Ultra high performance fiber reinforced concrete as strengthening material

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ULTRA HIGH PERFORMANCE FIBER REINFORCED CONCRETE AS STRENGTHENING MATERIAL

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ABSTRACT

The safety of structures is of high importance affecting people's lives. Structural evaluation, and possibly intervention, is considered necessary for old structures, structures which have been affected by accidental actions and also for structures in high seismic risk areas. Research should now focus on the development of new sustainable techniques that increase the safety of existing structures, and at the same time minimize the necessary to build new structures and to consume new materials and resources. The present research investigates the effectiveness of an advanced material, such as Ultra High Performance Fiber Reinforced Concrete (UHPFRC), for the strengthening of existing Reinforced Concrete (RC) structures. For this reason, an extensive experimental study on the properties of the material and the application for strengthening of RC members has been conducted. More specifically, parameters such the effect of fiber content on the performance, the workability and the cost of the material have been investigated. Based on the analysis, an optimum mixture design has been selected and applied for strengthening of RC beams using different configurations. The results indicated that the strengthening with UHPFRC is a well promising technique and the performance of the strengthened elements was increased in all the examined cases.

1. INTRODUCTION

Most of the new Reinforced Concrete (RC) structures which are built nowadays meet the criteria for safe building design. However, we cannot claim the same for structures were built in the past. Most of these structures have been designed without any regulations, or based on codes which have been proved to be deficient. Safety of structures also concerns structures which have been affected by accidental actions, while it is also very important issue in high seismic risk areas. Research should now focus on the development of new sustainable techniques for the strengthening of these structures, in order to increase their safety, and at the same time, to minimize the necessary to build new structures and to consume new materials and resources.

Existing techniques present crucial disadvantages which are related to parameters such as; the ease of preparation and application, the high cost, the total time taken to be applied and the disturbance on the occupancy. Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a material which is characterized by enhanced properties in tension and compression and high energy absorption in the post-cracking state. The unique properties of UHPFRC make the application of the material attractive for strengthening of existing RC structures. The present research investigates the application of UHPFRC as strengthening material. The advantages of the application of this material for strengthening purposes are related to the high properties of the material, the durability, and also to the ease of preparation of the material. Also, thin elements with high strength can be constructed.

The properties of UHPFRC have been investigated in a number of studies. Nicolaides et al. (2015), presented an experimental work which was focused on the development of Ultra High Performance Cementitious Composites locally available in Cyprus. In this study, different parameters that can affect the strength and the workability of UHPFRC have been investigated and an optimum mixture design was proposed. Paschalis and Lampropoulos (2017), investigated the tensile characteristics of UHPFRP for different curing regimes and different fiber contents. Based on the results, different stress-strain models for the different fiber contents were proposed, while an optimum curing period for the UHPFRC was suggested. The importance of fiber distribution on the performance of UHPFRC was highlighted by Ferrara et al. (2011), while the performance of UHPFRC under cyclic loading has been investigated by Paschalis and Lampropoulos (2016).

There are only limited studies on the investigation of the performance of UHPFRP as repair or strengthening material. Habel et al. (2006), presented an analytical investigation of the performance of composite UHPFRC-concrete elements under the assumption of perfect bonding between the old and the new elements, while a numerical study which investigates the structural performance of beams strengthened with UHPFRC layers was presented by Lampropoulos et al. (2016). Paschalis et al. (2018), presented a novel investigation on the interface characteristics between UHPFRC and RC.

The present study aims to investigate the application of UHPFRC as strengthening material and to give to the scientific community and practitioners useful information for the design of the technique. The first part of the present research is focused on the UHPFRC and the investigation of parameters which should be taken into consideration for the preparation of the material. A crucial decision for the design of UHPFRC is the amount of fibers. For this reason, the properties of material in tension and compression have been investigated for different fiber contents, and parameters such as the workability and the cost have been analysed. Based on the results, an optimum mixture has been selected and applied for the strengthening of full scale RC beam using different configurations. In this investigation, novel parameters such as the connection between UHPFRC and RC have been investigated and a comparison with the proposed values in the literature review for concrete to concrete interfaces is presented. Finally, the effectiveness of each configuration has been evacuated.

2. INVESTIGTION OF UHPFRC PROPERTIES FOR DIFFERENT FIBER CONTENTS

An important parameter which should be taken into consideration for the preparation of UHPFRC is amount of fibers in the mix. Different fiber contents may have effect on the mechanical properties of the material, the workability and the cost. For this reason, in the present section the properties and the workability of UHPFRC for the different fiber contents have been investigated. Additionally, a cost analysis of the material for the different fiber contents is presented. Based on the results of the present investigation, an optimum mixture for the UHPFRC will be selected and will be applied for the strengthening of RC beams using UHPFRC layers.

2.1 Preparation of the specimens

In the present investigation 5 different fiber contents have been examined, namely; 1 Vol.-%, 2 Vol.-%, 3 Vol.-%,, 4 Vol.-%, and 6 Vol.-%. Cube specimens, with side lengths of 100 mm, have been prepared for the investigation of the compressive strength of the material and dog bone specimens have been prepared for the investigation of the tensile characteristics.

For the preparation of UHPFRC, silica sand with a maximum particle size of 500 μm was used together with silica fume and Ground Granulated Blast Furnace Slag (GGBS). Additionally, straight steel fibers with a length of 13 mm, a diameter of 0.16 mm and a tensile strength of 3000 MPa have been incorporated in the mix. In Table 1, the mixture design for the preparation of UHPFRC is presented.

Table 1 Mixture Design of UHPFRC

Material	**Mixture proportions (kg/m^3)**				
Cement	620				
GGBS	434				
Silica fume	140				
Silica Sand	1051				
Superplasticizer	59				
Water	185				
Mixture	U1	U2	U3	U4	U6
Steel fibers	78.5 (1 Vol.-%)	157 (2 Vol.-%)	235.5 (3 Vol.-%)	314 (4 Vol.-%)	471 (6 Vol.-%)

2.2 Testing of the specimens and results

For the investigation of the tensile characteristics of UHPFRC and for each fiber content, six identical dog bone specimens were tested under a constant displacement rate of 7 μm/s. The experimental setup for these tests is presented in Figure 1a. As can be seen, the specimens failed due a single crack in the middle of the length of the specimens. The compressive on the other hand were executed under a constant loading rate of 0.6 MPa/s, according to BS EN 12390-3:2009 (2009) (Figure 1b).

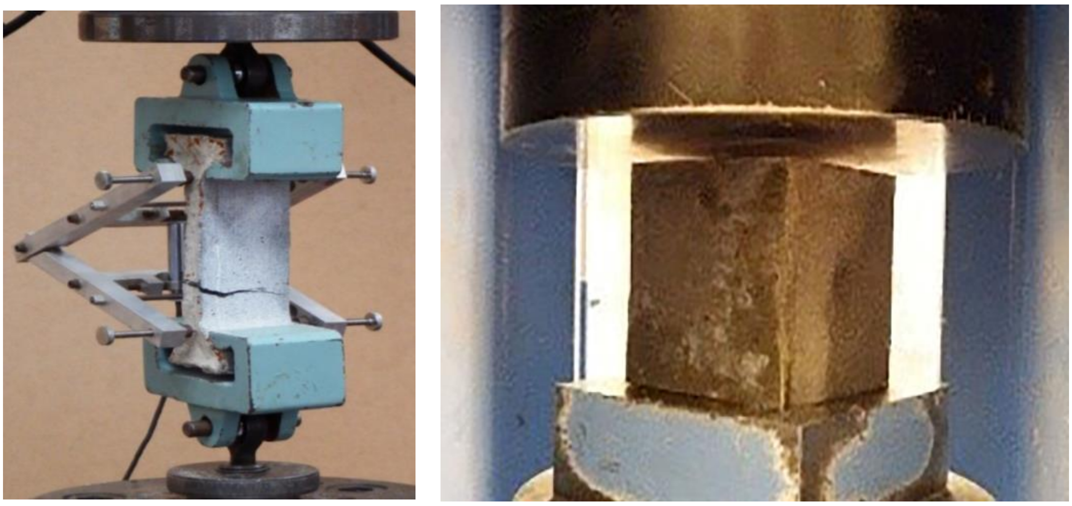


Figure 1 a) Dog Bone specimen b) Cube specimen

In Figure 2, the average tensile stress-strain curves, for the different fiber contents are presented.

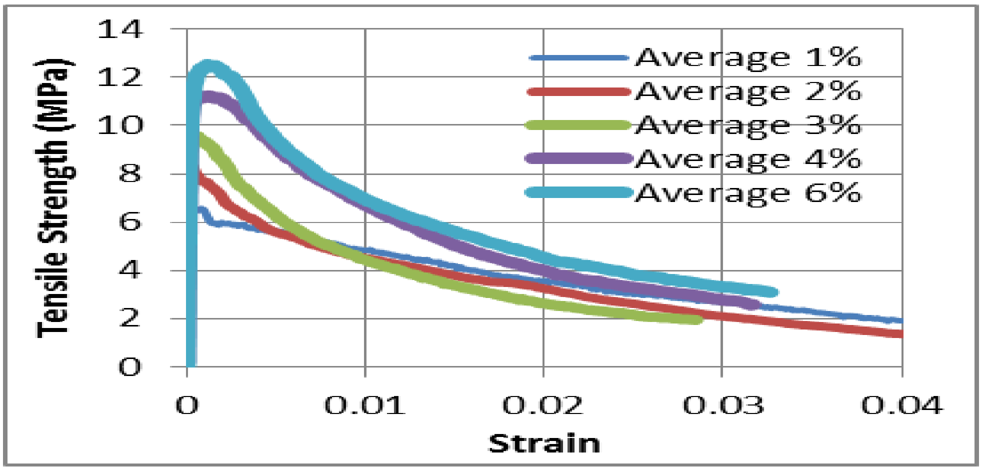


Figure 2 Stress-strain results in tension for the different fiber contents

In Table 2, the values for the maximum tensile strength and compressive strength are presented.

Table 2 Maximum tensile and compressive strengths

Fiber Content (%)	Tensile Strength (MPa)	Compressive Strength (MPa)
1	6.5	102
2	8.4	115.6
3	9.6	125.6
4	11.3	136.1
6	12.5	175.5

The results of Figure 2 indicate that the fiber content is a crucial parameter affecting the tensile characteristics of UHPFRC. It was identified that strain hardening was achieved for fiber content higher than 2 Vol.%. From Table 2 it can be seen that when the volume of fibers is increased from 1 to 6 Vol.%, the tensile strength is increased by 92% and the compressive strength by 73.4%.

During the preparation of the specimens it was noticed that for higher fiber contents the workability was reduced. This was confirmed with the measurement of the workability following the procedure proposed by BS 1015-3:1999 (1999). More specifically, the workability of specimens without fibers, as well as with 3 Vol.-% and 6 Vol.-% steel fibers was measured using a flow table. The applied cone had a height of 60 mm, a top diameter of 70 mm and a bottom diameter of 100 mm.

The result indicated that the flow diameter of UHPC, without fibers, was 255 mm and the respective values for the mixtures with 3 and 6 Vol.-% steel fibers were equal to 215 mm and 125 mm, respectively. These results indicate a good workability for the mixture without fibers, as well as for the mixture with 3 Vol.-%. On the contrary, the high volume of steel fibers in the mixture prepared with 6 Vol.-% caused a pronounced reduction in flow. For the application of UHPFRC for strengthening of RC structures, good rheological properties are required. From the measurements of the workability it is obvious that the incorporation of high volumes of fiber, such as 6 Vol.-%, have negative effect on the workability of the material and may cause problems to the application of the material.

Another important parameter which should be taken into consideration for the preparation of the material and the selection of the appropriate fiber content is the cost. Higher volumes of fibers increase the cost of the material. In Table 3, an estimation of the cost of UHPFRC for the different fiber contents is presented.

Table 3 Cost of UHPFRC for different fiber contents

Fiber Content (Vol. %)	Cost (£/m3)
1	1212
2	1542
3	1872
4	2201
6	2861

From the results of Table 3, an almost linear increment of the cost for increasing volume of fibers can distinguished. Therefore, when the fiber content is increased from 1% to 6%, an increment of 136 % on the total cost can be observed.

Taking into consideration parameters such as the cost, the workability, the ease of preparation and application and the mechanical properties, a fiber content between 3-4% is considered ideal. However, it should be noted that the decision for the selection of the optimum fiber content should be depended on the expected outcomes and structural requirements of the application.

3. STRENGTHENEING OF RC BEAMS USING UHPFRC

3.1 Preparation and testing of the specimens

In the present section, the effectiveness of UHPFRC as a strengthening material is investigated. UHPFRC has been cast as thin layers for the strengthening of RC beam, and the performance of the strengthened elements has been evaluated. For this investigation, six identical RC beams were constructed. Two beams were used as control beams, two beam were strengthened with UHPFRC layers and two beam were strengthened with UHPFRC layers and steel bars (Table 4). Following the results and the conclusions of the previous section, a fiber content of 3 Vol.% has been selected for the preparation of UHPFRC (Table 1). The mixture design for the preparation of RC beams is presented in Table 5.

Table 4 Examined beams

Beam	Strengthening Technique
P1	Control beam
P2	Control beam
U1	UHPFRC layer
U2	UHPFRC layer
UB1	UHPFRC layer and bars
UB2	UHPFRC layer and bars

Table 5 The concrete mix design

Material	Quantity (kg/m^3)
Cement	340
Fine Aggregates	1071
Coarse Aggregates	714
Water	205

The geometry and the reinforcement of the initial RC beams are presented in Figure 3. As can be seen in this figure, the existing RC beams were reinforced at the tensile side with two longitudinal ribbed steel bars with a diameter of 12 and a length of 2150 mm. The reinforcement at the compressive side of beams was used to support the stirrups. In order to avoid shear failure of the beams, shear reinforcement, according to Eurocode 2 (2004) was selected. The UHPFRC layers had a depth of 50 mm, a breadth of 150 mm and were cast along the whole length of the tensile side of the beams. Two ribbed steel bars with a diameter of 10 mm, a length of 2150 mm and a concrete cover of 25 mm were used as a reinforcement of the UHPFRC layers. All the steel bars of the present investigation were grade B 500C. Before the casting of the layers, the interface was roughened to a depth of 2-2.5 mm, which according to fib bulletin 55 (2010), can be classified as rough interface. The roughened depth was measured using the sand patch method.

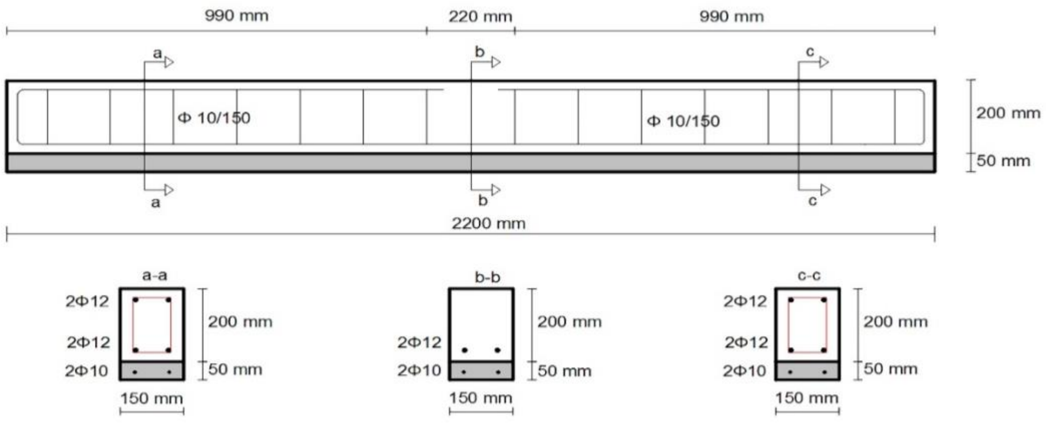
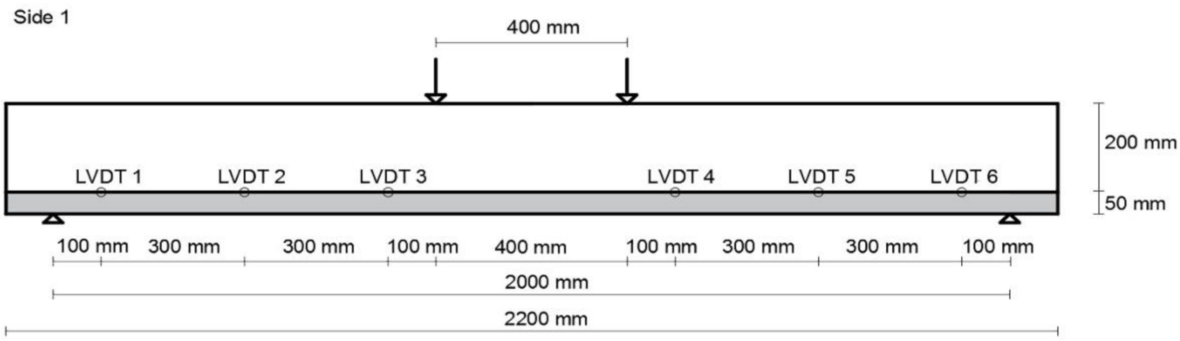


Figure 3 Geometry and Reinforcement of the examined beams

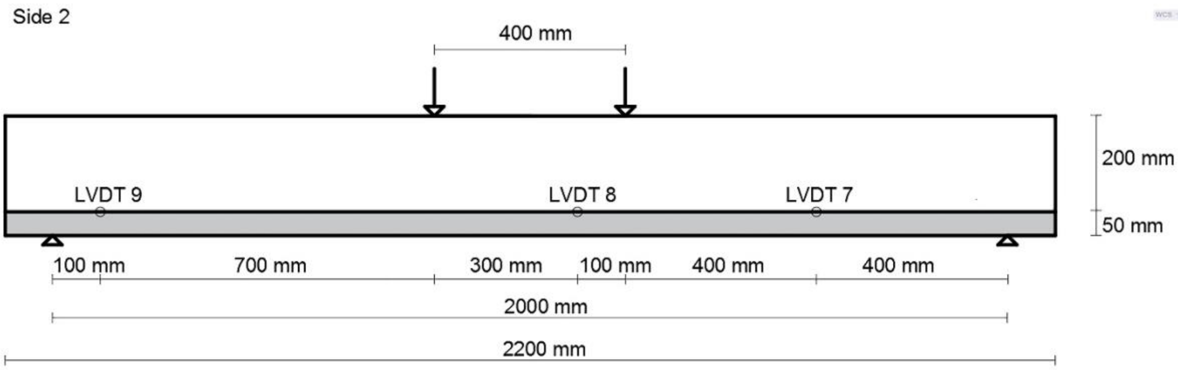
For the testing of the examined beams, a four point loading test under a constant displacement rate of 8 μm/s was conducted. The experimental setup for these tests is presented in Figure 4.

Figure 4 Experimental setup for the four point loading tests

As shown in Figure 4, during the testing apart from the load, the deflection of the specimens in the middle of the span length and both sides was recorded. The deflection was measured using Linear Variable Differential Transformers (LVDTs). Additionally, for the strengthened beams strengthened with layers, the slips at the interface were also measured using nine LVDTs. The position of the LVDTs is presented in Figures 5a and 5b.



a)



b)

Figure 5 a) Positions of the LVDTs for the measurement of slips on side 1 b) positions of the LVDTs for the measurement of slips on side 2

3.2 Experimental Results

From the testing of three concrete cubes with side length of 100 mm and following the procedure as described in section 2.2, it was found that the average compressive strength of concrete was 30.9 MPa and the standard deviation was 2.34 MPa. All the experimental results for the testing of the RC beams and the strengthened beams are presented in Figure 6.

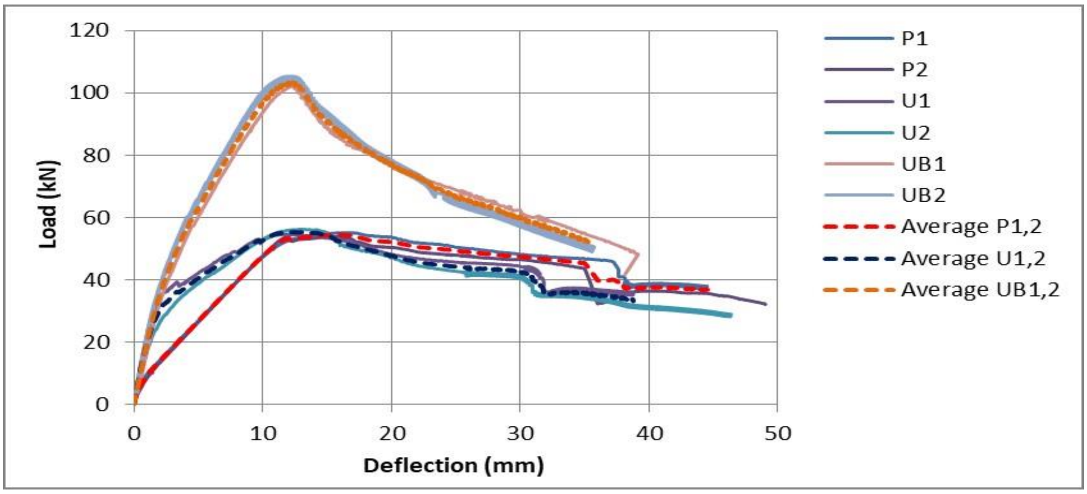
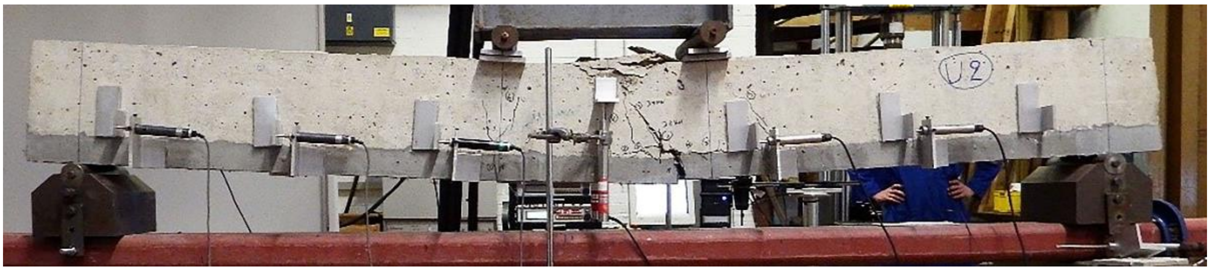


Figure 6 Load-deflection results for all the examined beams

From the results of Figure 6, it is clear that the addition of UHPFRC layers at the tensile side of the RC beams resulted in a large increase of the stiffness of the RC beams, while the load carrying capacity was also increased. The addition of steel bars to the UHPFRC layer on the other hand, had as a result a big increase of the load carrying capacity of the beams. More specifically, from the comparison of the average curves, it can be noticed that when steel bars are added in the layers, the load carrying capacity of the strengthened beams is increased by 90% compared to the load carrying capacity of the control beams.

The failure mode of the initial beams prior to strengthening and the strengthened beams with UHPFRC layers was identical, and a single crack in the middle of the span length of the tensile side of the beams was crucial for the failure. On the contrary, the damage of beams which were strengthened with UHPFRC layers ad steel bars started from the compressive side of beams. In Figure 6, the failure mode of the strengthened beams for different configurations is presented.

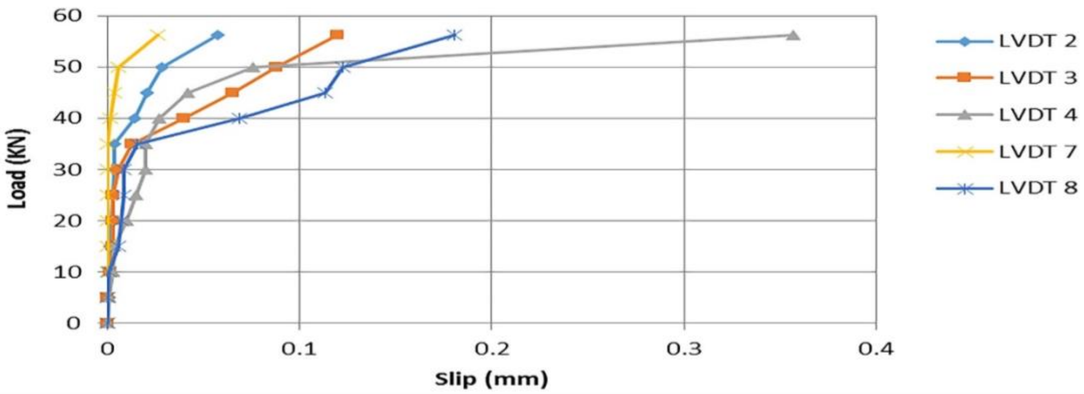


a)

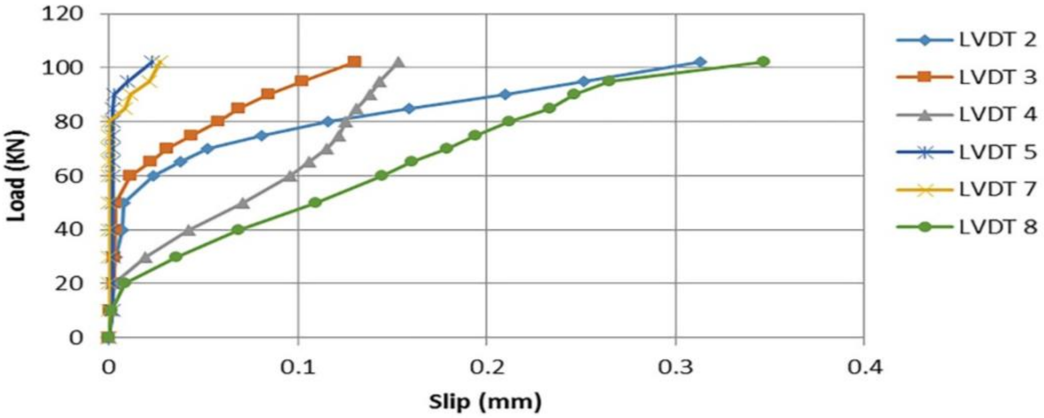
b)

Figure 7 Failure mode of a) beam strengthened with UHPFRC layer b) beam strengthened with UHPFRC layer and steel bars

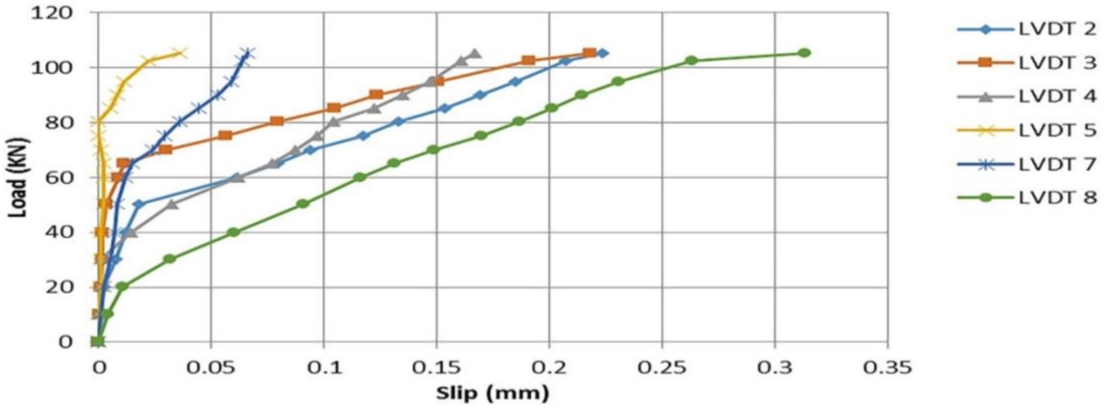
During the testing of the strengthened beams, apart from the measurements of the load and the deflection, measurements were also recorded for the slips at the interface in different positions (see Figures 5a and 5b). Due to the local de-bonding at the interface of beam U1, the measurement of this beams were ignored. The results for the load versus the slip for beams U2, UB1 and UB2 are presented in Figures 8a-c.



a)



b)



c)

Figure 8 load versus slip in different positions for a) beam U2 b) beam UB1 c) beam UB2

From the results of Figures 8a-c, it is clear that there are differences in values of slip in different positions. The slips close to support was almost zero. In case of high normal to the interface stress, like areas close to supports, the shear strength is higher than the shear stress and therefore interface slip is prevented. Also, it should be noted that despite the fact that in the present study the sand patch method was used to quantify the concrete surface texture, it is possible that there were local imperfections and variations of the level of roughening along the interface.

In existing codes, limit state values for the design of composite structures, are proposed. The Greek Code of Interventions (2013) suggests maximum values of slips for different limit states of composite elements. More specifically, a value of 0.2 mm is proposed for the immediate occupancy performance level, a values of 0.8 mm for the life safety performance level and a value of 1.5 mm for the collapse prevention performance level. In all the examined cases and for both the examined techniques (with and without steel bars), the recorded values of the present investigation were lower to 0.35 mm which according this code corresponds to the life safety performance level.

Comparing the obtained values, with proposed values in the literature for concrete to concrete interfaces, a better bonding between UHPFRC and RC can be identified. Tsioulou et al. (2013), recorded values of slip equal to 1.1 mm at the interface between RC beams and RC layers. This value corresponds to the collapse prevention performance level and it is significantly higher compared to the recorded values of the present study. The loading conditions, the loading rate and the dimensions of the specimens of this study were identical with the present study. Therefore, the results are comparable.

Conclusions

In the present study the application of UHPFRC for the strengthening of RC beams has been investigated. One of the crucial parameters for the performance of the examined technique is the amount of fibers in the mix. For this reason, direct tensile tests and compressive tests were executed and the performance of the material for different fiber contents has been investigated. Additionally, parameters such as the workability and the cost of the material for the different fiber contents have been investigated. The experimental results indicated that when the fiber content was increased from 1% to 6%, the tensile strength was increased by 92% and the compressive by 73.4%. At the same time, a reduction of the workability was noticed. In the present study the cost of UHPFRC for the different fiber contents was also estimated, and a linear increase of the cost for increasing fiber contents has been noticed. Considering these parameters, a fiber content of 3 Vol.% was selected for the next part of the study, which was the investigation of the performance of UHPFRC for the strengthening of RC beams. The experimental results of this investigation indicated that the addition of UHPFRC layers result in a big increase of the stiffness of the strengthened elements, while the addition of steel bars to the layers produced a dramatic increase of the load carrying capacity of the strengthened elements. Finally, from the measurement of slips at the interface between UHPFRC and RC, it was noticed that the bonding between UHPFRC and RC was effective with low value of slips. Comparing the recorded values with proposed values in the literature for concrete to concrete interfaces, a better bonding between UHPFRC and RC can be identified.

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