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Finite element modelling of different strengthening strategies for reinforced concrete deep beams

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Abstract. The paper is focused on the behavior of deep beams retrofitted with FRP sheets and layers In order to understand the behavior of these beams, and an advanced nonlinear finite element model is used. The nonlinear analyses were performed based on the Modified Compression Field Theory which is a smeared rotating crack approach implemented in program VecTor2. The predictions of the finite element models were compared to the test results in order to validate the models and to further understand the behavior of the test specimens. Finally, the validated model was used to perform parametrical studies to investigate the effect of FRP sheets and UHPFRC layers on the behavior of true-scale deep beams. The variables investigated in a systematic manner included the aspect ratio of the member, the layout of the FRP sheets, the thickness and fiber content of the UHPFRC layers. The results were used to compare the effectiveness of the two retrofitting techniques.

1. Introduction

Reinforced concrete deep beams are important structural elements, which transmit loads from the upper structure to widely spaced lower supporting elements. By definition, such members have small shear-span-to-depth ratios and their behavior is governed by shear. Due to the fact that these beams are used in lower parts of the building for architectural purposes or for shopping areas, their size has to be big enough to support the whole upper structure. In some cases these transfer beams can reach up to 2-3 floors height. In the case of bridges, cap beams create the connection between the deck and the columns. Thus their main role is to concentrate the distributed forces into point ones. Their span can vary from 25 to 150m, depending on the traffic on the bridge, the environmental conditions, etc.
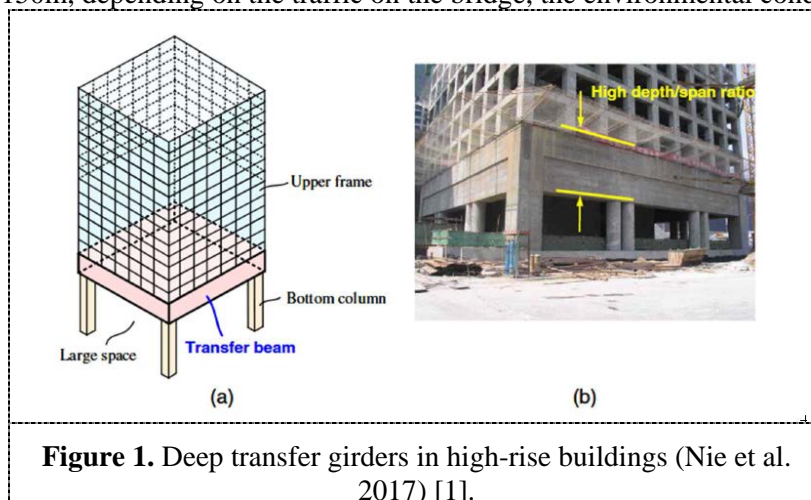

Figure 1. Deep transfer girders in high-rise buildings (Nie et al. 2017) [1].

Because some deep beams have suffered degradation in existing buildings and bridges, Fiber Reinforced Polymer (FRP) or Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) can be used for their retrofit.
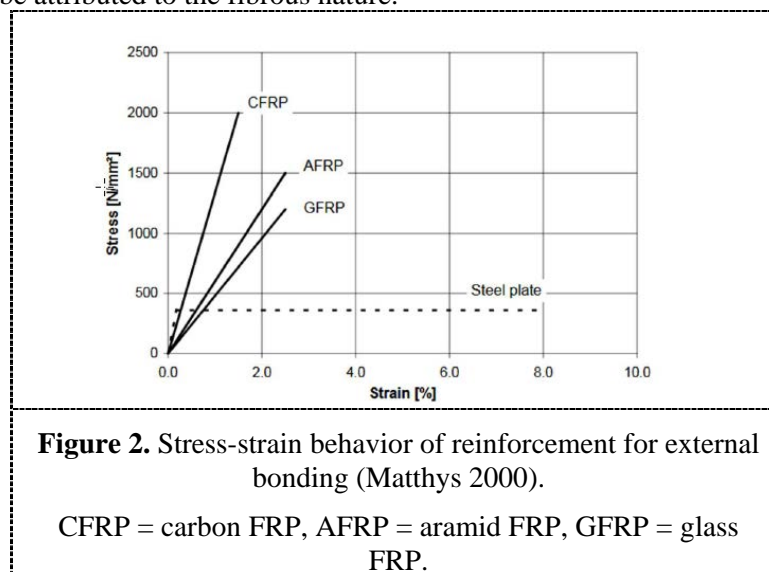
In this article we used an advanced nonlinear finite element model in order to understand the behavior of deep beams retrofitted with FRP sheets and UHPFRC layers and to try to make a comparison between these two solutions. For this purpose, general information about the behavior of FRP and UHPFRC is gathered and summarized. The selected approach for modelling is a smeared rotating crack as formulated in the Modified Compression Field Theory for elements subjected to shear.

2. Strengthening with FRP sheets

FRP strengthening systems have three main components, respectively adhesives, matrices and fibers. Adhesives bind together the concrete and FRP material in order to get a composite action (fib Bulletin no. 14 [8]). Because the load transfer is passing through the adhesive layer also, it is important to have necessary shear and bond strengths. One of the most used adhesives is epoxy, due to the fact that it has great strength characteristics and is commonly found. The key to a successful composite action lies on several preparation aspects. Such preparations are namely adherent materials, mixing temperatures, surface preparations, etc.

Firstly, when the material is transformed into fibrous form, its stiffness and strength is enhanced compared to the bulk form. Also, due to the high length/diameter ratio, the load transfer from the matrix to the fiber is an effective one [8]. This gives FRP composites a high tensile strength. As seen in Figure 2. Carbon FRP-s can have as high as 2000 MPa ultimate strength in tension. It can also be seen, that unlike steel, which has a bilinear response, FRP sheets behave linear elastically. This phenomenon can be attributed to the fibrous nature.

Figure 2. Stress-strain behavior of reinforcement for external bonding (Matthys 2000).

CFRP = carbon FRP, AFRP = aramid FRP, GFRP = glass FRP.

Secondly, due to FRP sheets superior characteristics, the thicknesses of the repairing layers are in the order of few mm. This combination of high strength and low cross sectional area greatly reduce the extra weight added to the structure, and also helps in maintaining aspects which are close to the initial architectural design. On the other hand, due to the thin layers, the material behaves only in tension, having almost zero compressive strength.

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2.1. Advantages and disadvantages of FRP sheets

There are several criteria, when selecting a proper strengthening system, namely the condition in which the structure is, environmental conditions, cost effectiveness being the most important one.

Mathys (2000) compared FRP sheets rehabilitation system with the steel slab bonding one. In the following list are some of the advantages of the FRP sheets:

- Unlike steel, FRP sheets don't need protection against corrosion.
- FRP elements are light weight rehabilitation tools and can be purchased in any kind of dimensions. These factors make them flexible and of easy use. On the contrary, steel plates are heavier, come in predefined dimensions, and when applied in large projects, a proper connection system has to be developed between the plates.
- Since FRP sheets are thinner than steel plates and have a large bond width/thickness ratio, stresses which are produced at the interface of materials are low. Hence in many cases there is no need of mechanical anchorage.
 FRP elements have excellent fatigue behavior.
- Small thickness and lack of mechanical anchorages make FRP sheets aesthetically pleasing. Also different types of finishing layers can be applied.

When comparison of two retrofit systems is made, it is also important to highlight the disadvantages, which for FRP are:

- In comparison to steel, FRP has higher initial cost. CFRP can be at least 6 times more expensive than steel plates. This difference can be reduced by the labour cost and future reparation expenses.
- FRP elements have low transverse strength. This makes FRP sheets more vulnerable to direct impact action. Hence, in some cases, a protective layer has to be added.
- FRP retrofit systems are exposed to high temperatures (e.g. in case of fire), some epoxy resins starting to soften even at low temperatures (45-70°C) [8].

All in all, this shows that there are several factors which have to be taken into consideration, when using FRP sheets as retrofitting systems. As future research is made in order to make the material more accessible for the market, so will its use be seen in more structural retrofitting works.

2.2. Modelling of deep beams strengthened with CFRP sheets

In recent times retrofit actions on old buildings being past their service life became imminent. Especially deep beams suffered damage due to constant loading, degradations due to hars environmental conditions, aging etc. For this, use of novel materials such as Fiber-Reinforced Polymers (FRP) and Ultra High Performance Fiber-Reinforced Concrete (UHPFRC) as possible retrofitting options will be tested.

In order to study the behavior of deep beams strengthened with FRP sheets, several articles concerning the topic were reviewed and test data were collected. One major criteria was to find experimental studies, which focused on deep beams that is beams with shear-span-to-depth ratios a/d smaller or equal to 2. This way a proper shear failure could develop in the samples prior to flexural failure. Another criteria was to find tests, which had samples large enough for the size of them not the affect the outcome of the results. An experimental study was selected, namely Bukhari et al. (2013) [2].

In this experimental program the main focus was on the behavior of different CFRP configurations applied to short beams, which were designed to fail in shear. For this cause the beams were reinforced only with longitudinal bars, adding no shear reinforcement. The same type of CFRP sheets were used for all the test specimens (there were to groups, A and B, where group A had CFRP sheets over the whole height of the beam, while group B was covered only half of the height). Each beam was tested under a symmetrical three-point loading and the deflection was measured at mid-span and at supports. The geometrical properties are presented in Figure 3.

Figure 4 shows the finite element model (FEM) of beam C-3 built in program VecTor2. As one can see, the beam is defined as a simply supported one, having a pin support on the left side and a roller on the right. The load was applied as displacements uniformly distributed on the top steel plate in order to capture the post-peak behavior of the beam. Steel plates (material C) were placed in both support and load points.
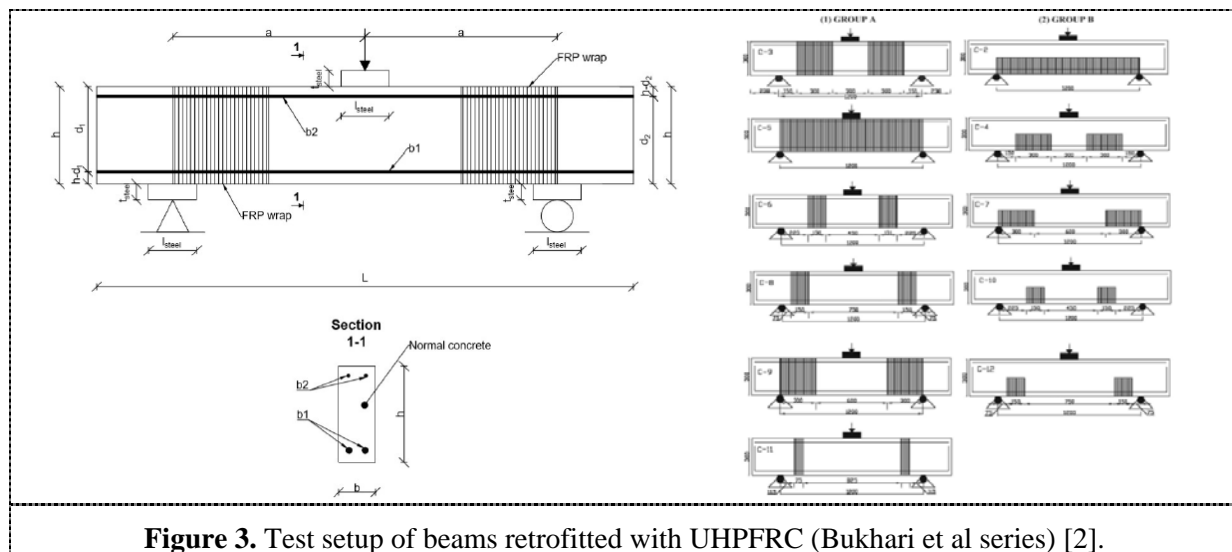
Figure 3. Test setup of beams retrofitted with UHPFRC (Bukhari et al series) [2].

The FEM consists of two types of finite elements: quadrilateral elements, used for the modelling of concrete and steel plates, and truss elements used for the longitudinal reinforcement. A perfect bond is defined between the longitudinal reinforcement and the surrounding concrete, as well as between the concrete and retrofitting material. The mesh size used in the model for the quadrilateral elements is of 15x15 mm, to avoid unrealistically stiff behavior. Because the FE program works in a 2D, with principal axes X and Y, the thickness of the element is given as property.
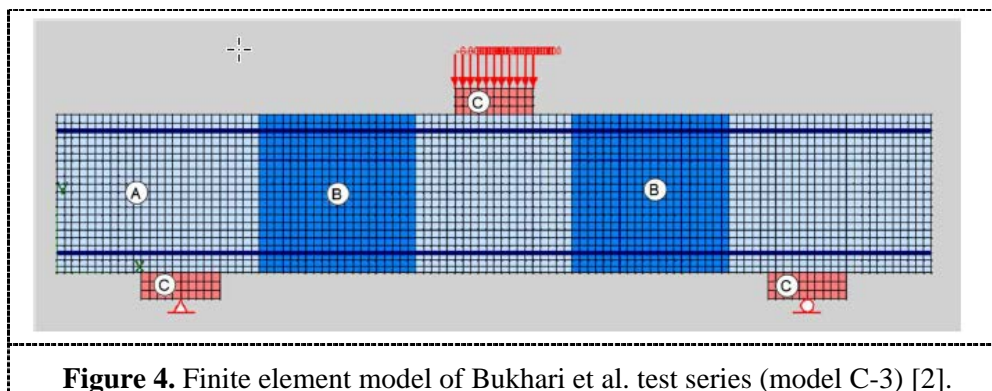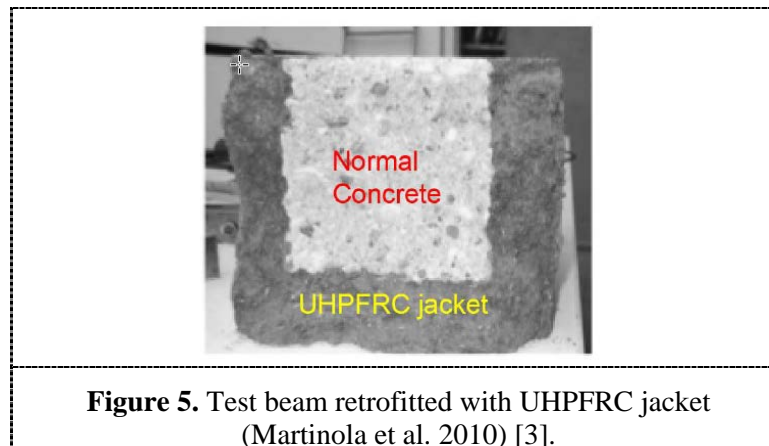

Figure 4. Finite element model of Bukhari et al. test series (model C-3) [2].

The test specimens from the two distinct groups showed different behavior which was captured with different accuracy by the finite element models. Group A, where the FRP sheets was applied on the whole height of the beam, showed better agreement between experiment and prediction results.

3. Strengthening with Ultra High Performance Fiber-Reinforced Concrete (UHPFRC)
When talking about ultra-high performance materials, UHPFRC is one of the major subjects. This novel material is composed of two main components, namely matrix and fibers. In the term matrix are included all the components of the matrix, such as cement, water, aggregates, additives, etc. Fibers are mixed in discontinuous and randomly oriented ways inside the matrix. They are mainly made of steel, carbon or glass. These two components are connected by bonding, hence one major characteristic of UHPFRC is its bond strength.
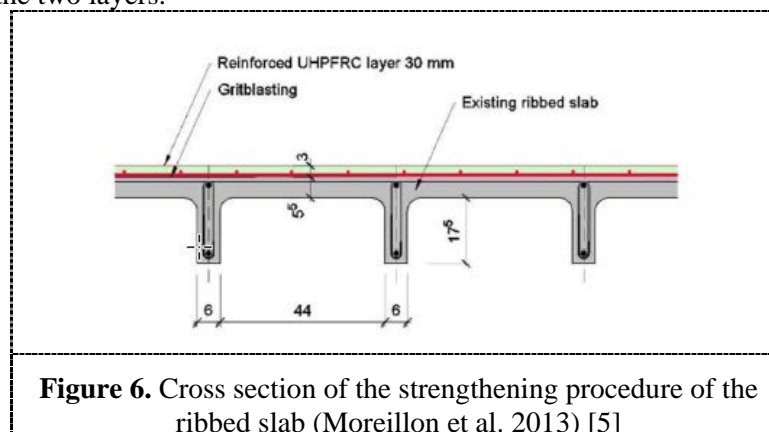In Figure 5 a test beam retrofitted with UHPFRC transversal section is presented.

Figure 5. Test beam retrofitted with UHPFRC jacket
(Martinola et al. 2010) [3].

3.1. UHPFRC jacket applications in retrofitting

Due to its superior strength and durability, UHPFRC is used more and more in retrofitting old RC and steel structures. Since the early 2000s it was a preferential choice in projects such as rehabilitation of bridges, buildings, maritime signalization structures etc.

An example is a building from GENEVA (Moreillon et al. 2013), erected in the 1920s, and has a RC slab supported by masonry wall type of setup. Due to requirements for higher load bearing capacity, its retrofit was imminent. UHPFRC layer of 30 mm with passive reinforcement was proposed as a retrofit design. This approach was selected due to reduced construction time, only small increase in dead load and the ability to neglect foundation strengthening. The connection between the old slab and the new UHPFRC layer is realized through Gritblasting, as seen in figure 6, thus the roughened surface connects the two layers.

Figure 6. Cross section of the strengthening procedure of the
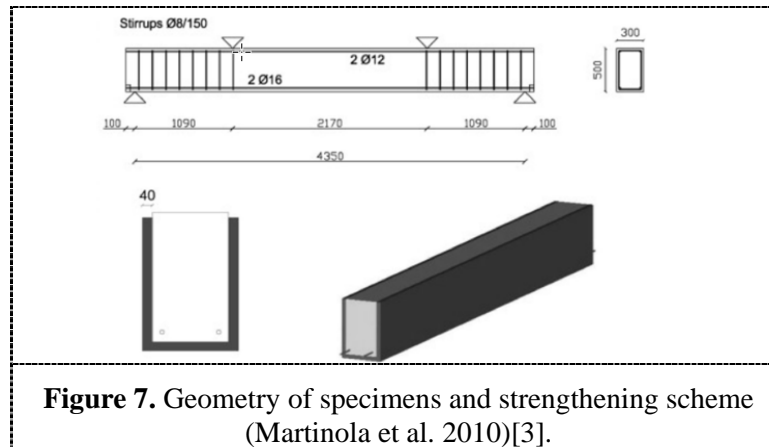ribbed slab (Moreillon et al. 2013) [5]

3.2. Modelling of deep beams strengthened with UHPCFRC

Another experimental program (Martinola et al. 2010) [3] was taken from the literature to investigate the effect of UHPFRC strengthening on full scale reinforced concrete beams.
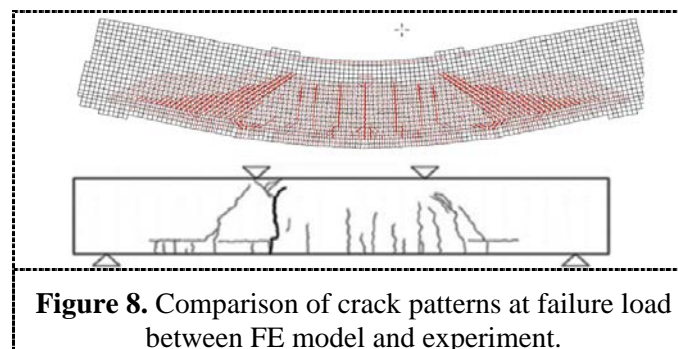
One beam with reinforcement was used as reference, while the other two were retrofitted with 40mm thick UHPFRC layers on bottom and side faces. In order to create an adequate bond strength between reinforced concrete and strengthening material, the beams were sandblasted prior to application of UHPFRC jackets. The jackets were applied directly to the beams, without vibration. Curing of test specimens was carried out at ambient temperature and humidity.

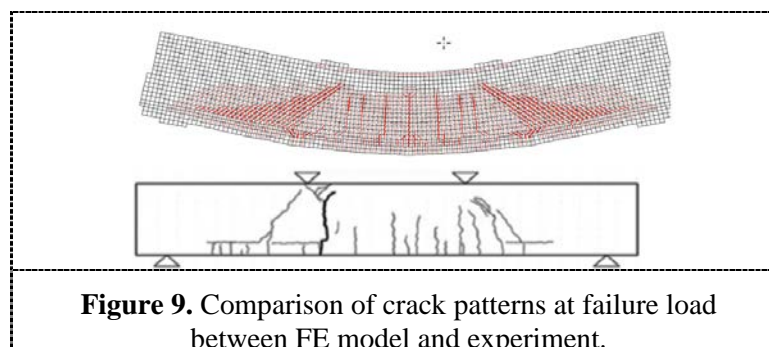Also, as in the first case, a finite element model was made, also built in program VecTor2.

It can be observed that in the FEM the critical crack is located in the middle of the beam, while in the in the experiment it was located near the left load point. This can happen due to material imperfections or localization of stresses in the reinforcement.

Figure 7. Geometry of specimens and strengthening scheme
(Martinola et al. 2010)[3].

Nevertheless several similarities can also be noticed, such as the multiple vertical cracks between the two loading points, or the existence of cracks at 45° between loading plates and supports. One can identify the horizontal cracks at the level of longitudinal reinforcements, which indicate shear failure.
In Figure 8 the crack patterns of FEM and experiment are presented and analyzed. For FEM the thin red lines represent the cracks in the finite elements, where the line thickness is indicative of the crack width. In FEM the FRP sheets prevented shear cracks and made the reinforcement yield, thus flexural failure was achieved. In case of experiment though flexural and shear cracks appeared at the same time, due to the cause of delamination of FRP sheets. Still the behavior of the prediction and experiment were in good accordance.

Figure 8. Comparison of crack patterns at failure load
between FE model and experiment.

As shown in Figure 9, the predicted crack patterns of the beam are compared to the measured pattern at failure.

Figure 9. Comparison of crack patterns at failure load
between FE model and experiment.

The FEM captures very well the behavior of the experimental beam at failure load. In both cases the critical crack appears next to the left loading point. It indicates flexural failure with localization of stresses. This observation is attested by the FEM, where the longitudinal reinforcement yields at the given moment and the fibers are pulled out of the UHPFRC layer. Also the smaller cracks appearing between the loading points in the experiment are well predicted by the FEM.

4. Effect of FRP and UHPFRC retrofit beams

In order to study the effect of FRP and UHPFRC retrofit on deep beams, a parametric study was carried out. Two parameters were studied in the case of FRP retrofit, namely span-to-depth ratio and FRP wrap configuration. For UHPFRC three variables were defined, namely span to-depth ratio, fiber volume ratio and layer thickness.

Figure 10 shows the geometrical properties of the beams from the parametric study. As one can see, some parameters are defined as variable, as follows: shear span a= 1900mm, 3800mm or 5700mm; L= 4800mm, 8600mm or 12400mm; and n x FRP wrap which represents the number of FRP wraps on a beam. This varies from beam to beam, having configurations of width/spacing of 100mm/100mm, 100mm/200mm, and 100mm/300mm or fully wrapped for each span-to-depth ratio case.
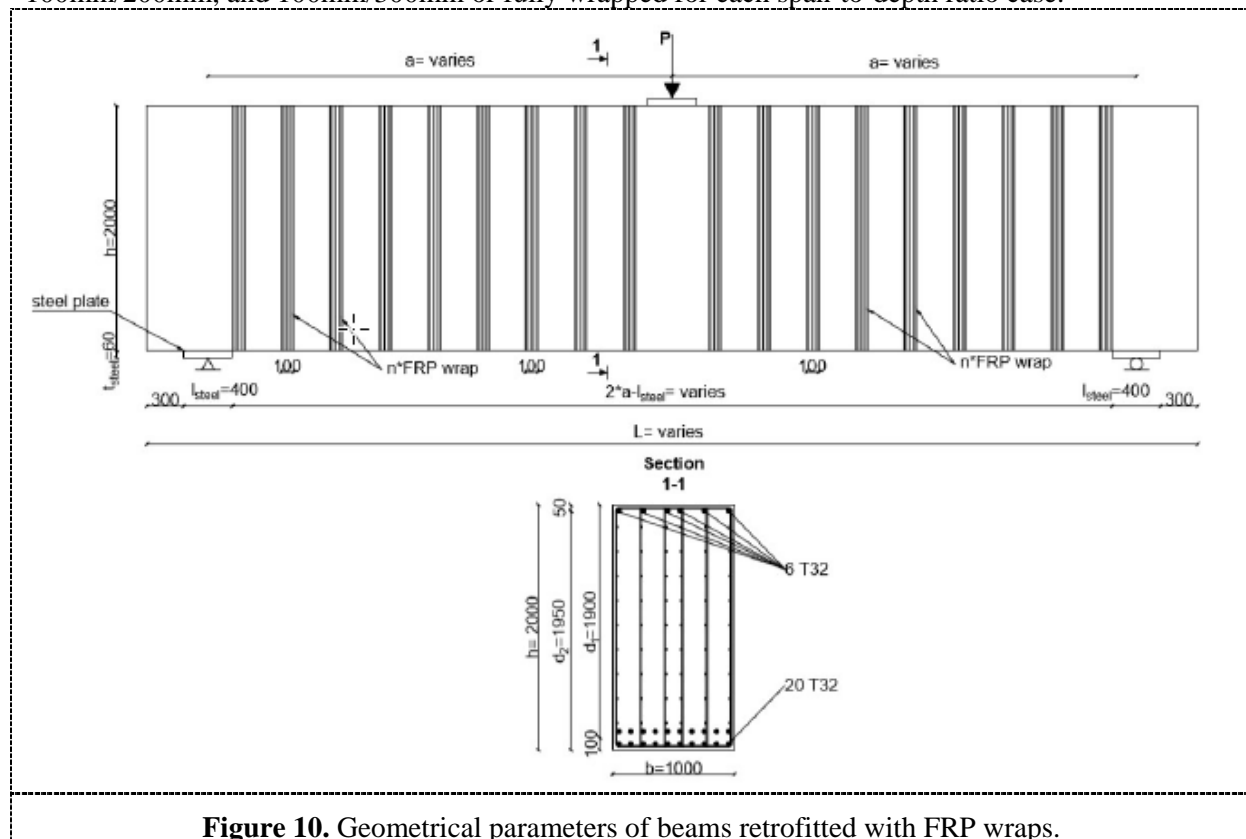

Figure 10. Geometrical parameters of beams retrofitted with FRP wraps.

4.1. UHPFRC retrofitted beam

Figure 11 shows the geometrical properties of beams from the parametric study. As one can see, some parameters are defined as variable. For these the values are as follows: shear span a= 1900mm, 3800mm or 5700mm, L= 4800mm, 8600mm or 12400mm,UHPFRC layer thickness UHPFRC= 50mm or 100mm; A final parameter, namely the fiber volume ratio has the given values Vf= 1, 2 or 3%.
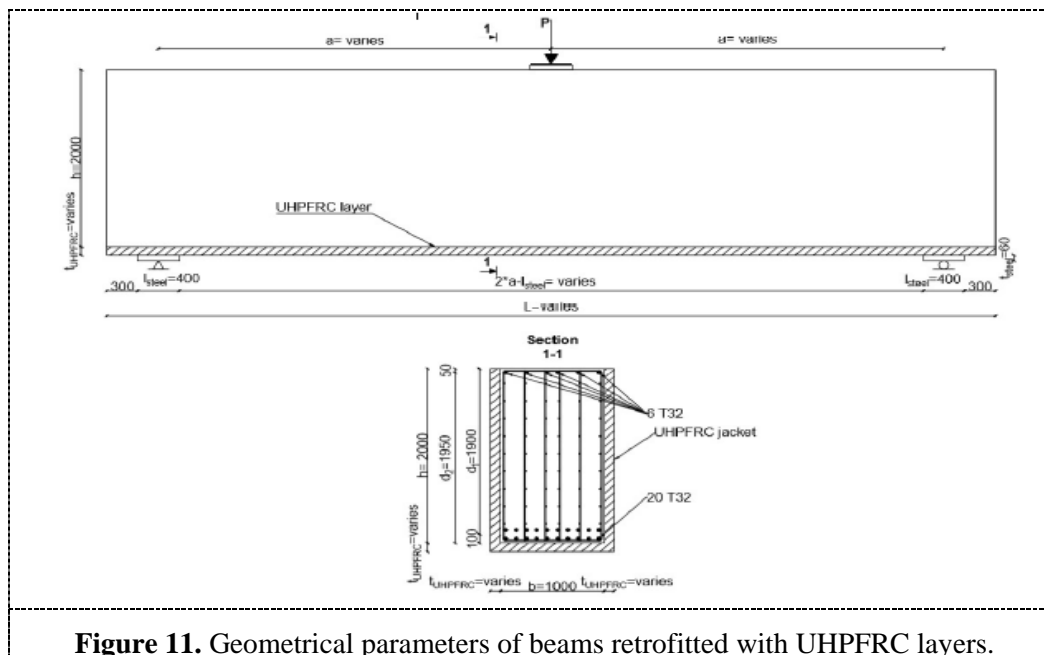
Figure 11. Geometrical parameters of beams retrofitted with UHPFRC layers.

5. Finite element models for retrofitted beams

In Figure 12 one can see the finite element model of beam FRPB-2-pw-100-200 built in program VecTor2 as Figure 13 shows the finite element model of beam UHPFRCB-2-100-1 built in the same program.

The first one has a span-to-depth ratio equal to two, and is wrapped with FRP strips of 100mm width with spacing of 200mm between them. The experimental specimens were modelled as half-beams, thus compilation time was greatly reduced. One roller was positioned at the end of the beam, while several others were installed in the place where the middle of the beam is in reality. Thus the whole system acts like a simple supported beam, and continuity of beam in the middle is not compromised. Several displacements of 100 mm were placed on the loading plate at the top of the beam in order to capture the post-peak behavior of the beam. Steel plates were placed over the support and under the load to prevent concrete crushing.
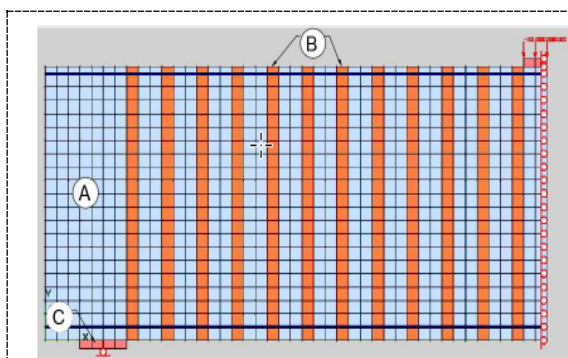

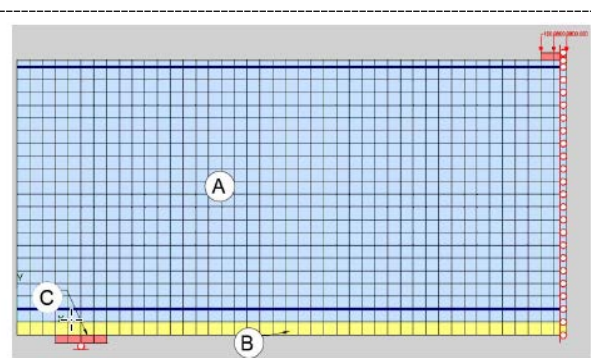**Figure 12.** Finite element model of beam FRPB-2.

Figure 13. Finite element model of beam UHPFRCB-2.

6. Results

Best retrofit methods from both FRP and UHPFRC are taken and compared. Nevertheless what can be noticed is a loss of ductility of beams, as retrofit methods are applied. All retrofitted specimens reach

failure load at less deflection than the control specimen. Same remarks can be made about FRP whole wrap retrofit and 50mm thick UHPFRC jacket retrofit as before, with the difference being the not so effective increase of strength with respect to control beam.This is caused by longitudinal reinforcement yielding prior to full exploitation of FRP and UHPFRC retrofits.

Figure 14 shows the load-deflection curves of FRP and UHPFRC retrofit for deep beams (a/d=1). For this analysis the best retrofit methods from both FRP and UHPFRC are taken and compared. As mentioned before, both retrofit methods increase stiffness of beams up to failure load. It is very important to notice how FRP whole wrap retrofit and 50mm thick UHPFRC jacket retrofit have almost identical curves prior to load failure. This shows that on one hand for the presented parametric study UHPFRC retrofitting does not cause loss of ductility of element, and on second hand FRP retrofit can be as effective as UHPFRC if applied on whole surface of the beam. As it can be seen, 100mm thick UHPFRC jacket retrofit has the greatest impact on both stiffness and load capacity of beams. Neither in this case can a loss of ductility be observed.

In Figure 15 the load-deflection curves of FRP and UHPFRC retrofit for medium beams (a/d=2) are presented. As before, best retrofit methods from both FRP and UHPFRC are taken and compared. In case of beams with a/d=2 the same remarks can be said as before. Nevertheless what can be noticed is a loss of ductility of beams, as retrofit methods are applied. All retrofitted specimens reach failure load at less deflection than the control specimen. Same remarks can be made about FRP whole wrap retrofit and 50mm thick UHPFRC jacket retrofit as before, with the difference being the not so effective increase of strength with respect to control beam. As mentioned before, this is caused by longitudinal reinforcement yielding prior to full exploitation of FRP and UHPFRC retrofits.
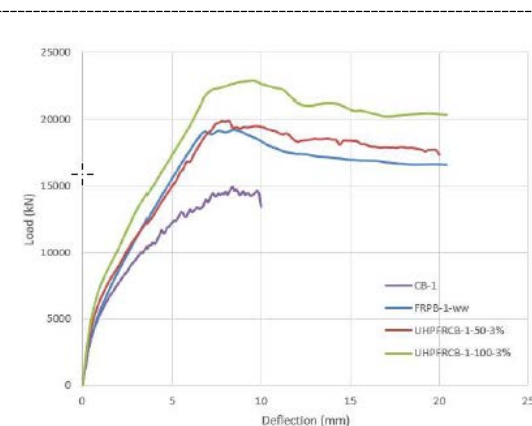

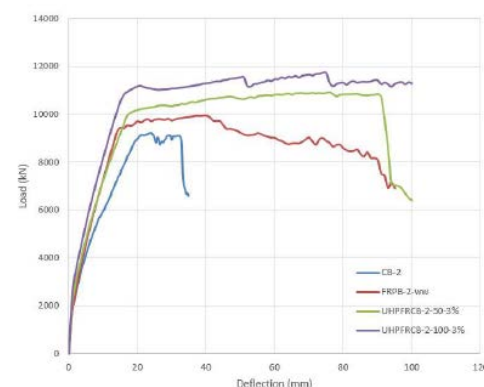**Figure 14.** Load-deflection curves of FRP and UHPFRC Retrofit for deep beams (a/d=1).

Figure 15. Load-deflection curves of FRP and UHPFRC retrofit for medium beams (a/d=2).

7. Conclusions

A number of tests were collected and studied in order to understand the effect of the test variables. The predictions of the finite element models were compared to the test results in order to validate the models and to further understand the behavior of the test specimens.

Finally, the validated model was used to perform parametrical studies to investigate the effect of FRP sheets and UHPFRC layers on the behavior of true-scale deep beams. The variables investigated in a systematic manner included the aspect ratio of the member, the layout of the FRP sheets, the thickness and fiber content of the UHPFRC layers, and the results were used to compare the effectiveness of the two retrofitting techniques. Based on these investigations we can assume that the finite element model based on the Modified Compression Field Theory captures well the complete behavior of FRP-retrofitted deep beams tested in the structural laboratory. Exceptions to this observation were the beams in which the FRP sheets were not applied to the entire depth of the section and exhibited early

deboning. It was shown that early deboning can be estimated reasonably well by imposing a limit on the strains in FRP sheets.

The nonlinear analyses were terminated when the strain reached the limit value recommended in American design code ACI 440.2R-08. As UHPFRC-retrofitted test specimens did not exhibit delamination of the UHPFRC layers, the nonlinear finite element model captured well the behavior of all studied deep beams. This included agreement in terms of load-deflection response, crack patterns and failure modes. It was however noted the models produced slightly higher stiffness that observed. The parametric study demonstrated that both FRP and UHPFRC retrofitting strategies have beneficial effect on the shear strengths of deep beams. Strength increase of up to 30% in case of FRP-retrofitting strategy was observed, while for UHPFRC-retrofitting strategy the value was 53%. A favourable effect in terms of ductility was observed when the UHPFRC layers changed the failure mode from shear to flexural.

8. References

[1]   Nie J G, Pan W H, Tao M X, Zhu Y Z 2017 Experimental and numerical investigations of composite frames with innovative composite transfer beams, *J. Struct. Eng*. 143

[2]   Bukhari I A, Vollum R, Ahmad S, Sagaseta J 2013 Shear Strengthening of Short Span Reinforced Concrete Beams with CFRP Sheets, *Arab J Sci Eng*

[3]   Martinola G, Meda A, Plizzari G A, Rinaldi Z 2010 Strengthening and repair of RC beams with fiber reinforced concrete, *Journal Cement & Concrete Composites*

[4]   ACI Committee 440 2008 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, American Concrete Institute, Farmington Hills, MI

[5]   Moreillon L, Menetrey P 2013 Rehabilitation and strengthening of existing RC structures with UHPFRC: various applications", AFGC-ACI-fib-RILEM Int. Symposium on Ultra-High-Performance Fibre-Reinforced Concrete, Marseille, France

[6]   Gergely V 2017 Finite Element Modelling of Different Strengthening Strategies for Reinforced Concrete Deep Beams, Disertation thesis, Universite de Liege, Faculty of Applied Sciences

[7]   Da Silva W R L, Svec O, Thrane L N, Pade C 2017 Effect of fibre orientation on the tensile strength of ultra-high performance steel fibre-reinforced self-compacting concrete, AFGC-ACI-fib-RILEM Int. Symposium on Ultra-High-Performance Fibre-Reinforced Concrete, Montpellier, France

[8]   fib Task-group 9.3 2001 Externally Bonded FRP Reinforcement for RC Structures, International Federation for Structural Concrete, fib Bulletin 14, pp 1-138

[9]   European Committee for Standardization EN 1992-1-1 Eurocode 2 2004 Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings", CEN, Brussels

[10]   Constantinescu H, Gherman O, Negrutiu C, Sosa I P 2014 Mechanical Properties of Hardened High Strength Concrete, 8th International Conference Interdisciplinarity in Engineering, INTER-ENG 2014, 9-10 October 2014, Tirgu-Mures, Romania

[11]   Negrutiu C, Sosa I P, Constantinescu H, Heghes B 2014 Crack Analysis of Reinforced High Strength Concrete Elements in Simulated Aggressive Environments, 8th International Conference Interdisciplinarity in Engineering, INTER-ENG 2014, 9-10 October 2014, Tirgu-Mures, Romania (ISI Proceedings)