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Abstract. This paper aims to describe the topic of origami folded plate structures and to design and built a small-scale model of such structure. To do so, firstly the properties of origami, in general, are discussed, then contemporary research of origami structures is described, and at last the concrete model is designed and built. During the work, the model was analysed with software and the process of building was experimentally tested on parts of the structure. The main outcome is a fibre reinforced concrete model of a bridge with a span of approximately 1.5 m, which competed in an international competition of FRC structures in Budapest in June 2019.

1. Introduction

Origami is world-wide spread ancient Japanese art of folding paper. The word comes from the end of the 19th century, but the folding of paper or other materials is much older and was existent all over the world.

There are many different types of modern origami, one of which is called origami tessellations. A tessellation is a collection of figures filling a plane with no gaps or overlaps. The most famous origami tessellation is probably Miura-Ori (see figure 1), this tessellation was invented to fold a solar panel into an aircraft and then to be easily spread once the satellite is deployed in the space. Miura-Ori has one degree of freedom; this means it is developable in one single motion executed by pulling any two parts of the tessellation apart. [1]

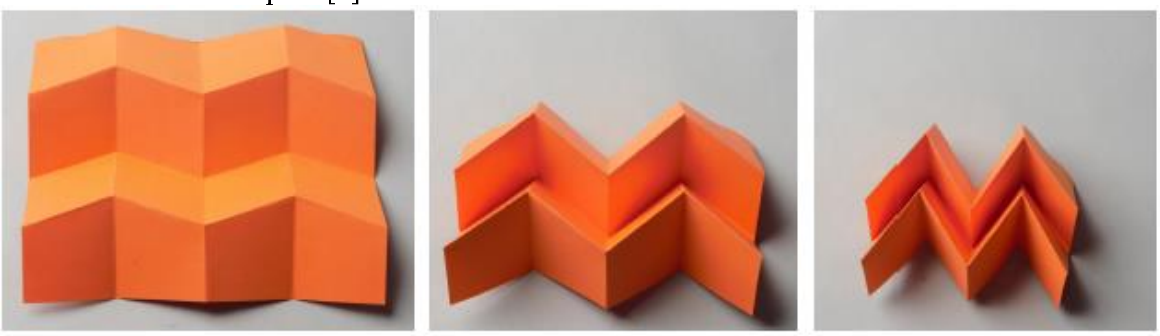

Figure 1. Folding of Miura-Ori tessellation.

Modern technology offers great opportunities for origami structures. Contemporary design techniques supported by CNC milling machines can very easily create formwork from timber panels using non-repetitive, creative shapes. Even though there are not many large concrete origami structures these days, it is clear that the research goes on and origami inspires architecture. In figure 2 you can see two structures inspired by origami; on the left there is Yokohama International Passenger Terminal by Foreign Office Architects built in 2002, using folded steel plates and concrete girders. On the right hand side, you can see wooden pavilion from Osaka built in 2008 by Ryuichi Ashizawi Architects. [2], [3]

Figure 2. Modern origami structures: Yokohama International Passenger Terminal (left) [2] and wooden pavilion in Osaka (right) [3].

Many universities research new ways of fabrication and usage of concrete origami. Among others, Martin Bechtold from Harvard built in 2006 experimental structure by subdividing the structure into pre-fabricated units that are poured flat over a simple formwork. The joint lines are left free when adding the cement matrix, but the mesh reinforcement continues through these joints. This allows the flat system to be later folded into its final three-dimensional shape. The flexible joints are then made rigid by filling them with expansion grout. [4], [5]

At RWTH Aachen University Rostislav Chudoba, Jan Dirk van der Woerd and Josef Hegger developed their concrete origami system. They tested different folding processes, one of them was using a crane and suction cups attached to the origami structure. Another tested possibility was to build the structure flat as before, then hang it upside down to form an arch to let the grout dry in the final position. [6], [7]

The aim of this work is to describe the design and the production technology of the innovative bridge model built at the Department of Concrete Structures and Masonry Structures, Faculty of Civil Engineering, CTU in Prague. The origami model was built for a 4th concrete bridge competition that took place in Budapest, Hungary on 21st June 2019, affiliated with periodical concrete canoe races. The bridge design is governed primarily by the rules of the competition. The critical parameter is the use of only non-rigid reinforcement. [8]

2. Bridge Design and Structure Analysis

The design process started from scratch by exploring origami tessellations that form an arch when folded (see figure 3). For further investigation, the Yoshimura pattern was chosen (figure 3, bottom right) for its simplicity and repetitiveness. This tessellation is flat foldable and developable, made by repeating an isosceles triangle.

The stiffness of the origami arch was analyzed using software Autodesk Fusion 360. Linear analysis of two arches with the same volume was done to compare them; one origami arch with a thickness of 20 mm and the other regular arch with a thickness of 26.5 mm, both with the same span of 4.5m and width of 0.9 m. They were both loaded with its weight only and the deflection in the middle of the span was measured as shown in figure 4. The origami arch deflection is an order of magnitude smaller then deflection of regular arch (0,3 vs 4,2 mm), thus the analysis demonstrates one of the key benefits of origami structures - higher stiffness. (figure 4)

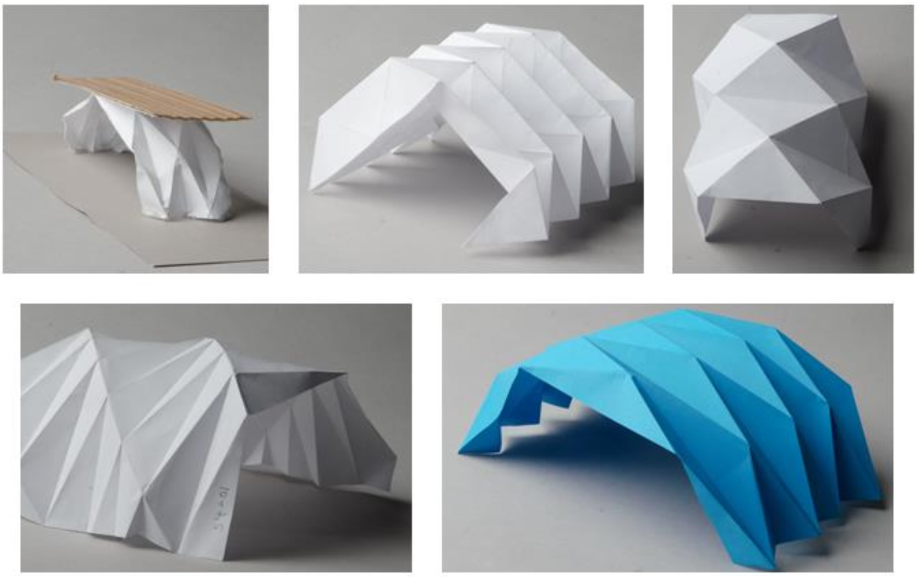

Figure 3. Exploring and searching the shape of the arch.

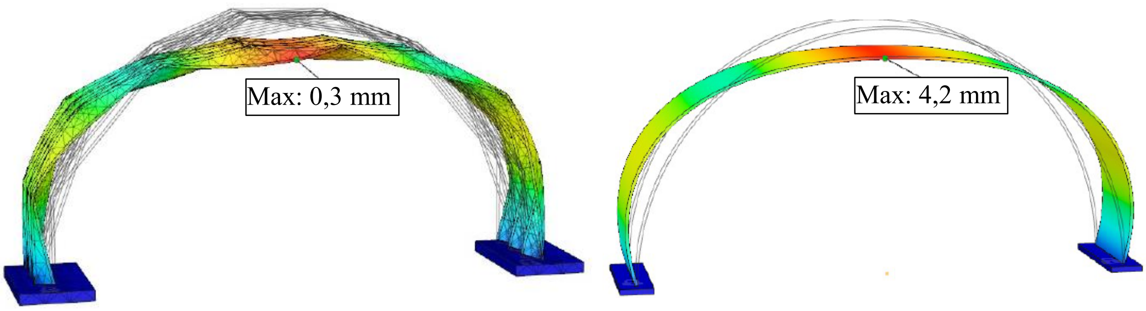

Figure 4. Comparing the stiffness of origami and regular arch using software.

The origami model was built according to the rules of the 4th concrete bridge competition that took place in Budapest [8]. The span is 1.5 m and the thickness of all components is 20 mm. The final design consists of three separated parts highlighted in figure 5 by different colors.

Figure 5. Model of FRC origami bridge.

The design was done in Fusion 360 by Autodesk, because it offers great ways of 3D modelling and also the simulation of static stress is a part of the software, as shown in figures 6 and 7. The model was then loaded in Fusion 360 by gravity and force located in the middle of the span to simulate loading during the competition. It is expected that the load of a 150 kg will cause the failure of the structure.

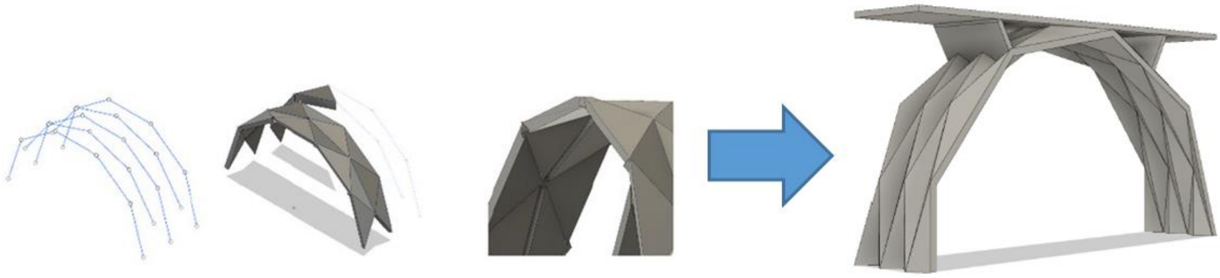

Figure 6. The design process.

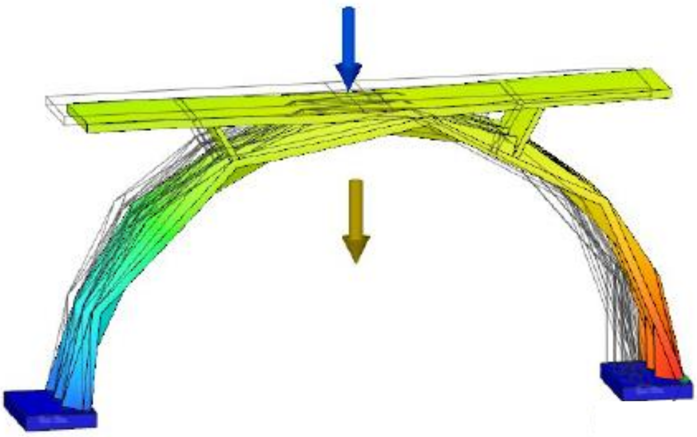

Figure 7. Structure analysis.

3. Realisation Process

3.1. Material properties

The material used to build the model was chosen to comply with the rules of the competition and to enable pouring the thin and curved concrete structure. Fibres of 12 mm length were used - MasterFiber 401 by BASF. The mixture is shown in table 1. The combination of mixture and fibres was successfully used in 2018 during concrete canoe fabrication [9]. The experimentally tested tensile strength of this fibre reinforced concrete is 8.1 MPa.

Table 1. Mixture design

CEM I 42,5 R		600 g
Microsilica		120 g
Lime		150 g
Water		215 g
	0 – 0,25 mm	150 g
Sand	0,25 – 0, mm	550 g
	0,5 – 1 mm	250 g
Plasticiser (Stachema 2000)		30 g
PVA fibres		10 g

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3.2. Formwork and Process of Concreting

The model consists of three parts, each concreted separately. These three parts; the deck of the bridge (30x160 cm), two struts and the origami arch, will be then put together. The arch will be concreted laying on its side, as shown in figure 8. This process was tested to examine whether the mixture can fill such formwork properly.

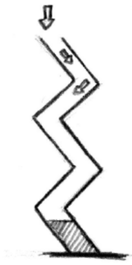

Figure 8. Process of concreting.

The testing was done on 1/9 of the structure of real size. The formwork was created from 4 mm thick plywood and assembled with glue. The process and the final product are shown in figure 9.

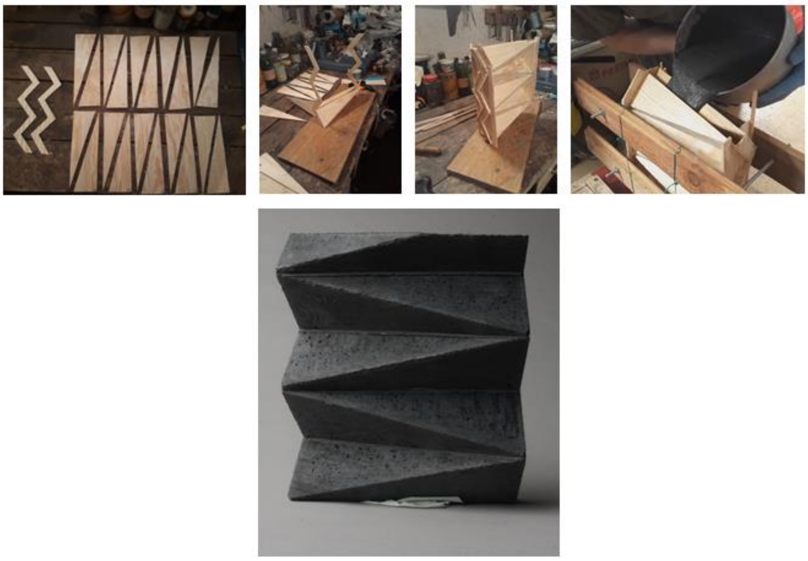

Figure 9. Testing the mixture and the formwork.

The testing was deemed successful, thus next work followed the same path. The outer and the inner parts of the formwork were built using the plywood, both consisting of 50 triangles. The wood was then treated to be suitable for concreting. (see figure 10)

Figure 10. Building the formwork.

The formwork was then fixed on its side and it was concreted by pouring the mixture inside as shown in figure 11.

Figure 11. Concreting the origami arch.

The finished product is visible in figure 12. The arch was successfully built, slightly thicker then designed. The arch weighs 56.5 kg, the whole bridge weighs 79.5 kg, the inner span of the arch is 140 cm and the height is 80 cm.

Figure 12. FRC origami bridge.

4. Destructive test

The finished model took part in international competition in Hungary to represent CTU. As part of the competition a destructive loading test was performed which confirmed the calculated 150 kg maximum load. The bridge model collapsed at 149 kg load.

5. Conclusions and Future Work

This work aimed to describe contemporary research of origami structures and also to build such structure. The process of concreting and the formwork was chosen to fit the needs of the competitive model and it was successfully tested on a smaller part of the structure. 3D modeling and loading simulation of the model were performed. Results of the model were confirmed by a destructive test during an international competition. The FRC origami bridge model was awarded second place overall.

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