occurring details. Obviously, 2D drawings were also made of the glass façade. However, in this particular case making only 2D drawings proved to be insufficient. Due to the complex geometry, the standard squared-angled representations of the various connections as they had been drawn did not actually occur anywhere at all. These details had to be seen in 3D. After a few weeks from the start of the definitive design phase (June 2000), the geometrical complexity made it necessary for the architect to describe the many connections in greater detail.

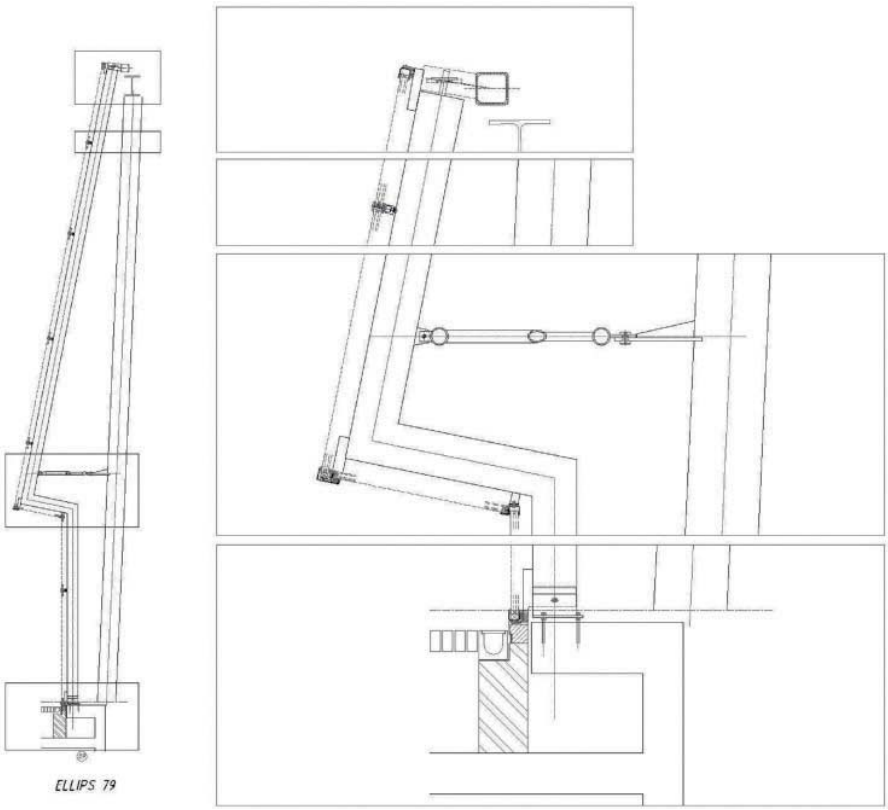

FIG. 235 Intersection ellipse 79 (east façade)

Based on the 3D model of the architect, Octatube set up its own special 3D work model. In this 3D work model, all engineering conclusions and actions were brought together. The 3D work model eventually contained a complete description of the building component 'façade' and provided total insight in all interpretations Octatube had with regard to the ideas of the architect. Therefore, it had to be thoroughly studied. Approval of the 3D work model of Octatube meant no less than the clearance to make work drawings for production. Unfortunately, at the time of the testing rounds of the façade parts, a correct infrastructure for the exchange of such a model was yet lacking. Therefore, the 3D work model of Octatube was assessed only in 2D and thus approved by the client. For a following project it is an absolute must to have 3D work models of the various co-engineering producers checked, approved and recorded (certified) by the architect. To this purpose, the models must be recorded in a compatible program.

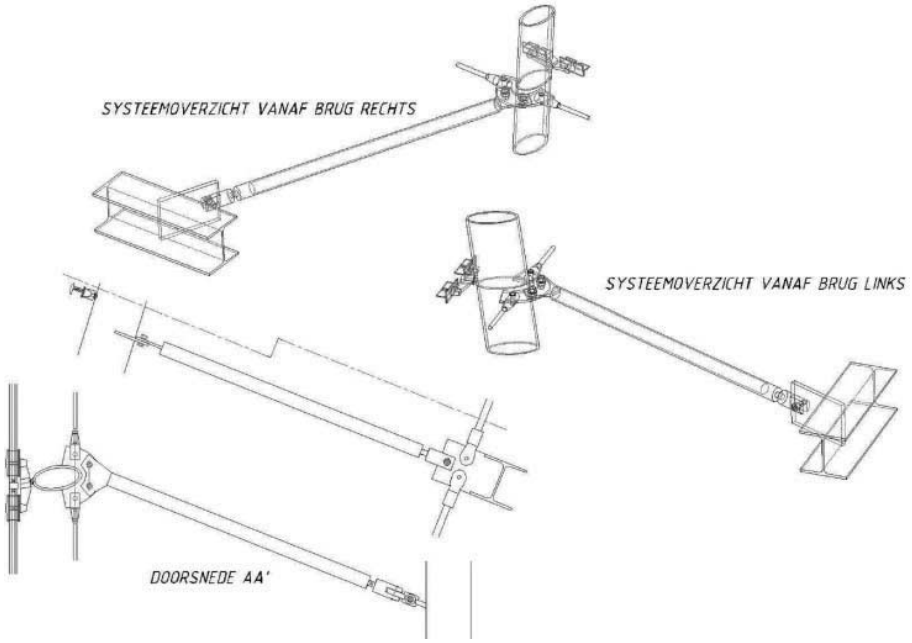

FIG. 236 Principle-building up of bridge connections, located at the atrium

Now, Engineering Office Van Veen, which was responsible for the engineering of the main supporting steel structure, had also developed a 3D work model. Van Veen's model was set up with the 3D steel package StruCAD. Via the generally known DXF-format, the 3D model could be imported into AutoCAD and subsequently compared to the assumptions of Octatube. By means of these unofficial checks, a finger could be kept on the pulse of the project.

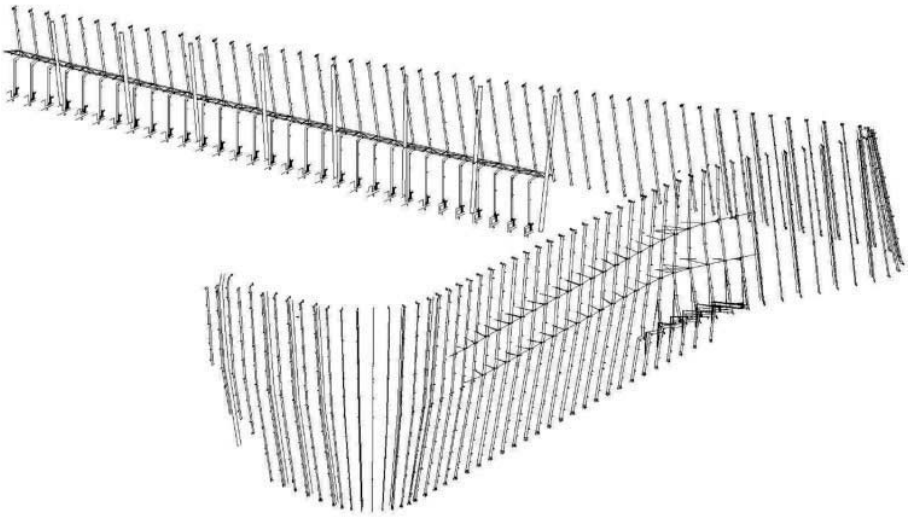

FIG. 237 The entire 3D work model of Octatube of all façade columns

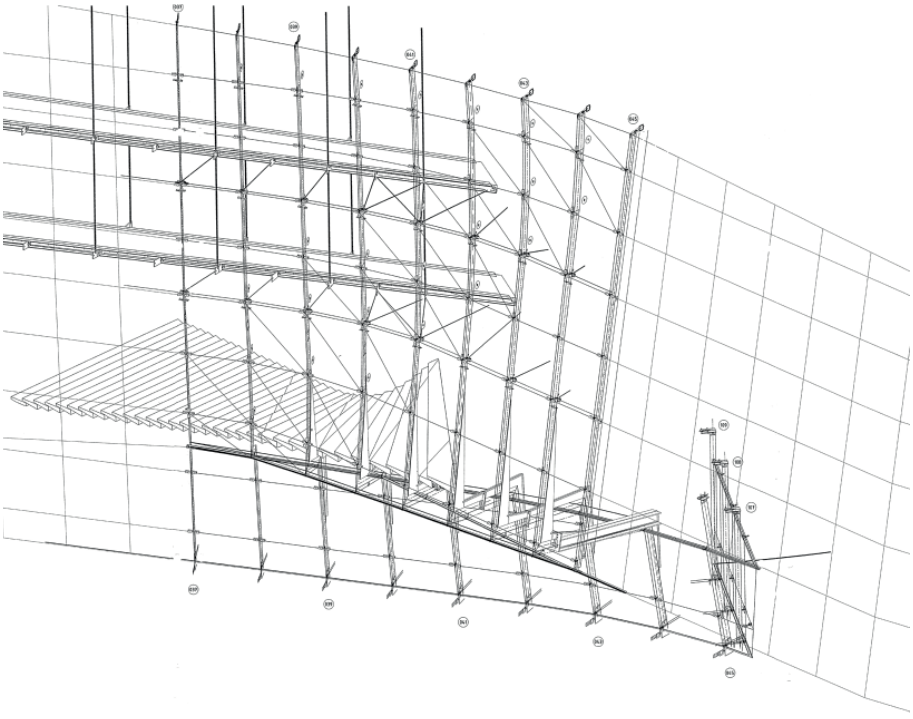

FIG. 238 The 3D work model of Octatube, located at the torsion facade

13.08 VALUE OF THE 3D MODEL WITH REGARD TO ASSEMBLY

The value of a very accurate 3D work model became particularly clear during the assembly phase. The geometry of the façade was set up by the contractor with the help of 'Total Station'. With help of this system, the positions of small reflecting stickers can be accurately established. Such a measurement results in the x, y and z coordinates of the measured point with regard to a point of reference that is determined in advance (0,0,0). Because this reference point was established at an early stage (as early as during the engineering phase), correct coordination of the work of all various parties was made possible.

13.09 WORK MODELS IN THE FUTURE

For the future, it should mean that all different work models of the various designing, engineering and producing parties (= companies) should form a perfect match. Due to the diversity of different development tools on the market, this is not currently feasible. Yet, it is important to take this direction actively and to develop all relevant aspects with expert knowledge. The choice for the exchange format, the manner of distribution and the way of assessment and control over the models are the central point. In the field of parametrical solid modelling, rapid developments occur and it is expected that within the near future this will lead to new useable uniform exchange formats for 3D solid modelling. It is also recommended to determine the design and engineering management as early as in the planning phase, so that both the tendering and the organizing parties will know that their rights and obligations are recorded. The current planning only includes obligations of the (sub)contractors, and hardly describes the responsibilities of the organizing parties. In the working manner described, the periods of having to wait for each other made the progress of the engineering process very irregular.

13.10 SPAGHETTI GLASS STRIPS

In September 2001, HGB approached Octatube with an additional request, namely to think up an alternative for the elongated window frames (strips) of the rear side of the main building, the so-called 'spaghetti strip façade'. A producer of wooden window frames had engineered these façade strips for six months. For the most part, these wooden frame

strips formed twisted glass ribbons between zinc strips of the coverings of roof and walls. The price for an alternative to the material wood (as specified by the architect) i.e. aluminium frames, was considerable, but because no decisions had been taken with regard to this building component in the same six months, the necessary time for preparation had elapsed. The main contractor called for Octatube's inventive thinking.

Octatube's first concept was to make an identical structure as that of the skylights: double glazed glass panels, sealed to a structure of rectangular supporting steel sections. In the skylights, it is possible for these steel RHS to form a span up to 3 m. The initial idea was that the twisted frame strips could be made in the same manner. However, when the wide variety in torsion of the individual panels as a new phenomenon became clear (for the most part 40 mm over a width of 900 mm), the idea of square tubes was immediately rejected, because the square planes would never perfectly connect to the twisted glass plates.
The second idea, therefore, was to consider the frame material that caused the problem as being superfluous and to continue development only on the basis of the strength and capacities of the glass. After a first analysis of how strong the glass was and a 'common sense' test of a cold twisted double glazed glass panel in the Octatube factory, the definitive proposal to have flat double glazed glass panels produced and cold twisted on site, could be developed. They would be force-rotated on top and bottom in a continuous U-profile with rubber fasteners, and silicone sealant would glue this ensemble. It would become (as Eekhout reckoned) the world's very first cold twisted double glass façade.



FIG. 239 The 'spaghetti' glass strips with cold twisted glass

The idea was to make a package as flexible as possible of the thinnest and most flexible glass gauges and sealants in the rims. By means of a floating support with a circular disc fixed on a circular section, internal steel façade post centred in between the larger spans, (the maximum is 1,8 m) the required wind rigidity would be obtained. The bending tensions, brought along by the forced rotation of the panels, were only 7 to 10 N/mm^2, while the fully pre-stressed glass panel is proven to be capable of withstanding an approved total tension of 50 N/mm^2. There remained 40 to 43 N/mm^2 to take the tensions from wind load. That was sufficient. On that basis, the quotation was made for double glazed glass panels 5/15/5 and for the oblique planes 5/15/4.4.2 (with respectively 4 mm laminated and 5 mm non-laminated pre-stressed glass with an air cavity of 15 mm). Although the risk was high, but the purchase costs foreseeable, the client could be offered considerable cost reduction for the contract.

A number of tests were immediately carried out in Octatube's laboratory; first for the engineers of Octatube, then for the supplying and also guaranteeing subcontractors of Octatube: Lerobel and Tremco as sealant suppliers and after that for HBG and the client. Initially, the regular glass suppliers did not feel comfortable at all to guarantee their products according to the concept. Tremco did it, but their guarantee does not go beyond the 'free of charge' re-supplying of sealant. (The same problem occurs when sealing double glass panels upon stainless steel disks for regular Quattro glazing). Eventually, after a few discussions and the submission of the definitive calculations, glass supplier Lerobel put the required guarantee on paper, but with a few conditions by which Octatube remained the main risk taker. The installation of the twisted panels was well feasible in practice, although honesty compels to admit that there was much more breakage while twisting on site than usual. The first façade in the world with cold twisted frameless glass panels of fully tempered double glass was now an accomplished fact. For the rest, despite the warnings of the engineering parties, the design does not provide any possibility for upkeep of the façade strips or to clean them: there is no façade maintenance installation designed or realized and no service platforms provided for, in spite of warnings in writing from the side of the producing parties. In the year after the completion of the spaghetti façade, TU Eindhoven student Dries Staaks developed a theory for cold twisting of glass panels at Octatube.

13.11 ADVICE

After involvement of the author and Octatube in six projects with 'Liquid Design' buildings, there are several lessons to be learned. They are worth while discussing with a broader professional audience and involve different aspects of the 'Liquid Design' Architecture processes. I have composed the lessons for these special design & engineering processes, involving the introduction and development of innovations in Blob architecture in 18 hypotheses as follows:

'Liquid Design' buildings have been possible since the last decade because of increasing accuracy and 3D geometries of computer hardware and software. Design & engineering is the core of the operation and within this process the design decisions are most important. Complex issues can be dealt with by an analytical engineering approach. There is not a problem that cannot be solved. The most advanced technology has to be developed further in order to meet the new geometrical demands, which places buildings at the same level of complexity as yachts, but at a lower economical level. Cold bending and twisting of glass panels, even laminated and insulated panels mix low cost prices with complex form results. The new generation of 'Liquid Design' buildings with their computer designed arbitrary and non-rectilinear form are mainly generated out of sculptural considerations by architects. All lessons from the past decades where systemized spatial structures and economical building industrialization with the most sophisticated products as well as their salutary regularities, do's and don'ts were developed, seem to have to go in a higher gear. The structural glass components of these buildings require an enormous effort in collaborative design and engineering. It is recommendable that at least in the design phase the concept of the building technical composition would be developed simultaneously with the architectural concept. Both during the design & engineering phase as well as during the production & realisation phase, an extremely high degree of collaboration between all concerned building parties, is an absolute necessity to reach the goal of successful 'Fluent Design' Architecture, that is successful for all parties. Frameless glass structures contribute to that higher level of technology in Modern Architecture.

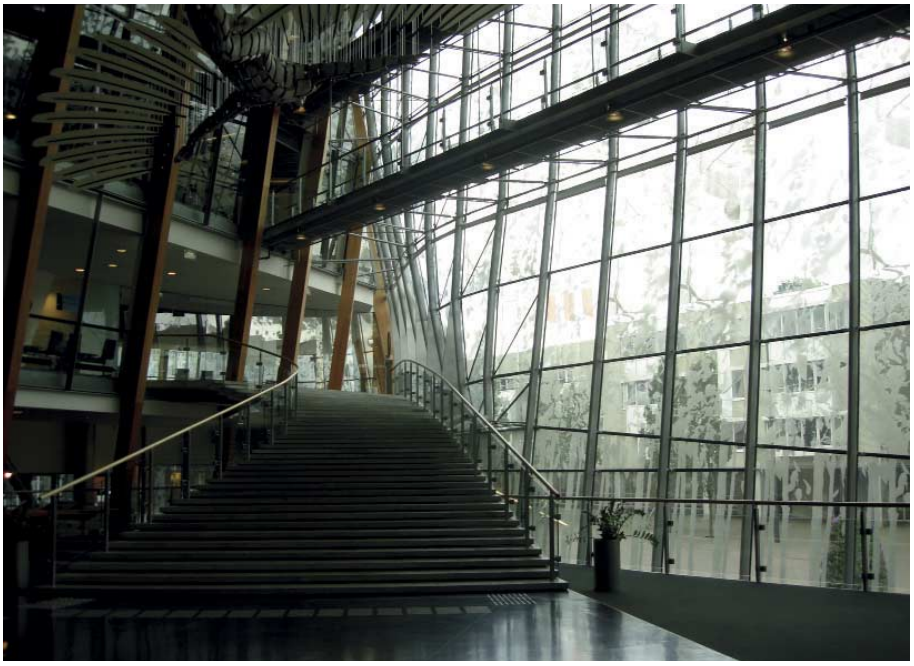

FIG. 240 Interior view

14 TRANSPARENT CUBICAL GLASS BUILDING IN MADRID

14.01 INTRODUCTION

An ultimately transparent glass building in almost cubical form of 30 m x 30 m x 21 m, to function as the future entrance building of the Santander Bancopolis complex southwest of Madrid. Conceptual design by architect Alfonso Millanes and structural design by Octatube. The structure is composed of ultra slender cable fixed tubular columns and trusses placed in a grid of 5 m and clad with insulated glass made from fully tempered outer panels and heat strengthened laminated inner panels. Size of all glass panels is 2,5 m x 2,5 m. The insulated glass ensures additional stabilisation of the overall enveloping structure. The roof panels are partly twisted to obtain a fluent slope for drainage. The roof gutters are positioned at 2,5 m from the roof edge, thus creating a free glass edge. The side walls of the gutters are made of insulated glass panels. The glass type chosen is 'extra-white', emphasizing the glass cube as a sparkling crystal in the landscape.

14.02 HISTORY OF DESIGN OF DIFFERENT GLASS CUBES

In the history of the design & build company Octatube of Delft NL we have designed, co-designed and engineered, produced and built a number of cubical glass volumes. The cube is a prime and basic symbol of geometry in architecture, very recognizable, but difficult to execute in glass, especially for larger volumes for construction (the way you put things together) and structure (the way loadings are distributed from the glass panels to mother earth). We have designed these glass cubes as architects, structural engineers and industrial designers integrally in one.

GLASS CUBE PROPOSAL FOR THE CENTRAL MUSEUM IN UTRECHT AND THE FLOWER SHOP IN ROTTERDAM

In 1988, cubical glass pavilions were designed by architect Wiek Röling and structural engineer Mick Eekhout for a Dutch Museum in Utrecht. The project was not realised. Cancelled just before we had developed a method by which we could join 3 x 3 panels into one big glass panel. Our target at the time was a stable glass plane of 6 m x 6 m, structurally bonded together by connectors, cables and compression rods. The first step was not even prototyped properly when the idea came up to make a 3D cubical pavilion. However, we did not know how to do it. Looking at the drawings it became apparent that the corners, where the roof plane would lay upon the wall elements and the corner between two vertical walls were not solved. How to introduce larger forces from one plane into another? We did not know, 20 years ago.

Hardly one year later, architect Kas Oosterhuis came to Octatube, and together we conceived a glass flower shop on the famous Lijnbaan, where the problem of the connection between roof plane and wall plane and the wall-to-wall connection was neatly solved as a separate cubical tubular structure. The cube measured 12 m x 12 m x 6 m (l x w x h) and was subdivided into units we knew (6 m x 6 m, each composed of 3 x 4 or 4 x 4 panels). The design drawing indicated that the roof panels were 1,5 m x 1.5 m; smaller than the maximum panels available from the industry of 2,14 m x 2,4 m. With regards to structural integrity we were not sure. But the ambition, the dream was on the table. This structure was conceived in single glass panels, fully tempered. This structure was not realised either, but its publication in a book as the starting point of Dutch glass structures [Ref. 14.01] served its purpose.

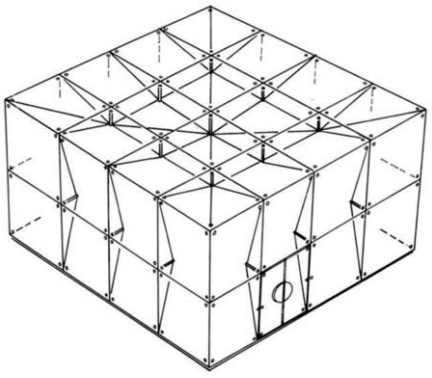

FIG. 241 Glass cube proposal for the Centraal Museum in Utrecht

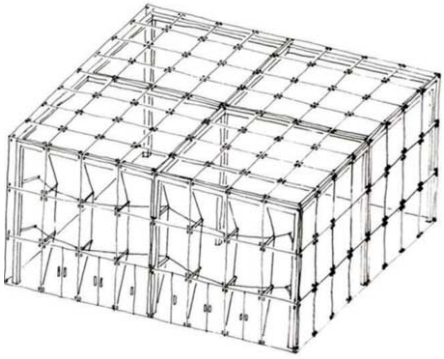

FIG. 242 Flower shop on the famous Lijnbaan in Rotterdam, not realised

GLASS MUSIC HALL IN THE EXCHANGE OF BERLAGE, AMSTERDAM

In 1989, Mick Eekhout designed the structural scheme for an all-glass envelope for architect Pieter Zaanen to house the concert and rehearsal hall for the Chamber Music Orchestra of the NedPhO, the Dutch Philharmonic Orchestra. Pieter came to Mick after a modest publication of the study model by Rik Grashoff, one of Mick's early students at Civil Engineering. The model was built for a Boosting publication [Ref. 14.02].



FIG. 243 Experimental model of glass. Structural glass panels 1989



FIG. 244 Model of Glass music hall, Amsterdam

The footprint of this hall had to measure 10 m x 22 m, and it was to be around 10 m in height. Architectonically, built inside of the famous exchange building of Dr. H. P. Berlage from 1903, it had to be a volume completely independent of the existing building. Also, maximum transparency was required. Built on separate piles driven through the cellar floor, the concrete floor structure would enable a completely independent glass box, a reversed giant glass battery box. During a number of design brainstorms with Pieter Zaanen, the idea came up to have one of the two walls not parallel, to improve the acoustics as flutter would be minimised. The structural system of tiny cables or tensile rods and short compression studs was designed pre-stressed between the roof and concrete floor structure. It was not the floor, but the roof structure that gave the greatest worries. Parallel to the glass flower shop in Rotterdam, the first idea was to make a tubular structure in the ribs, but the fire brigade officer did not allow for a structural glass roof, without abundant experience or proven examples proven or engineered. They were right, it could be added later. So the roof structure was taken as an ordinary space frame structure, stiff, supported on six columns only, stabilised with wind bracings and covered with laminated glass panels. Opened in 1990, it was the first structural glass building in the Netherlands. All glass panels were suspended vertically from one another. So the highest glass panels, 8 mm thin and fully tempered, carried the deadweight of the lower panels, and the vertical trusses of 8 mm rods stabilised the facades horizontally, and occasionally against leaning architects, as there was not much wind to be analysed, apart from the overpressure of the air-conditioning. That was the invention. It was a giant step forward. A book was written about this adventure [Ref. 14.03].

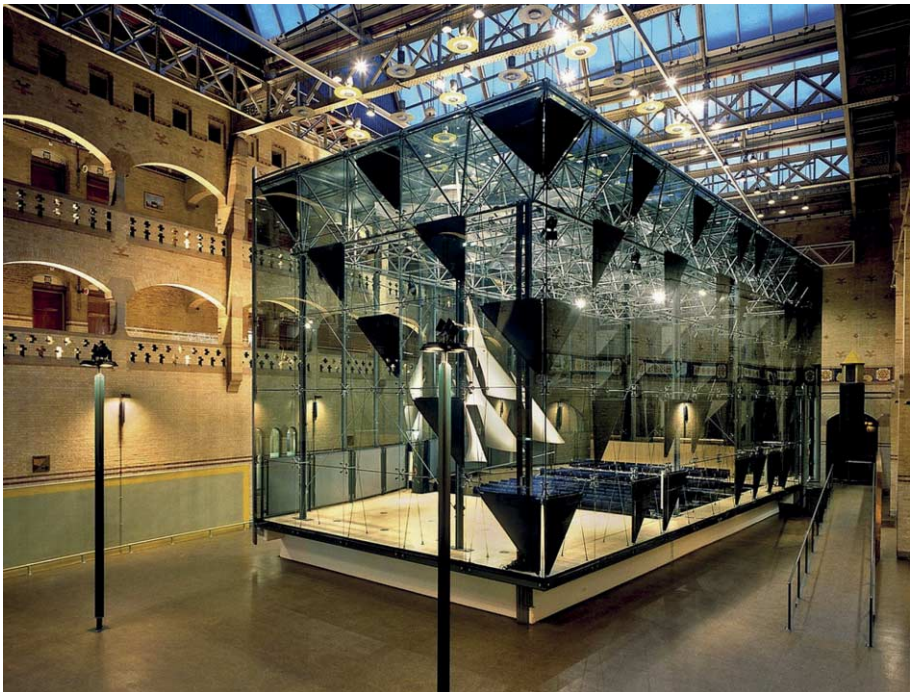

FIG. 245 Glass music hall, Amsterdam



FIG. 246 Interior view of the music hall

GLASS ROOF ON BRICK CUBES IN HULST, NL

However, the roof, built as a conventional space frame, was a source of annoyance. A few months after the design was approved by the fire brigade a young Belgian / Dutch architect, Walter Lockefeer came to Octatube to co-design a glass roof for a double cubical pavilion with dimensions derived from the golden rule: 6.870 m x 6.870 m x 6.870 m. The walls, according to his architectural philosophy, were the dominant feature, and the roof was unimportant. So the roof had to be invisible and made of glass, preferably without any steel. Thus, he stimulated the development of the first glass panel roof, stabilised like a bicycle wheel with vertical compression studs and tensile cables underneath the glass panels. The first Dutch tensile stabilised roof had been realised. The roof was composed of double glass panels with laminated lower panes. All glass plates were fully tempered. The stainless steel connectors on the lower side of the roof panels were glued between roof panel and connector. In this case the deadweight was more than the eventual uplift, so even a glued connector without glue would have worked, as the panels were fixed horizontally between the roof edges. This experiment gave us enough confidence that a tensile under-spanned structure would work, even if a surrounding steel tubular steel frame balanced the tensile cables. The second benefit was the gluing experiment. It was just a project invention, nothing more. The pavilion was published in colour and attracted much interest [Ref. 14.03]. The roof leaked for a number of years, but the cause lay in the surrounding brickwork. The silicone sealant worked quite satisfactorily for a roof with a pitch of only one single degree.

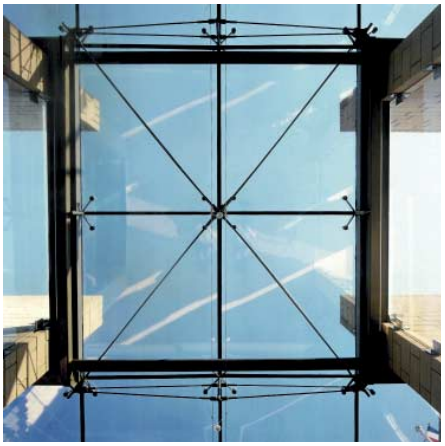

FIG. 247 Detail flower shop in Hulst

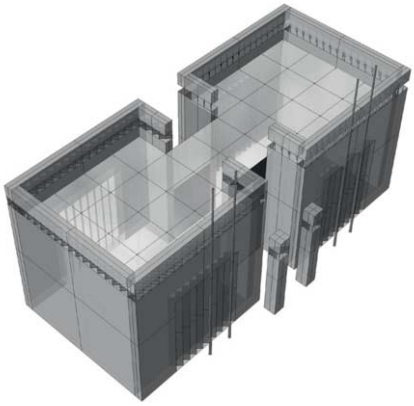

FIG. 248 Flower shop in Hulst

ATRIUM COVERING DROOGBAK IN AMSTERDAM

In the meantime, the system of a surrounding tubular frame on top of 4 x 4 square glass panels, stabilised by counter-spanning tensile rods, was designed and applied in a number of roof structures in single and double glazing and proved to work quite well; visually very

light when backlit. After the introduction of the generation of insulated glass instead of single glass panes, the necessity arose to come up with cleverly designed connection modes. Initially there was a double mechanical fixing, with 2 perforations in the glass. Thereafter, an initial alternative system was developed for the Rotterdam Netherlands Architecture Institute (Nai): with a mechanical fixing on the inside, and the outside pane chemically bonded by silicone; so half mechanical and half chemical. It was published in a separate book [Ref 14.01].



FIG. 249 Droogbak in Amsterdam

PRINSENHOF GLASS MUSEUM HALL IN DELFT

The next step was, of course, to make a completely chemically bonded system. The glued connection was initially developed for roofs, where the tangential loads were restricted and uplift could be avoided by choosing thicker and heavier glass panels; the first sample in the Court of Justice in Maastricht, 1995.

The first frameless façade was built in the Prinsenhof Glass Museum hall in Delft one year later, in 1996. The extra problems structurally for the glued connections were the vertical deadweight of the glass panels and the quite large distances between the panels and the Quattro nodes. In first instance the distance was too large, causing large bending moments in the connection bolts. A number of panels broke during the initial installation. Soon enough it was discovered that the cause of breakage mainly lay in the diagonally stressed wind bracings, as a result of which the Quattro nodes were not accurately positioned. It was

mid winter, her majesty the Queen came for the inauguration and the installation was done too hastily. For security reasons, the deadweight of the glass saddles, fixed on the Quattro nodes, carried the panels. In other vertical facades, the distances between the glass panels and the Quattro nodes were kept as short as possible. Glass panels in their glued connections can take as large an amount of compression as tension and shear forces, but glass panels are only capable of carrying 10% of these forces in bending.



FIG. 250 Prinsenhof Glass Museum Hall in Delft

14.03 GLASS CUBE OF MUSEON IN TEL AVIV

In this short history of incremental product development, the material glass, single panels and laminated and double panels, the Quattro nodes, welded and later stainless steel, the tensile trusses from 8 mm in Amsterdam to a heavily typhoon loaded project in Hong Kong with 2 x 30 mm, the glued connections and the architectural detailing were successively developed to the current level of design perfection. The entrance cube of the Museum of Modern Art of Tel Aviv offered the opportunity to make a single span cube with only the tubular compression frame elements in the corners. The size is roughly 12 m x 12 m x

12 m. The system worked, even though, in this case in single laminated glazing and a little building physical problem due to abundant solar radiation entering the building part in the Israeli desert climate.



FIG. 251 Entrance cube of the Museum of Modern Art of Tel Aviv



FIG. 252 Interior view

14.04 THE SANTANDER GLASS CUBE OF MADRID

The apotheosis of this contribution, and its main subject is the cubical glass building serving as the entrance building for the Santander 'Bancopolis' in Boadilla del Monte, near Madrid. The Bank town has been designed by 85 years old Kevin Roche from New York, Pritzker Architectural Award winner 1982. In 2003, a 30 m diameter circular glass roof was designed by his office and detailed and realised by Octatube. The structure was post-stressed, based on the 36-piece bicycle wheel principle with multiple compression studs and stainless steel tensile rods of 30 mm diameter. It opened the eye of the client for lightweight tender structures. Some years later he issued an order for a cubical glass building as the entrance cathedral for the bank premises as a building with a maximum amount of glass. Madrid architect Alfonso Millanes was the architect who developed the cube, much in line of the above-described know-how with the engineering office of Typsa and Octatube. The predominant features of this building are: overall size 30 m x 30 m floorplan, 21,4 m high; large insulation glass units (IGU), 2,5 m x 2,5 m; custom designed large Quattro node nodes 350 mm x 350 mm; compression tube grid of 5 m x 5 m;

integrated wind braces glass supporting structure; mechanical connection of glass to nodes through the inner plate of each IGU; twisted roof panels; insulated glass roof gutter; integrated water drainage system.



FIG. 253 Interior design Glass Cube



FIG. 254 Design Glass Cube



FIG. 255 Installation of the Glass Cube

Integration of several functions into the components comprising the structure of this particular cube was imperative to reach the accomplished transparency level. For instance, the wind bracings of the main structure not only serve to stabilize the structure against external horizontal forces, but are also designed to support the glass panels of the façade. The roof also has a unique feature: a completely flat roof can only exist in theory; when put into practice, rainwater needs to be drained to prevent stains on the glass, or even worse, excessive accumulation of water on the surface of the roof. The roof is designed to drain water to the gutter running on all four sides, thus raising the central point. The glass panels of the roof are twisted to avoid the use of triangular glass panels. The glass gutter is positioned directly above one of the compression tubes of the main steel structure. This not only disguises the gutter, but also leaves the corner of the roof-façade connection to be very transparent as well; no structure other than a mechanical glass-on-glass connection is used to support this corner. The vertical corners of the cube are designed in a similar fashion; the main difference being a vertical corner profile used to support the weight of the glass panels (another example of integration of functions).

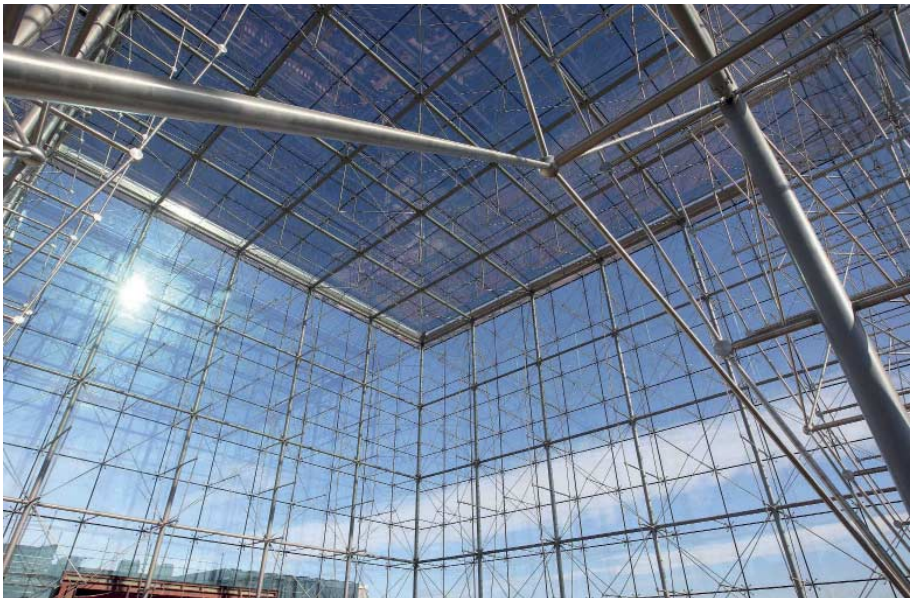

FIG. 256 Inside view of the Glass Cube Santander Bank, Madrid

In true Octatube style, the structure is prefabricated to the maximum possible extent in the factory in Holland. This, together with the just-in-time arrival of components on the building site leads to a short and effective assembly. This also applies to the glass panels; glass shipments are called to arrive on site with little advance to minimize the risks of damage during storage on the building site. This approach results in the total assembly of all glass panels (516 in total) without any damage.



FIG. 257 Outside view of the Glass Cube Santander Bank, Madrid



FIG. 258 Outside view of the Glass Cube Santander Bank, Madrid



1



2

FIG. 259 Details of the Glass Cube

14.05 EVER BIGGER GLASS CUBES?

The Santander Glass Cube in Madrid is an example of high tech know-how on different levels that, for the main part has been obtained on a project-to-project basis. This careful incremental approach took place on different scale levels:

- Glass and glass panels;
- Connections glass to Quattro nodes;
- Tensile structural systems;
- Refinement of constructions;
- Industrialisation/prefab components;
- At the engineering department there is a general feeling that the resulting glass cube structure is about the lightest possible;
- The next step could be to use glass panels to function as shear force holders in the plane of the façade and the roof, and or to have the glass panels provided with internal tubes so that vertical pre-stressed cables could be inserted through the panes to stabilize the façade against wind pressures.

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15 GLASS ROOF AND ZINC DOME IN BUCHAREST

15.01 INTRODUCTION

An Israeli consortium developed a plan for the new shopping centre in Bucharest, Romania. The glazed atrium covering was designed as a semi-circle with a 53 m radius. This covering had to comply with the maximum height regulations of Romania, show an attractive interior design and efficiency in material usage. Within these constraints the design was developed in collaboration with the architect and structural engineer. The engineering had to comply with the local regulations concerning earthquake loads, which led to a shell structure of trusses and purlins, fixed to form a rigidly connected ensemble that could freely move during earthquakes without damaging the vulnerable glass covering. Octatube Delft was the consortium leader and contractor for the atrium covering as well as for the 42 m large IMAX sphere on the same project. The steel structure of the atrium covering was partly made in two factories in the Netherlands and partly made in a factory in Israel. The assembly after shipment was done by a Dutch subcontractor.

15.02 DESIGN CHALLENGE

Romania joined the EU in 2007. In Bucharest, several initiatives have been started since then to develop new real estate. Since the fall of the Iron Curtain in 1989, Romania functioned as one of Europe's low wage countries. Many Romanians worked in Israel. The relationship between Romania and Israel has been adequately tested. Several international building consortia have been active in Romania since its accession to the EU. They started projects based on the increased prosperity of the local population. The shopping Centre Cotroceni Park is an initiative of Africa-Israel Investments, originally from the South-African diamond industry. Investment money was loaned from a German bank. Octatube has designed and built around 30 projects in Israel and is internationally known for its special designs, 3D accuracy and inventiveness. Its local agent received the enquiry from the architect office Avram Yaski (More, Yaski, Shivan) in Tel Aviv. This way, Octatube became member of the Israeli consortium for an export project: the design, engineering, building and finishing

of a large (200.000 m²) shopping centre in Bucharest, Romania. The main contractor for the entire shopping mall was the Israeli company Danya Cebus. Octatube was invited as a subcontractor of the project consortium to price the atrium roof covering of steel structure and glass panels for the consortium. Also, the 42 m diameter three-quarter sphere for the IMAX theatre belonged to the project. This contribution will mainly focus on the tubular steel structure of the atrium covering. Otatube's design & build contract was signed in May 2008. The atrium was completed in September 2009; the inauguration of the shopping centre was celebrated in December 2009. Octatube created the design of the roof in close collaboration and a number of brainstorms with the architect and the project developer. The company elaborated design alternatives and compared their characteristics; after which a choice was made between these alternatives. It also carried out the main structural analysis of the steel structure, the detail analysis and determination of the connections, welded and bolted, and supervised the engineering drawings of the co-makers in the Netherlands and in Israel; Octatube was also responsible for the assembly and erection of the steel structure; the production of the skylight purlins was effectuated in the Delft factory; glass panels were ordered from Turkey via an Israeli middle man. The installation of the glass roof was done by the Dutch installer under supervision and responsibility of Octatube Delft.

ARCHITECTURAL REQUIREMENTS

In 1995, the collaboration with architect Avram Yaski had resulted in a 52 m high façade for an office building in Ramat Gan, Israel. Yaski saw the design & build capacities of Octatube Delft and its principal Mick Eekhout as strongly innovative on the Israeli market. Avram Yaski's office (www.m-y-s.com) is often involved in commercial buildings in Israel. This building under project architect Alon Yithzaki was one of a growing series of export projects. The maximum allowed height of the shopping centre was 25 m. The top level of the concrete roof posts and beams was 15 m. So the entire roof structure had to fit in between these two heights: 10 m maximum. The radius of the semi-circular floorplan between the concrete beams was 53 m. During the design brainstorms, both a rectangular space frame was studied, as well as a number of diverging schemes, fitting in the radial semi-circular geometrical set-up. 2D as well as 3D schemes were included. The architect favoured an expressive structure which would emphasize the atrium and make a festival of the atrium as the centre of the shopping centre.



FIG. 260 View of the frameless glass façade of the OZ building



FIG. 261 Interior view

STRUCTURAL REQUIREMENTS

The structural requirements were logical, although the structural engineer commissioned with the concrete structure did his own proposals before Octatube was engaged in the game; and of course there are large differences in reaction forces between an orthogonal scheme of parallel trusses, a square space frame and a system of radial trusses, 2D or 3D. Quite some mystical discussions resulted from the fact that the structural engineer had estimated his own scheme, and that Octatube came to a different scheme anyhow.

COMMERCIAL REQUIREMENTS

As is the case in ad-hoc building teams, the price/quality level of the building team partners has to be measured before they are allowed into the inner circle of the building team. An average price for a simple tubular steel structure was prepared for that reason, discovering that the different schemes showed differences of up to 20% in their deadweight consumption assumption. It was known that a Chinese consortium was also invited to tender for the job, but according to the architect, they were not as creative, imaginary and designer-like as Octatube could offer. An average deadweight value was assumed plus average prices for the covering package, on the base of which Octatube was invited into the building team. This all happened before the design brainstorms took place.

OCTATUBE'S DESIGN & BUILD ATTITUDE

The core of Octatube's business is designing & engineering spatial and special structures. The company was founded in 1983, originating from the architect's firm of Mick Eekhout, and has functioned as a design & build company for innovative light weight structures and constructions ever since. Reasoning from the designer's point of view, the factory was an enormous model and prototype workshop and production facility in one. The author has more than 25 years experience in designing, engineering, experimenting, production and realization of building technical products and systems in his design & build company. The results and philosophies of this design & build portfolio has been described in the book *'Delft Glass Design Innovations'*, Octatube, Delft [Ref 15.01]. The splits between practice and theory, between industry and academia that is usually seen, also has its distinct benefits when both worlds are combined in order to obtain new knowledge, insight and material innovation. [Ref 15.02]. To put it even stronger and more outspoken: in the process of inventions and innovations in building technology, experiments are continuously colouring the development processes, and in order to lead these processes to a successful result, the 'design & build' process leader should lead both the design & engineering part as well as the prototyping, productions & realization part of these processes. In the opinion of the author the design & build attitude is the main factor for continuous success in the attained material innovations in his office. Large progress was made thus. Historical examples were realized by great names: Gustave Eiffel (1822-1923) and Jean Prouvé (1901-1984) in France, Pier Luigi Nervi (1891-1979) in Italy and Felix Candela (1910-1997) in Mexico. They were pioneers in their time. These historic pioneers would have made a similar claim of experimenting by prototyping, thus boosting the state-of-the-art, had they lived in our times. For normal building projects with a clear division between the designing and

the building parties, separate contracts for designers and engineers on the one side and producers and builders on the other side work perfectly well and the building industry is based upon this setup. However, in case of a daring or innovative project or project part, it would be better to place all responsibilities in the hands of one contractor. He would be called the design & build contractor, and has a final say on all items under his responsibility. Thus he can guarantee that all phases in the development are optimized in a perfect symbiosis in his contract. It has proven as the proper way to work innovatively during a great number of projects each year.

OCTATUBE'S INTERNATIONAL OPERATIONS

In the more than 25 years of its existence Octatube has been active on the international market. The lightweight elements and components that make up the production of Octatube are well suited for long distance transport by containers. This started in the 1980ies with tubular space frames. One could ideally stack 1600 m^2 of space frame in a fully loaded 40 ft container. Since the 1990s, the market for regular space frames turned over into a market for special 3D designs, because of the standard availability of computer programs to analyze 3D structures and machinery to produce industrially elements with individual characteristics. The current international interest focuses more in the direction of specially designed, engineered and produced spatial structures with glass coverings. This Cotroceni project is such an example. Octatube may be one of the smallest amongst the internationally operating design & build companies for glass and steel structures; but quality-wise its projects show interesting processes and products.



FIG. 262 View of the 42 m diameter sphere, built up as s steel structure, aluminium battens, timber planking and zinc cladding as the covering of the IMAX theatre



FIG. 263 Detail of the cladding

15.03 DESIGN OF THE ATRIUM STRUCTURE

DESCRIPTION OF THE PROJECT CONDITIONS

The shopping centre has a floor area of more than 200.000 m^2. It is the largest shopping centre in Romania and belongs to the larger shopping centres in Eastern Europe. It has two storeys of space on top of a two-story parking garage. The structure of the shopping centre is made in reinforced concrete. Local conditions require earthquake-resistant design and engineering. Which resulted in large and heavy concrete columns. The very centre of the complex is an open atrium, semi-circular in form with a radius of 53 m. The atrium would become the lively and elegant counter design of the heavily dimensioned shopping centre. The architect's thinking was focusing on elegance and flamboyance. The first negotiations took place on the basis of space frames and a square modulation of the tubular elements. Architectonically too much in line with the design grid of the building and not fitting in the semi-circular plan. The spatial exception of the atrium roof asked for a radial solution of some sort as a more suitable solution.

DESIGN SESSIONS IN DELFT

In total, there were 3 design sessions in Delft at Octatube's office and one in Tel Aviv at the architect's office. During those brainstorms the grid design, direction of the main grid, 2D of 3D composition of alternatives, rectangular or radial arrangement of the steel structure, the form of the structure in vertical cross-section, the architectural effect, the graphical effect, earthquake resistance, manufacturability, transportability and assembly and hoisting methods as well as the connections to the anchor points and the resulting forces on the concrete substructures were all looked at in alternatives.

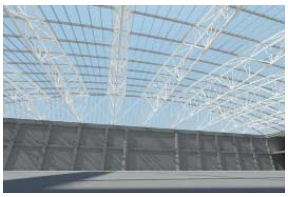

FIG. 264 Interior view of parallel trusses as one of the studied alternatives

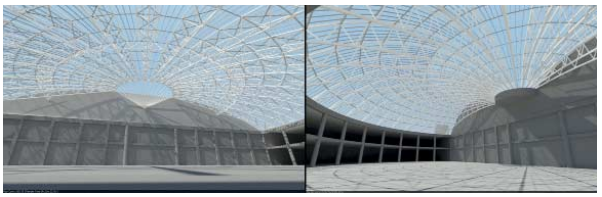

FIG. 265 Sketches of the different radial alternatives for the tubular structure

Out of all the considerations on the brainstorm table, the architectural design, the visual logic of the semi-circular plan, the structural efficiency of the roof and the graphical design were the main items. Delft engineers know this game as they are knowledgeable in the fields of architectural design, structural design and industrial design and as they are used to be responsible for design, engineering, production and realization up to the completion of their projects. Their attitude is different from the attitude of the project architect, project engineer and contractor, who first of all promote their own interests. During the Delft brainstorms, principles were drafted on whiteboards, represented in models and mock-ups of elements and connections made in the factory; they were discussed and considered. Topics were characteristics to be balanced, erased and improved in principles, materialization and salient details. In the weeks between the brainstorms, variations were studied and analyzed and considered in the respective offices of the brainstorming parties. Also minor details and alternatives were sent back and forth. Figures 3-5 show some of these variations. Besides the already mentioned straightforward space frame systems, slightly curved roof forms were considered with 3D trusses and flat (2D) trusses as well. At the time of assembly, the ground level would be fully occupied with workers.

During the foundation stage, more than 1.000 Chinese workers were occupied with the parking garage levels. It would not be possible to assemble the entire roof structure on ground level and then hoist it in at once as one does with a complete space frame. Moreover, the anchor forces were very high, too high to use cantilevering brackets. The structural concept became one of an entire shell structure where all trusses would be rigidly connected by means of horizontal CHS stabilizers to form a rigid space frame, able to 'shake' on the roof during earthquake loadings on Teflon plates with restricted

movements. This meant that the bracings were to be connected rigidly in form of a shell, which would be able to move and yet return to its original position after the quake. As mentioned, the maximum height allowed by the authorities was 25 m. In the atrium, the client wanted to place a climbing wall of 20 m height. Thus the structure would be improved by a strong curve upward. A modestly curved roof form would result in higher steel forces in the steel chord members; a more upward directed and higher form in smaller forces. The varying reaction forces of the variants drove the concrete engineer wild. His premature assumptions were too modest and the 2nd garage floor was already cast. The higher form was clearly the most wanted, but not allowed by the authorities as it was 30 m high. In the meantime, it was clear that the flat trusses would be complex enough and that 3D trusses would not add to the structural efficiency as the transverse direction of a radial arrangement does not contribute structurally. Quite different from the orthogonal space frame. The graphical rhythm of the trusses was already dense. The composition of the members in the 2D trusses was regarded in CHS and SHS/RHS. Much to our astonishment the architect agreed with the more sturdy SHS for the upper and lower chord and RHS for the diagonal bracings in the trusses, compared with the alternative and gentler CHS. Instead, the CHS profiles were preferred as the horizontal bracings.

The function was clear: square for the trusses and circular for the stabilizing tubes. On the photographs one can clearly observe that the RHS trusses in their banana form make a strong impression and that the choice between square and round tubes was only a secondary consideration. In the backlit atrium one does not observe the different profiles, except maybe on the second floor level, when looking at them at an angle. Gradually it became apparent that the round tubes had to be connected rigidly on the trusses and for that purpose connecting drums were conceived, on which the circular end plates of the CHS profiles fitted neatly. These connections needed tension indicators to indicate the degree of pre-stress inserted in the bolts due to deformation. The banana-form of the truss actually is a polygonal line both in the upper and lower chord members. The square profiles were butt-welded on the drums; the diagonal bracings were mounted on the site with bolts.

The semicircular shape of the roof, accompanied by the radial arrangement of the flat trusses turned out to be the most challenging aspect of the structural design of the roof. Placing the 20 trusses in a radial manner means they need to start from a single geometric axis. A radial design also concentrates forces on this axis. In the case of the Cotroceni mall, the axis is placed exactly above a non-bearing portion of the roof. Added to the challenge is the fact that the nearest bearing columns were placed asymmetrically from the roof's axis. The combination of these factors meant the centrepiece of the roof required special attention. The principle of the centrepiece is based on a heavy duty cantilever, which diverts the vertical forces directly to the top of the asymmetrically placed main columns of the building. The cantilevering element is fixed to the top of the concrete roof. This centrepiece, also called "the crown" of the roof, supports ¼ of the loads acting on the roof. In the event of an earthquake, the crown will also act as a horizontal stabilizer; the roof will "turn" around this point, as this is the stiffest point of the roof regarding sideways movements.

Another structural challenge was reducing the horizontal forces on the semi-circular concrete beam on which the other end of the trusses would rest. The initial design of the main building only accounted for horizontal forces during an earthquake. The chosen curved shape of the trusses, together with their interconnecting horizontal bracings would result in high horizontal force concentrations due to vertical loading at both ends of the semi-circle (such as snow loading on the roof). Avoiding this force completely was neither possible nor desired; the design needed would lead to a reduced stability of the structure. Instead, the structural scheme of the roof remained unchanged. The mentioned forces were reduced by executing a so called "building stage analysis". In short, this means the connections of the bracings were not tightened until 98% of the glass was placed on the roof. This allowed the individual trusses to set under the weight of the glass before bracing them. The result is a reduction of the horizontal forces of about 40%. As a result of the structure's light weight it is not the earthquake loading which is critical, but the snow loading on the roof.

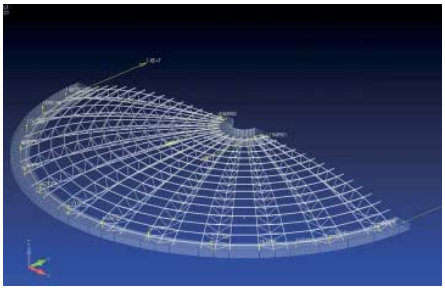

FIG. 266 Overview of 3D trusses in flatter curved form

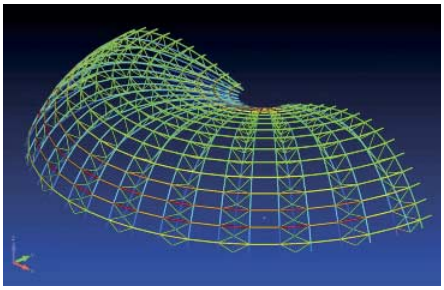

FIG. 267 Overview of 3D trusses in steeper curved form

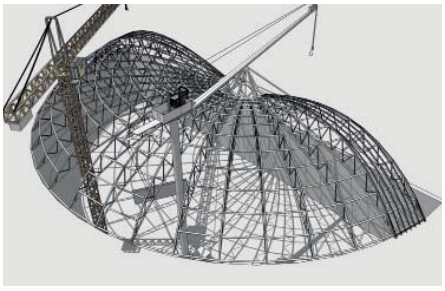

FIG. 268 Overview of 2D trusses in radial composition and meridional bracers to form a 3D shell structure for better resistance against earthquakes

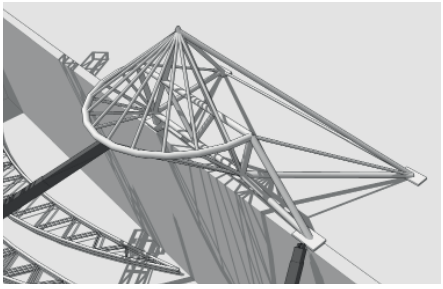

FIG. 269 3D picture of the central crown

15.04 PRODUCTION AND BUILDING

PRODUCTION

The design of the steel structures was finally chosen in form of a composition of 20 flat trusses in banana form, which were separately produced in a welding jig to obtain the necessary accuracy. The trusses have a pinned connection on the higher end and a sliding Teflon plate foot connection on the lower side. The components had to fit on a transport lorry, so the welded endings of the trusses were completely welded, while the rest of the lower and upper chord members were transported as separate elements, fitted together flat on the ground on site, butt-welded, and bolted in diagonals. As flat trusses they were hoisted separately, pinned at the upper joint and connected with some of the transverse stabilisers. The trusses were made at Rijndijk in the Netherlands. The central crown, the heaviest loaded building part of the steel structure was not engineered in time and was thus awarded to another steel fabricator: Agam in Israel, used to heavy steelwork as they also produce turrets and armour plates of army tanks with all the necessary certifications. Agam had engineered the complete crown within two weeks from the contract change, and showed the strength of adequate engineering skills and engineering programs, fitting in the 3D mother model of Octatube. The trusses were to be pinned on the crown. The sideward space for the pins determined the spacing on the perimeter of the crown.

INSTALLATION

The assembly and hoisting was performed by the Dutch firm of Peter van der Geest, who was very well equipped with the gear to perform all measuring, bolting, welding, assemblies, hoisting and installation. They also did the installation of the steel purlins on top of the steel structure and the glazing. The glass layer was composed of short tubular studs, welded in jigs perpendicular to the upper chord members of the steel structure, with top saddle plates on which the steel purlins in the Stabulux system were fitted and bolted. The Stabulux profiles are 60 mm x 180 mm in cross-section and 3 mm thick, hot dip galvanized from the factory and provided with special rubber gaskets, screws and cover caps. The glass panels are rectangular in the regular surface and triangular near the 20 angle ridges. In these areas, the Stabulux profiles also have to be shaped and modelled. The glass panels are double glazed, laminated lower panes and all panes fully tempered. The glass has been manufactured by Yildiz in Turkey, the panels have a Low-E coating for better performance in winter and a solar transmission coating for better performance in summer. Yet the atrium was designed to also contain a solar screening system in its construction, which, as yet, has not been installed.



1



2



3



4

FIG. 270 Details of the assembly and hoisting process

EXPORT CONSORTIUM

There are mixed feelings on the quality of co-makership in steel structures. First of all parties who did not work together before, have to cooperate, or even collaborate. The progress and fate of one company relies on the productivity of others. In this case, the main contractor had never worked with the subcontractor Octatube and, like most contractors, is mainly focused on local site productions, which they can supervise and control and push on if needed. In the case of the steel structure, where the entire design and engineering had to be done after closing of the contract, the contractor initially had to come to the Netherlands monthly to see the progress of the engineering. Steel structures require a long preparation time; in this case for design, analysis and engineering, shop drawings, ordering of steel, production and conservation. Only then the first truck will be loaded. So the main contractor had to wait long before the first steel components arrived onsite. He was almost desperate, looking at the overall planning. Then there was the question whether all components would fit. They fitted perfectly. Luckily enough the site assembly and installation of the steelwork was much quicker than anticipated, so the rate of progress, nearing completion date of the atrium covering, was seen as a relief. Quite

some time was lost as one of the steel manufacturers did not have a proper engineering department; meaning that part of the engineering had to be done by other parties, which in turn appeared to be the basis of an internal conflict. If a company is not geared up to do a perfect job, both in engineering, collaboration, production and supply ex factory, then it should better refrain from taking on such rather complicated sort of steel structures. All of the consortium partners need excellent engineering departments, and must be versed in the art to collaborate.



FIG. 271 Detail of the crown

15.05 CONCLUSIONS

The integral design of architectural, structural engineering and industrial design resulted in an architecturally appealing structure with structural efficiency that could be made industrially for an affordable price. The design & build attitude allows for a high degree of innovativeness of design. The collaboration of co-makers will only work when the collaborating engineering departments of these co-makers offer state-of-the-art quality in their work and have mutual trust as the basis of working together instead of mistrust. Even for long distance productions, transporting in breakdown position and local assembly and hoisting tubular steel structures have once again proven to be reliable and efficient. We called it 'Ikea' packages. The structural steel world is confirmed in its efficiency, and architecture is enriched.



FIG. 272 Dome after completition



FIG. 273 Overview of the dome



FIG. 274 Overview of the total complex

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16 DEVELOPMENT OF A SUPER SLIM FAÇADE FOR INHOLLAND

Lecture given at façade conference Delft 2009

16.01 INTRODUCTION

Design, engineering, prototyping, production and realisation of an innovative insulated façade system with integrated pre-stressed cable stabilisation for application at a polytechnic school INHolland and a laboratory for composite materials in Delft, NL. The process consisted of 4 major phases:

- The experimental ('Sia Raak' subsidy) design phase;
- The experimental design and engineering phase;
- The production and realization phase of the commercial façade system;
- The production and realization of the original composite façade system.

The initial conceptual 'wild idea' for the INHolland project by architect Rijk Rietveld, New York, was elaborated through different design brainstorms towards a radical innovative system for ultra-slim glass façades. In this façade system, insulated glass panels with a maximum depth of 50 mm are integrated with internal pre-stressed structural composite cables, stabilising the façade against wind forces. Deadweight to be taken over by vertical deadweight rods in between the vertical silicone seams between the panels. The insulated glass panels are sealed by composite spacer frames. Many different solitary tests were done with the sealing and the carbon fibre components, with adhesion of silicone sealant on the carbon fibre frames and on the perforation of the carbon fibre used through the frames. During the actual engineering phase, structural analysis was performed and tests on several levels were executed. The composite frames were substituted with conventional metal frames. The system is suited for facades of 14 m high. Under wind loading the facade system deflects like a sail membrane, with the deflections at the perimeter taken up by adequate detailing at the sides so that no breakage occurs; the membrane façade is regarded as fail safe system. A prototype of the corner was constructed and tested for practical approval. Due to the refusal by the glass panel manufacturer to

supply a guarantee based on an inadequate number of tests with inadequate quality, the integrated system had to be changed into a duo-system with internal pre-stressed cables and integrated deadweight suspension rods. The project consisted of 2 large facades executed in this manner and one narrower segment façade exactly in the experimental mode, for performance evaluation. The façade had to keep pace with the progress on site. The building was opened in September 2009. All-glass facades for larger spans need stabilising systems for wind and deadweight loadings. Frameless facades show ultimate visual lightness as daylight is not obstructed by steel purlins and aluminium framing profiles. In an experimental process of design and development of a composite façade for the INHolland Polytechnic in Delft, a system was selected and developed in which pre-stressed cables were developed for taking up horizontal wind forces while deadweight suspension rods transfer the vertical deadweight of the system. Both types of pre-stressed cables and suspension rods were initially designed to be located within the air cavity of the insulated glass panels. The pre-stressed aramid cables are located inside the tubes in the inner spaces of the double glass units, while the suspension rods are located in the end zones, seams, between the panels. The development of the process highlights the many obstacles and risks involved in this dense integration of the two independently developed 'alien' components: the double glass units and the pre-stressed cables. The experimental design scheme and the realistic engineering answer for it are described in this contribution.

16.02 FIRST PHASE: EXPERIMENTAL SIA-RAAK DESIGN PROCESS

The INHolland Polytechnic has a Composites Laboratory that wishes to announce itself to the world. In 2007, an experimental design process was started to design a composite glass façade system with the aid of members from the Polytechnic School, the Composites Laboratory (Dr. Michiel Hagenbeek), two professors of the Delft University of Technology (Prof. Dr. Ulrich Knaack and Prof. Dr. Mick Eekhout) and a number of companies (Octatube and Asahi Glass Company) and advisory engineers. A major role was played by the project architect of the new Polytechnic School in Delft, Rijk Rietveld of New York (www.rietveldarchitects.com) who challenged the development team by his very design of the school building, to design an innovative composite glass façade system, as the facades in his design could function as the zero-series of application. However, the architect had 'wild ideas' that, together, posed too many experimental challenges that in the first phase could hardly be met. This experimental process started after the award of a Dutch research grant 'Sia-Raak' to stimulate research at polytechnical schools. The immaterial goal of the approved Sia-Raak research program of INHolland was to promote the use of composites in architecture, and to transfer and adapt the knowledge of these materials by designing a glass-composite façade system. A challenging starting point was: "which knowledge and experience has to be gained to come to applications of composites in glass façades for architecture?"



FIG. 275 Impression of the living composite glass facade (image Rietveld Architects)

Composites offer a combination of durability, freedom to create shapes and high strength and stiffness per unit weight. Over the last 2 decades in architecture particular interest arose for façades without metal window frames. This makes it possible to create highly transparent glass façades, leading to transparent architecture. Material goal of the research program was to develop a façade system with a new combination of glass and composites. The initial idea of the architect was to introduce solid composite rods of 50 mm x 300 mm in between glass panels in half-brick fashion to improve the structural stability of the façade panels and of the façade as a whole. But this suggestion did not prove to be useful for a realistic invention, even after further development. The ambition of the INHolland Sia Raak program was to research the feasibility of glass-composite façade systems. In this process, the transfer and adaptation of knowledge on composites between design and engineering companies, co-makers and knowledge institutions was foreseen. After the initial phase, the target became to develop building concepts, as well as spreading the knowledge, best and bad practices. And to improve the education on composites. Parties involved were INHolland architect Rijk Rietveld, TU Delft, TNO Gluing Institute of TU Delft and Syntens, Octatube Delft, and Asahi Glass Company amongst others. The grant enabled the development team members to brainstorm for a year with changing success to develop a more or less realistic scheme for an integrated composite façade as a compromise between the wishes and capacities of the architect, the Composites Laboratory and the building industry members. During the process, many meetings went by without any leap forward, due to the contradictory demands and wishes of the team

members involved and the general timidity during these brainstorms, caused by the uncertainties of the global experiment. The finale came into sight when the suggestion was seriously drafted on the whiteboard to integrate the supporting and stabilising cables inside the air volume of the double glass units. They were seen as sealed off by a composite framework of four spacers instead of the usual metal spacers. The composite spacers themselves were integrated with composite tubes for the penetration of the composite cables. These composite elements formed the point of invention. This composite glass construction had to be developed intelligently and with care so that from this originally 'wild idea' a solid and trustworthy technical solution could be developed. On behalf of the development team a patent application was filed by INHolland, with the penetration of the cables through the air cavity as its primary invention. The usual and quite linear product development methodology as described in the book 'Methodology for Product Development in Architecture' [Ref. 16.01] showed many loops and feedbacks. The central design concept resulting from the first phase of experimental design was to stack the double glass panels, penetrated by vertical cables spaced at 600 mm carrying the wind load, and with a suspension system of steel rods through the vertical joints between the glass panels.



FIG. 276 The set-up of the experimental façade concept and sketches from brainstorm sessions

The experimental design also contained a large number of small scale prototype tests of the glass panels, the adherence of the sealant to the composite spacers, the air-tightness of tubes and tubular end connections and finally a full scale prototype of a segment of the designed façade application in the new premises: a 6,0 m high and 4,5 m wide façade segment with pre-stressed cables and penetrations of aramid cables through composite spacers in double glass units. The experimental aspects resulting from the first experimental design phase to the prototyping development phase were threefold:

- The insertion of the composite tubes, penetrating trough top and bottom spacers;
- The perforated weakness of the spacers and the overall stiffness of the glass panels;
- The bonding of the silicone and other sealants to the composite and glass surfaces.

Because the carbon tubes around the cables penetrating the spacer are designed to be sealed off air-tight to create an air-tight box of the insulated glass. The architect was attracted to the high tech look of the resulting system and was inclined to compromise many of his further wishes. The second function of the tubes, in a part of the façade, is to transport the deadweight of the façade to the foundation as the tubes would stick out through the insulated glass panels and the deadweight would be transferred by stacking

the glass panels on top of each other. In this way, two functions are integrated in these tubes: holding the cable and dispersing deadweight. It was planned that the dimensions of the tube, cable and spacer are synchronized with extremely small tolerances.
The composite spacers had to be developed such that a real overvalue of the composite spacers over the metal ones would be accomplished. The end of the first experimental design phase was in fact the full size mock-up in the factory of Octatube, on the other side of the street of the actual INHolland building under construction. The mock-up was used for obtaining experience with pre-stressing of the aramid cables and stacking and tolerances of the glass panels.



FIG. 277 Overall view of the mock-up



FIG. 278 Detail of the mock-up

16.03 EXPERIMENTAL ENGINEERING AND PROTOTYPING SECOND PHASE

After the initial design phase in summer 2008, Octatube, up to then one of the design team partners, was asked to make a quotation for the designed system. At that moment, the free brainstorming first phase changed into a potentially dangerous engineering

and prototyping second phase. Now it became really serious, and Octatube took up the challenge. Ultimately, the client expected a fully guaranteed façade system, developed up to a trustworthy level of maturity. The process was now connected with the execution of the building of INHolland as the prime application. The deadline for the opening of the building was anticipated for September 2009, the starting date of the new school year. Wind loading on the façade as a whole was to be accommodated by vertical pre-stressed cables. As these cables are flat and quite in contradiction with the usual engineering practice of stiff structures, the system would work as a linear cable system with no structural depth, acting as a sail as it were. It would have large deflections as a consequence. The structural action of the individual glass panels would be to bend in a polygonal line under wind loading, the glass panels would act as stiff members in a vertical chain. In the detailing, the degree of movement between the glass panels was to be watched carefully, so as not to lead to breakage of any kind in the glass panels. The individual glass panels were regarded as multiple supported against wind force by the continuing cables in horizontal direction. For a long time, the development of the carbon fibre tubes through the panel frames was quite insecure. Hence, at that moment in time it was decided that the deadweight would be transferred through vertical tensile action to the top of the façade, rather than via a downward action to the foundation. This was reached by the introduction of vertical stainless steel suspension rods in between the vertical seams, within the central space to be sealed off from both sides with silicone sealant and hence invisible. Fig. 279 The consequence of stacking these cables was that the vertical seams had to be in line, contrary to the brick-mode proposed by the architect, which was still maintained in the full-size prototype.

The principal of the 13,2 metre high façade is based on a sail. At the horizontal seam, the insulated glass panels have the freedom to rotate slightly under wind loading. The glass panels are tied in vertical direction like a chain around the aramid cable. Horizontal wind loads are transferred by these cables to both ends: the top of the building and the bottom, near the foundation. Under extreme wind conditions, statistically occurring only every 50 years, the façade is supposed to deform max. 330 mm inward and 330 mm outward without any problems. After market investigation, the composite cable was selected. Phillystran HPTG cables with a high modulus elasticity consisting of a yellow aramid fibre core in parallel construction, protected by a black extruded polyethylene jacket. The cables have an excellent resistance against fire and changing loads. The common contemporary applications are bridges, towers and rigging for sailing yachts. The idea was conceived that during installation of the façades the glass panels are temporarily attached to a complete scaffolding on the inside of the building. The feeding of the cables would occur from the top downwards. Pre-stressing and certification of sufficient pre-stress would follow later. By placing the cables in the spacer of the glass the system is, structurally seen, very efficient for the glass panels. Structurally, each glass panel has multiple supports by means of the cables. Therefore deflections and stresses in the glass planes are quite low. Due to safety reasons, all glass panels are not only fully tempered, but laminated from two fully tempered glass panels as well. This system would result in a façade with a super minimal thickness of only 50 mm! Neither outside nor inside of the two glass planes would there be any structure; both sides of the facade were designed to be totally smooth.

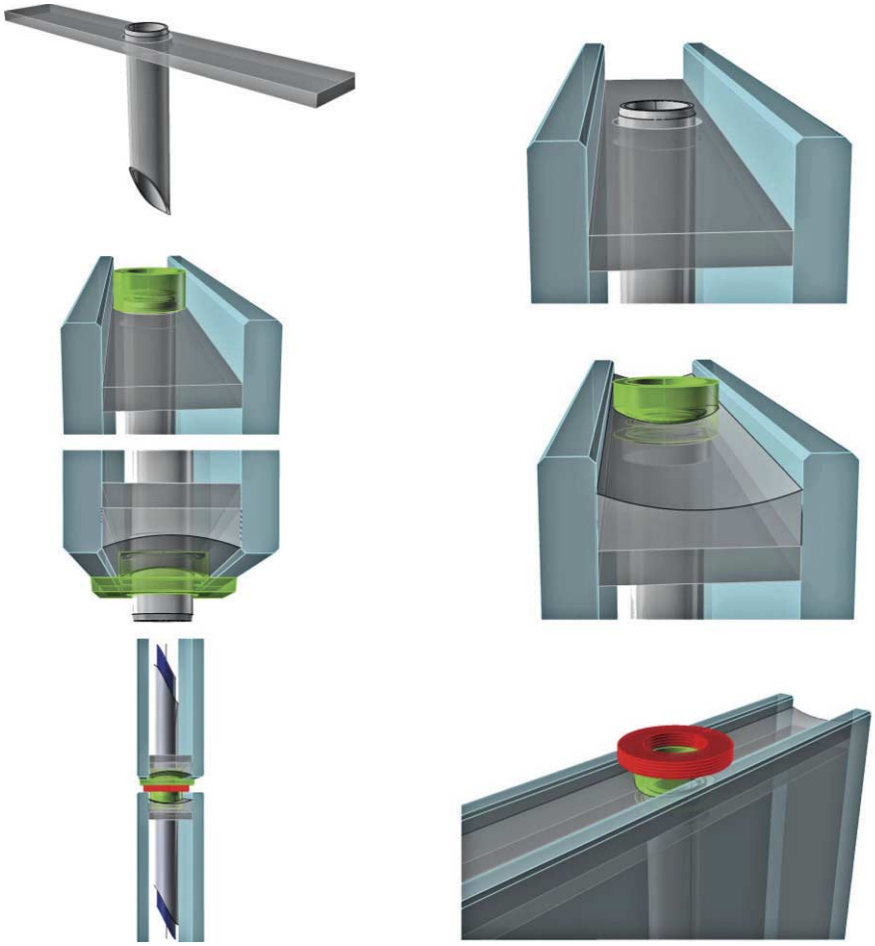

FIG. 279 Engineering set-up of aramid cables inside the double glass panel

16.04 ADDITIONAL TESTING

The velocity of a real construction process is ruthless for experimenting engineers. Every uncertainty has to be tested and tests take time, especially when long term behaviour has to be imitated as well. Often, the obvious choice is to go back to tested and certificated elements and refrain from new and unknown elements in the construction, or in case of selecting new elements to test these and come to a certification level in a short time, testing only individual aspects one after the other. Some hesitation on the part of Asahi

Glass Company (AGC) as the nominated glass panel producer was related to the connection between composite tubes and the metal spacer frame. In practice, AGC was familiar with other examples of composite spacers; however they always had a steel backing for vapour tightness and proper sealing off. The glass producers refrained from using composite spacer frames and went back to metal frames, as the sealing would provide trustworthy air-tightness, and the tests of composite gluing did not appear to be satisfactory for all usual guarantees on the glass panels. The client hesitated as the INHolland Composited Laboratory was not amused at all by this manoeuvre, although it was obvious that further tests were necessary for the certification process, which would make it hard to have the façade ready simultaneously to the actual building process. Prof. Ulrich Knaack TU Delft was asked for a second opinion on the degree of innovation of the proposed façade scheme with metal frames. After having received his positive advice that the proposal of Octatube had a high degree of innovation the client.

INHolland Real Estate department, decided to use the experimental façade system with metal spacers as a launching customer. The atrium consists of three facades. It was agreed in this stage that the two large facades would be executed as proposed by Octatube/ Asahi with the metal spacers, and the third, more narrow façade of only one glass panel wide and 13.2 m high, would be executed with composite spacers as per the original design. The narrow composite façade would demonstrate the innovation possibilities with composites in architecture. The further developments and realization of the two main façade were all executed directly by Octatube, the composite façade was executed under responsibility of the INHolland Composite lab, but produced and built by Octatube as well.

16.05 STRUCTURAL ANALYSIS OF THE REALIZED FAÇADE SYSTEM

The façade is a planar one-way cable system which stabilizes the glass façade through the resistance against deformation of the pre-tensioned cables. The façade system has large service deflections for maximal wind load occurrence. The lateral deformations are necessary for the system to transfer the (wind) loads and are resisted by the tendency of each cable to return to its straight line configuration between supports. The maximum deflection of the façade is L/40 of the facade height. In this project the façade is 13.200 mm high, the deflection is maximally 330 mm, inward and outward. This leads to rotation angles in the horizontal façade seams of approximately 1 degree. This protected the integrity of the glass and sealants and minimized perception by the buildings occupants. A first impression of the forces in the cables of the façade can be determined with a very simple formula. With the wind load, the height of the façade and the maximal allowed deflection, the vertical and horizontal forces can be calculated.

- Wind load effect on deflection of the wall;
- Low force needed for first movement, deformation is necessary to obtain routing of forces, the cables have no bending stiffness;
- Number of elements determines deflection: constraint stiffness, stiffness cables, pre-stressing cable, wind loads. The critical design goal is limiting deflections through adjusting axial stiffness of the cables, and pre-tension;
- This also influences the own frequency of the façade;
- No vortex at the edges so that the wall does not resonate / swing. Relative high preload so that the deformation of the recessed construction does not become too high during wind. Everyday deflections of L/150 = 13200/150. The wall components are (of course) designed to accommodate this movement without compromising wall performance. The cable of aramid has excellent durability qualities;
- The tensioning of the cables must be accomplished with all cables. This requires rigorous methodology frequently involving sophisticated hydraulic jacking gear. Compensating adjustments in the tensioning can be computed and implemented. The trick of the cable structures lies in the tension: first determining appropriate theoretical cable pre-tension with respect to the boundary conditions, then realizing those tensions exactly in the field on site. Any adjustments must be done systematically and not locally;
- In practice, cable structures are remarkably forgiving as they are designed to move. They can deform many times the deflection criteria of conventional steel or aluminium structures without any permanent deformation or failure.

16.06 THIRD PHASE OF PRODUCTIONS AND REALIZATION

Transferring the deadweight to the surrounding structures has been deliberately separated from taking care of the wind loads on the facades. The wind loads were taken over by vertical aramid cables. The deadweight of the separate panels is guided by means of tensile stainless steel rods, in the space between two adjacent double glass panels. The rods are equipped with supporting steps, made of POM, to carry the glass units. The suspension rods and steps are located within the joints of the glass units, to be sealed off later. Gravitational loads are carried by the suspension rods, because it is hard to make mechanical node attachments on aramid cables. The upper structure had to be provided with the proper suspension provisions, which were not present in the main steel structure due to the late decision for the experimental façade. In the concrete foundation structure at the bottom of the glass facades, the usual drillings had to be made, this time in large holes of 300 mm diameter which was complicated because of the heavy reinforcements and the uncertainty about the actual location of reinforcement bars. On the inside of the façade, a complete scaffolding had to be built up with clamps on the outrigging elements, so as to enable temporary purlins to be attached. On these purlins, the individual glass panels are temporarily attached, stabilised against wind loadings, while the deadweight is already

carried by the suspension rods and saddles. The glass panels are positioned in alignment of the vertical and horizontal seams, but even more precise will be the alignment of the tubes, through which the cables are fed. This was the situation of development in spring 2009. In the meantime the reaction forces, not only from the suspension rods, but mainly from the pre-stressed cables had an important stiffening effect on the substructure of the roof, from which the cables were stressed. The substructure had to be redimensioned. The 2 corners of the glass facades presented a further engineering challenge as during wind compression both façade corners would bend inward 330 mm and damage each other. This is the reason why the façade corners were executed in a hollow lens form to allow the inward movement without breakage. Yet these lens-formed openings were to be closed off. This was done in a rounded deformable form and in a rubber sandwich. The two glass planes of the 2 facades can move outward as well as inward, 330 mm from the neutral position. The largest deflection would be in the middle, decreasing towards the top and bottom of the corner. The material is a double rubber membrane with a rubber insulation material as a sandwich in between.

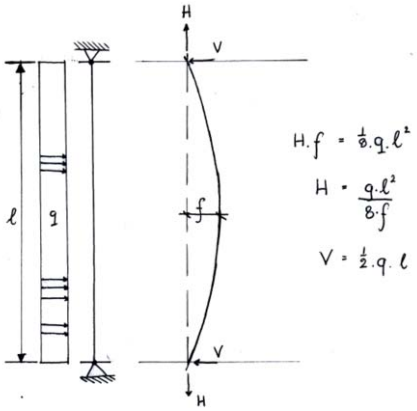

FIG. 280 First determinations with simple formula

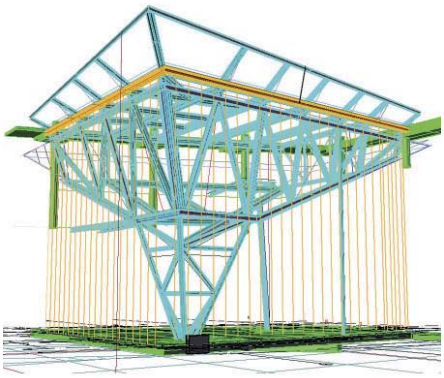

FIG. 281 3D view of overall structure with aramide cables

In this experimental process, production appeared to offer unsuspected problems as well: the glass panel manufacturer had discovered that the tests did not provide satisfactory results as to the air-tightness of the tube-to-frame connections and the air-tightness of the carbon fibre tubes themselves. Asahi would not issue the normal guarantees of the glass panels in this case. This became apparent in the month of May, just before production of the glass units was to begin. This potentiality, however, could easily lead to the necessity of a complete replacement of the entire façade when the insulated glass panels would indeed show air leakages after some time. The replacement had to be done at the cost of the supplier within 10 years and at cost of the client after that date. Both supplier and client saw their own responsibility. During a dramatic week in May 2009, the author took the decision to reposition the cables from the inside of the double glass units to the outside, in the inner space of the building in fact, with the carbon fibre mantle tubes to the inside

of the space, adjacent to the insulated glass panels. So with this engineering manoeuvre, factory guarantees were issued, but the project had again lost one of its innovative potentialities. The client agreed as well. The architect indicated that Octatube would have to develop the system further as he would want to apply the original integrated glass/ cable system in a future building. Other set-backs ware caused by the supplied stainless steel end pieces of the aramid cables that were produced by a yachting supply company in New Zealand. They appeared to have only 60% of the breaking strength compared to the ultimately expected breaking strength. In an ultra short time period, these end pieces had to be re-dimensioned, produced and flown in not to cause essential delays in the crucial construction time, where the work of steel structural engineers, concrete engineers, Octatube erection crew en glass producers collided in the planning.

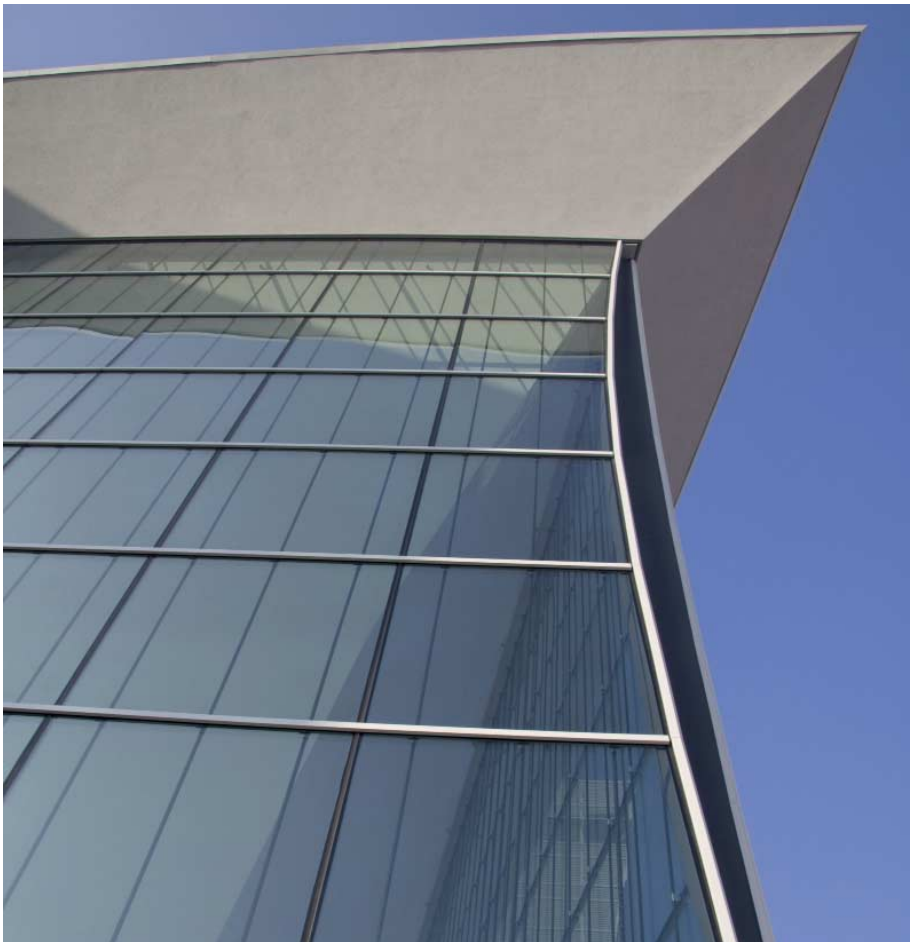

FIG. 282 Detail of the flexible corner

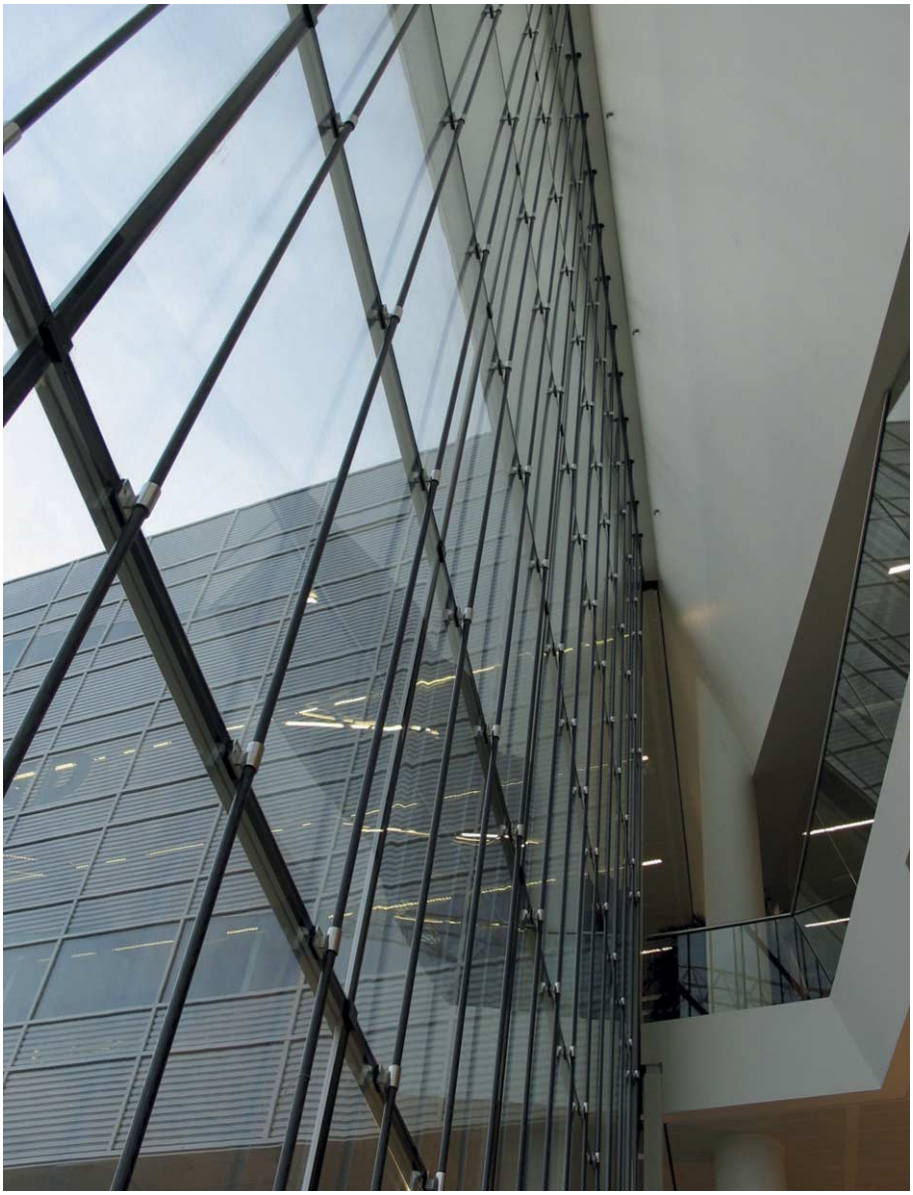

FIG. 283 Detail of the glass structure as realized

16.07 FOURTH PHASE OF PRODUCTION AND REALIZATION OF THE ORIGINAL FAÇADE CONCEPT

The third façade has been executed with the original composite frames, which were produced (cut, glued in the corners and provided with composite tubes) in the Composite Laboratory and on their own responsibility. The solid composite spacers do not have a possibility to contain hydrating material, which usually fills the metal spacers. So separate cylinders of hydrogen are positioned on the bottom spacer with a measuring device to read off the air humidity inside of the double glass panel. The required accuracy of the glass panes versus the composite frames required remounting of the double glass units and re-assembly two times. The onsite installation of the aramid cables through the tubes in the spacers did not cause any unforeseen moments. The engineering of the part of the façade required even more intensive work than that of the two regular facades. This façade, however, provides the most advanced state-of-the-art technology of integrated composite glass façades in the world to date.

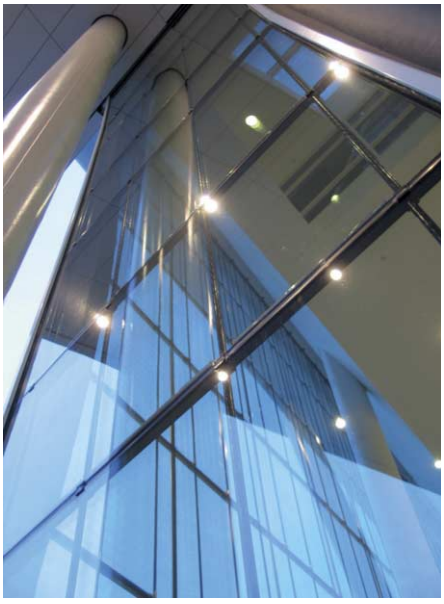

FIG. 284 External view of the original experimental façade part with the internal aramide cables inside the air space

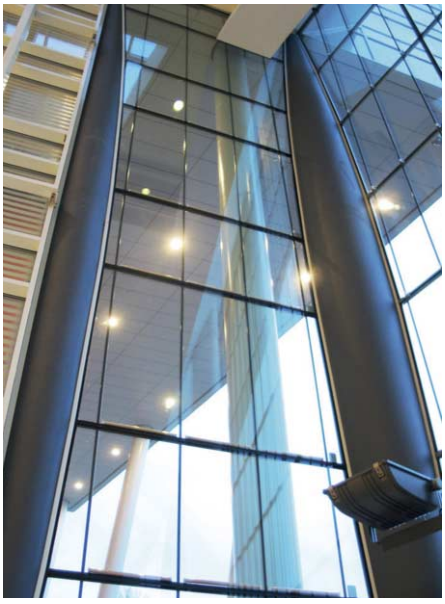

FIG. 285 Internal view

16.08 EXPERIMENTING IN A RUNNING PROJECT

An experimental design and development process is best to be organised separately or preceding an actual application (or: zero-series) construction process. Independent team players who have their own agendas are often hard to integrate in the process. In principle, it is wise never to combine a highly experimental project with a fast running building construction process. It is worthwhile to maintain incremental steps forward in the development of systems. One small step at a time. In the first experimental design phase, progress was slow and many times contradictory, until the stage of the integration of pre-stressed cables with insulated glass panels was reached. After a selection, it finally led to a design with an air-tight system not easy to be executed as all construction details had to be solved within the thickness of the 50 mm insulated glass panel. In the feasibility study it appeared that the chosen composite-glass façade was technically possible in conformity with the process on the market for design facades. A demonstration model of 3,6 by 5,0 metre was realised to explore the production of the insulation glass panels in detail in this early phase. The mock-up did not only give a good overview of the production and assembly aspects for the material suppliers and producers, but also offered other technical information. It is possible to make the façade with very small tolerances of less than 1mm. In the second experimental engineering and prototyping phase, several parts of the concept façade have been developed in more detail and tested in a small parts testing program. Major drivers for the tests were structural behaviour and durability. Most important was the influence of temperature and moisture on the composites in the façade, the always changing loads and above all the production and assembly processes. An unexpected draw-back occurred caused by the composition of the insulated glass panels where the composite frames had to be substituted by conventional metal frames with proven performance and guarantees. The composite frames did need much more testing before they could be applied in practice with the usual guarantees from the producer. The third phase of experimental productions and realizations had two problems. One in engineering and production of the end pieces of the aramid cables. The other, as a result of the testing, was insufficient trust in the performance of the air-tightness of the feeding tubes through the framings of the double glass panels, so that for the two larger facades the cables and tubes were repositioned on the inside of the glass panels.

The fourth phase of the original concept was produced with the original composite frames and tubes at the Composites Laboratory on the basis of which the double glass units were assembled with visual hydrogenous material in cylinders. The stacking of the cables through the panel tubes was executed and the system proved to be laborious. But it worked. This façade is being watched regularly as a part of the Composites Laboratory education program. The developed façade concept, in its entirety, with pre-stressed aramid cables, is characterized by its innovative character on multiple levels. The application of composite materials in this type of façades is exclusive. The total picture is an ultra slender, frame-less façade, with a height of 13.200 mm. This led to a very slender ratio of almost 1:300. But the built façade proves that the original 'wild idea', when properly and seriously developed, can be realised within a few years. This is the convincing force of design.



FIG. 286 Overall view of the two large facades. Clearly visible are the two lens-formed rubber corner fillings. The third façade on the right hand side around the corner, only 3 m wide

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REF. 16.01 Mick Eekhout, *'Methodology for Product Development in Architecture'*, IOS Press, ISBN 978-1-58603-965-3

EPILOGUE



Adriaan Beukers [© Schnepp Renou]

When I started to write the epilogue on Mick Eekhout's monograph 'Innovation in Building Technology' and spelled Eekhut, Eikhout instead of Eekhout, I realised that in his surname (in English translated as: 'Oakwood'), his professional destiny was foreseen. An architect pur sang: 'the master of the building (*arkhi 'chief'* + *tektōn 'builder*), artisan, academic and innovative, transforming building materials into functional morphologies and spaces to protect people at rest or work against all possible nasty environments'.

What resembles excellent architects and aerospace engineers is their use of the lightest materials available for their creations. So designing and building structures with a minimum of material and with maximum performance, whatever that may be. For example, concrete is per unit volume lighter than aluminum, an aerospace material par excellence, it could be even at component level, when structurally well dimensioned for both mechanics and physics. However in the selection of (building) materials, their intermediates and final assemblies, a less known criterion is important and that is the total travel history of structures during a lifetime which determines the acceptable acquisition cost per unit mass (and volume). According to scholars of ancient and contemporary transport there is a universal tariff for transport of goods, which is about 3% of the price of sale. The more precious the good, product or application, the further the transport distance for commercial supply (salt, spices, silk) is accepted. Even in the world of architecture no different rule is observed, think about the one-way transport of Greek marbles and Mediterranean tiles in Roman times, and nowadays, about Russian titanium for cladding of Frank O' Gehry's Bilbao museum and the Dutch composite roof structures for the Moshe Safdie's Rabin Centre in Tel Aviv by Mick Eekhout.

So the one-way transport distance of building materials is an important element in architecture too and the distance of transport is a measure for the intrinsic quality of the materialized design (appearance, functionality and integration of mechanics and

physics). In other words: 'the more valuable the product, the more transport kilometers are accepted and financed'.

Bearing this in mind makes that excellent engineers and architects of advanced structures take the responsibility for the total design, design of the concept, design of the structure and morphology of materials, interactive and inter-disciplinary, so for design in optima forma. Open mindedness and creativity are of course a pre-requisite for a successful international career and statue, like Mick Eekhout shows in his monograph(s). Not limited by one technology like national guild architects, but continuous seeking for new building solutions to bridge gaps. The attractiveness to be an innovative building designer in architecture is the continuity and diversity of projects, continuous R&D by doing and finally by finishing a large number of complex projects, never anonymous.

To the contrary in aerospace a successful career and statue is based on the participation in only a few projects and, when successful in operation, to support them for decades by detailed analysis and optimization, to monitor and proof their durability and viability.

One possibility to escape guilds, who serve a small home market, is to have a honorable position at an academic institution of technology where the continuity of innovation is guaranteed by a never lasting influx of gifted young students educated and formed by 'masters' who disseminate the latest knowledge and skills supported by an active R&D of tools, hardware and concepts (actually Design, Research & Development). Those professional masters are not only visible by publications and citations, but by science based design and engineering, with radical innovations as a result, too. To prove the viability of and to valorize technological innovations it is essential to cherish an infrastructure of workshops and laboratories, both for technological and business development, and manned by staff and students.

Provided that a university is willing to invest in or to maintain such infrastructures for a long period of time the result is an institution, MIT and ETH alike, instead of being a sole graduation factory. Such institutions, self supporting, innovative and vivid and are very attractive for the best international students, PhD's and postdocs due to the high fidelity visibility of successful innovations. The 'Prototype Laboratory' at TU Delft founded by Mick Eekhout, is example as such.

If we lack visionary leaders in technological sciences, in possession of proven and recorded experience and capabilities, or when those scientists are overruled by short-term cost driven managers, we have to rely on entrepreneurial professors who create their own infrastructure and societal responsibility in academia. It is striking that in the Netherlands the top researchers of the (multi) national research institutions and companies, with their fantastic laboratories, do not have a part time position in the (technical) universities and vise versa. In the 1950s this type of cross fertilization was common, probably the disappearance was caused by the same phenomena, a lack of top researchers in the crucial management positions.

In reference and as a reaction to this tendency, visionaries like Mick Eekhout, show that innovative research and business development can be structured and organized by starting an innovative company, in the periphery of the university itself, but in future hopefully participating too. When more (applied) Research & Development and Design & Engineering firms, with roots at the university, emerge. When more clusters of techno-starters go to seed in the Delft Science Park(s), driven and sound by open and smart innovation. Then and there our future technical university members and our real innovators, the talented MSc and PhD students, can flourish, guarantee and revitalize, the original tasks of the technical university, as stated in the following phrase:

'Together with scientists who study the world as it is, engineers and designers have to solve emerging global problems, to create a new world for mankind that never has been'[1].

Adriaan Beukers

[1. A liberate interpretation of a phrase ascribed to the world famous engineer and physicist Theodore Von Kármán]

BIOGRAPHY



Mick Eekhout [© Nadine Maas]

Prof.dr. Mick Eekhout
Born 1950, born in The Hague, The Netherlands.

After high school at the St.Stanislascollege in Delft studied Architecture at TU Delft. Worked as a student at the Institute of Lightweight Structures (IL) of Frei Otto in Stuttgart and at the studio of dr. Renzo Piano in Genova. Graduated in 1973 in the faculty of Architecture TU Delft as a building engineer (Cum Laude). In 1975 the start of architect's office Mick Eekhout, followed in 1978 by the start of Octatube Engineering. 1983 the architect's office was closed and Octatube Space Structures bv / International bv was started, specialized in design & build of membrane structures, space structures, glass facades / roofs, glass fibre reinforced shell structures and cardboard structures. Average 80 staff employed and 50% turnover in export. Worked in his office with Renzo Piano, Frei Otto, Norman Foster, Moshe Sadfdie, Shigeru Ban, Erick van Egeraat, Benthem + Crouwel, Cepezed. In 1986 he founded 'Delft Design', association of TU Delft designers. In 1988 he co-founded 'Booosting', Dutch association for accelerating industrial design and production in architecture. In 1989 he received his PhD degree (cum laude) under prof. Jaap Oosterhof and prof. Moshe Zwarts with the dissertation 'Architecture in Space Structures'. In 1991 he was appointed as the full professor on the Chair of Product Development, faculty of Architecture, TU Delft. Between 1995-1998 and 2003-2008 het was the research nestor at the department of building technology. Between 1999-2002 he was the department head of Building Technology Design. From 1997-2003 he was a member of the Council of Professors at TU Delft advising directly the Rector Magnificus. 2000-2007 he was the chair of the Research Advisory Board Industrial Design Engineering TU Delft. In 2003 he was appointed as a full member of the Royal Academy Science and Arts / KNAW and as a member of the Academy for Technology and Innovation / AcTI (Dutch Academy of engineering). 2005/2007 organized congress Delft Science in Design 1/ 2 on multi-disciplinary Design on TU Delft. Between 2005-2008 he was the Special Professor of Space Structures at Nottingham University. He received Several awards: Kho Liang Ie Award for Industrial Design. 2002 Pioneer's Award University of Surrey, department of Space Structures. Wrote 20 books (methodology, product development, tubular steel structures, glass structures, aluminium)

and over 400 publications. 2007-2009 Assignment to form a Dutch 3TU research umbrella organisation 'Spearhead Building Research' with a Master plan for the Dutch building industry. 2012 he was awarded 'Knight in the Order of the Dutch Lion' by H.M. the Queen Beatrix of the Netherlands. In June 2015 he retired as the full professor and continues to engage in large term research visions.