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# Basic recommendations for strengthening of RC beams with Ultra High Performance Fiber Reinforced Concrete (UHPFRC) – conclusions from experimental investigation

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# Basic recommendations for strengthening of RC beams with Ultra High Performance Fiber Reinforced Concrete (UHPFRC) – conclusions from experimental investigation

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**Abstract**. In modern engineering practice, it is very often necessary to look for alternative solutions for increasing the load-bearing capacity and stiffness of various structural elements of buildings, due to unsatisfactory requirements of the current regulations, increasing the load, occurring damages and defects. The modern approach, which implies that construction contributes to the sustainable development of society, requires the use of high-tech materials with significantly higher strength characteristics than traditional ones. One such material is the Ultra High Performance Fiber Reinforced Concrete (UHPFRC), which differs significantly from conventional concrete because of its specific structure and composition. In this aspect, there are a number of challenges that need to be overcome in order to provide the practical application of UHPFRC in Bulgaria – optimal mixture, technological problems, national regulations, economic indicators, etc. All this necessitates a thorough study of the actual behaviour of structures strengthen by UHPFRC. This paper presents an experimental study of the stress and strain conditions of a reinforced concrete beam with rectangular cross section strengthen with a 5 cm layer of UHPFRC concrete in the compressive zone. The analysis of the results from the experimental tests provides a number of important practical conclusions and general recommendations for the application of UHPFRC for strengthening of reinforced concrete beams in real structures.

## 1. Introduction

The contemporary structural solutions for rehabilitation and strengthening and the philosophy of the sustainable design are related to the application of new generation construction materials. A lot of challenges shall overcome during rehabilitation and strengthening of structures, which imposes high performance materials to be applied – usually based on fiber reinforced composites. In our country the challenges are related additionally to the requirements for resistance to seismic actions, and thus the use of conventional materials and processes is very often unsatisfactory.

During the last decade, UHPFRC has been used in structural rehabilitation and strengthening works. The concept was born in 1999 to enhance conventional reinforced concrete. UHPFRC is a smart, light and durable material. The main objective is making existing structures durable and strong enough for future needs and to update their performance and increase their structural capacity (stiffness, ultimate resistance, fatigue resistance). The strengthening method using a layer of strain hardening UHPFRC is an effective method in terms of technical performance. The application of one single layer can fulfil

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several functions: 1) increase resistance in bending and shear, 2) increase stiffness, 3) reduce fatigue stresses, 4) act as a waterproofing layer if necessary.

The UHPFRC technology to improve the resistance and the durability of existing concrete structures is cost-effective at execution. Actually, lower intervention costs (when compared to traditional methods) are the main reason for the increasing number of applications of this technology.

The very first scientific studies on this subject in Bulgaria and the possible steps to the implementation of UHPC (Ultra High Performance Concrete) as structural material of new generation are obtained within the project „Ultra High Performance Concrete – alternatives for construction of high-rise buildings and transport equipment in Republic of Bulgaria", which has been funded (2010-2014) by the National Research Fund within Ministry of Education and Science in Bulgaria [1].

In [2], [3] is made further analysis of the challenges and the opportunities in the application of UHPFRC for rehabilitation and strengthening of existing reinforced concrete structures.

Up to 2018 the research for the application of UHPFRC in Bulgaria was mainly focused on the properties of the material and recipes. In 2018 a research project started in the University of Architecture, Civil Engineering and Geodesy (UACEG), Sofia. One part of the investigation was dedicated to the application of UHPFRC for strengthening of reinforced concrete beams [4]. The main results concerning the beam specimens are discussed in [4] and [5].

This paper is a continuation of [5] and presents the experimental test of one of three specimens of reinforced concrete beams. The goal of this investigation is to explore the potential of the strengthening in the local Bulgarian conditions.

## 2. Theoretical determination of the capacity of the unstrengthen and strengthen beam

For the analysis, the main characteristics for the unstrengthen beam are presented:

### *2.1. Moment of resistance of the beam before strengthening*

$$M_{Rd}=33{,}26\ \text{kN.m} \rightarrow F=47{,}51\ \text{kN (available bars } 3\varnothing 12)$$

### *2.2. Design shear resistance of the beam before strengthening*

$$V_{Rd,max}=72{,}9\ \text{kN}$$

$$V_{Rd,s}=36{,}92\ \text{kN (available stirrups } \varnothing 6/15)$$

### *2.3. Theoretical calculation of deflections*

For the calculation of the deflections the following geometrical characteristics of the cross section are found:

#### *2.3.1. Geometrical characteristics of the non- cracked and cracked section*

$$I_I=288380935\ \text{mm}^4 - \text{second moment of area of the non-cracked section;}$$

$$\frac{1}{r_I}=0{,}0000129\ \frac{1}{\text{mm}} - \text{curvature of the non-cracked section;}$$

$$I_{II}=180955426\ \text{mm}^2 - \text{second moment of area of the cracked section;}$$

$$\frac{1}{r_2}=0{,}00002063\ \frac{1}{\text{mm}} - \text{curvature of the cracked section}$$

#### *2.3.2. Average stiffness:*

$$W_{red,1}=2323217\ \text{mm}^3 \rightarrow M_{crc}=f_{ctm}W_{red,1}=4{,}41\ \text{kN.m}$$

W- first moment of area;

$$\psi_s=1\text{-}\beta\left(\frac{M_{crc}}{M}\right)^2=0{,}975$$

$$\frac{1}{r}=\psi_s\frac{1}{r_2}+(1-\psi_s)\frac{1}{r_1}=0{,}00002044\ \frac{1}{mm} \rightarrow \text{The theoretical deflection is: } f=s\frac{1}{r}L^2=13{,}34\text{ mm}$$

## 3. Experimental programme and results from the experiments

The research project in UACEG includes the analysis of the behaviour of strengthen with UHPFRC orthotropic steel decks and RC beams [4].

The three RC beam specimens have length of 3000 mm each and cross section 250/150 mm. The layout of the reinforcement is presented in [4], [5]. The characteristics of the materials used for the test are:

### *3.1. Materials for test specimens*

- Concrete C20/25 with compressive strength $f_{ck}$=20 MPa and modulus of elasticity $E_{cm}$= 30000 MPa;
- Ultra-high performance fiber reinforced concrete (UHPFRC) with cube strength $f_{frc,cube}$=141,3 MPa and cylinder strength $f_{frc,k}$=0,8.141,3=113 MPa;
- Reinforcing steel B500 for longitudinal reinforcement with yield strength $f_{yk}$=500 MPa and modulus of elasticity $E_s$= 200000 MPa;
- Reinforcing steel B235 for transverse reinforcement with yield strength $f_{yk}$=235 MPa and modulus of elasticity $E_s$= 200000 MPa.

**Figure 1.** Laboratory test of strengthen beam

### *3.2. Experimental set up and experimental programme*

The test of the specimens was carried out in two stages: before strengthening and after strengthening. The strengthening consists in the application of UHPFRC with 50 mm thickness in the compressive zone. Initially the top surface of the beam is cleaned and a layer of special additive ADIPLAST for good bond between existing and new concrete is placed. Later the layer of UHPFRC is applied. The production of the UHPFRC was done by Hidrobeton according to their original recipe. The main components include cement 52,5R, micro silica fume, metakaolin, quartz powder (sand), superplasticizer, steel fibers and water. Three different mixes were made. The details for the production of UHPFRC are given in [4]. The general goal was to obtain an optimal mix of UHPFRC on site, not only in laboratory.

All specimens were tested as “simply supported” beams. The load was applied as concentrated in the middle of the beams, statically. Figure 1 and 2 show the experimental test set up of the strengthen beam. For the relative deformations of the reinforcement, strain gauges were used ($X_i$). The relative deformations of concrete were measured by Hugenberger’s strain gauges ($T_i$). The deflections of the beam were registered by deflection indicators ($U_i$).

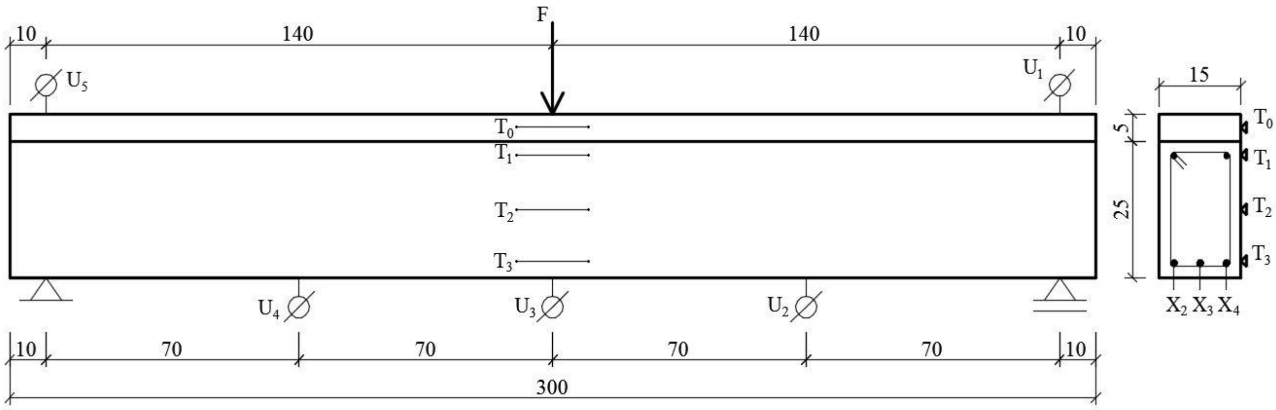


**Figure 2**. Experimental test set up

Before strengthening RC beams (specimens 1 and 2), the experimental moment of resistance (bearing capacity) was found after the loading of 47,7 kN, when the width of the cracks was 0,3 mm (taken as a limit value according to [6]):

$M_{Rd}$ =33,41 kN.m $\rightarrow$ F=47,7 kN

The third beam (specimen 3), presented in this paper, was subjected to loading of 49 kN before strengthening. The opening of cracks was less than 0,3 mm.

After strengthening, the experimental moment of resistance (bearing capacity) was found at loading of 66,41 kN:

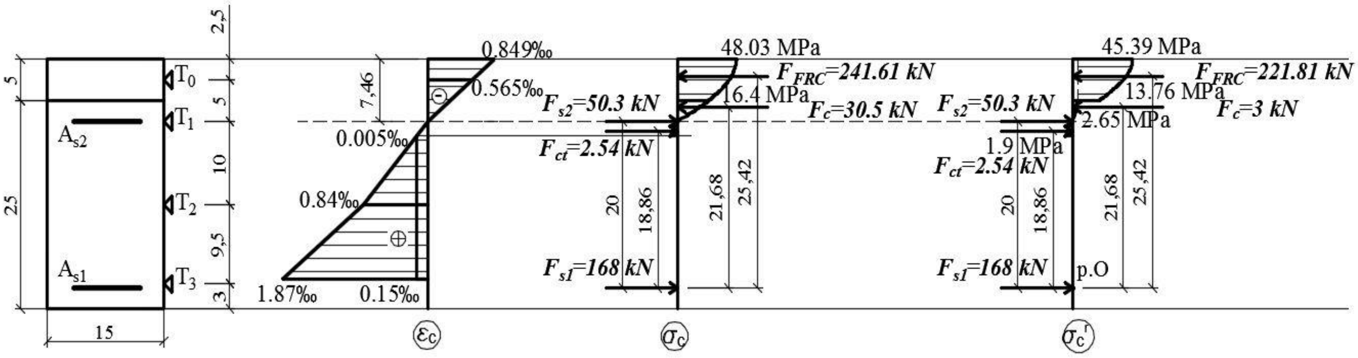


**Figure 3.** Stress and strain distribution in the strengthen beam

$$\sigma_{ci} = f_{frc,k}\left(1-\left(1-\frac{\varepsilon_{frci}}{\varepsilon_{frc2}}\right)^{2}\right) = 113\left(1-\left(1-\frac{0,849}{2,6}\right)^{1,4}\right) = 48,03 \text{ MPa} \quad (1)$$

$M_{Rd}$ =46,49 kN.m $\rightarrow$ F=66,41 kN

When the load reached 75 kN, the opening of the cracks was 0,45 mm and the yielding of the reinforcement was reached.

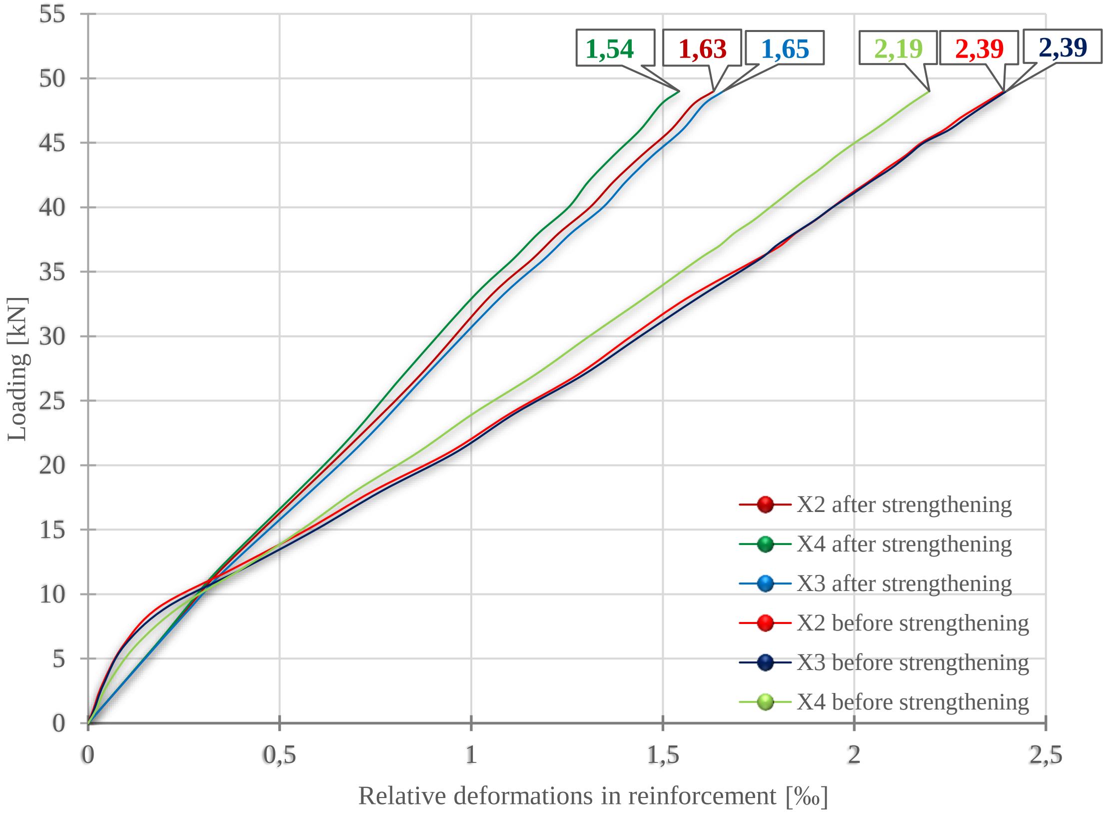


**Figure 4.** Diagramme „Relative deformation in reinforcement - Loading“ before and after strengthening

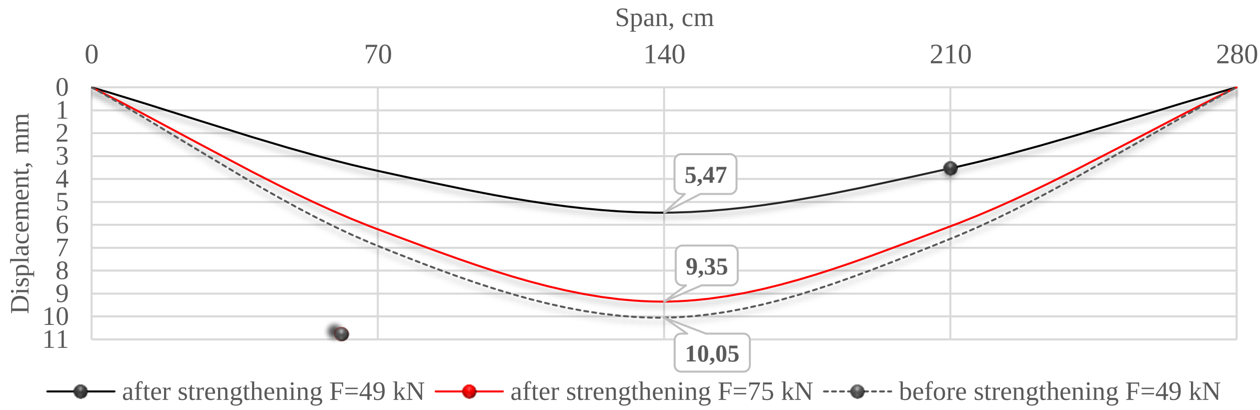


**Figure 5.** Beam’s displacements before and after strengthening

*3.3. Evidence and results of the laboratory work*

Based on the test and the calculations for the stresses as in equation (1), the paper presents the following results:

- Stress and strain distribution for concrete in the strengthen beam – figure 3;
- Diagramme „Relative deformation in reinforcement - Loading“ before and after strengthening- figure 4
- Beam’s displacements before and after strengthening -figure 5.

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The analysis of the diagrammes could be summarized in some very important conclusions:

- The stress diagramme in concrete is reduced, because of the big difference between the strength of the original concrete and the UHPFRC layer and the additional stresses in the interface-figure 3. There is a good agreement between the theoretical calculation and the experimental results.
- The crack 0,3 mm in the strengthen beam appeared when the load is F=66 kN. For the beam before strengthening the crack 0,3 mm is fixed at loading F=49 kN.
- The relative deformations in the tensile zone (T3) in the strengthen beam decrease with 40% at loading F=49 kN in comparison with the unstrengthen beam.
- The deformations of concrete in the compressive zone (T1) for the strengthen beam at loading F=46 kN, decrease significantly in comparison with the same results in the unstrengthen beam.
- At loading 49 kN the deformations in the reinforcement of the strengthen beam decrease with 42-46%.
- The bearing capacity of the strengthen beam at loading F= 49 kN increase with 40%.
- At level of loading F= 49 kN, the deflections after strengthening decrease twice.

## 4. Summary and recommendations

Analysing the results of the experimental test, the following summary and recommendations could be drawn:

1) The application of UHPFRC is one effective contemporary solution for rehabilitation and strengthening. UHPFRC can considerably enhance the performance of existing reinforced concrete structures. The properties and the characteristics of this material are excellent for improvement of the maximum strength and the stiffness of reinforced concrete beams. The results obtained in the laboratory test in UACEG and some other experiments [7] show that the technique using UHPFRC gives significant results in strengthening of reinforced concrete beams with a slight change in the own weight. Future application for reinforced concrete structures, using thin layers 4-8 cm of UHPFRC, is very good opportunity to upgrade their behaviour without additional increasing of the self-weight. A possible application of UHPFRC in real RC structures are available in [8], [9].
2) The bond between the old concrete and the new layer of UHPFRC is decisive for the behaviour of the strengthen element. Usually the bond between UHPFRC and concrete is obtained by preparing the concrete substrate surface by high pressure water jetting or sand blasting. The concrete substrate has to be wetted and needs to be wet when the layer of UHPFRC is cast. This surface preparation provides a full bond between the UHPFRC and the concrete substrate. In the presented laboratory tests the application of a special additive on the interface, showed very good results.
3) In terms of life cycle cost, the application of UHPFRC is related to serious reduction of maintenance and environmental impact added value for owner and society.
4) The cost for high fiber content is largely outbalanced by improved mechanical properties. The use of fiber content as high as possible to obtain tensile strain hardening is recommended. The content of fibers should be kept around 2,5% -3% to avoid cracking and provide durability.
5) Next generation of UHPFRC is related to the reduction of energy and carbon footprint while maintaining high packing density and mechanical properties of UHPFRC. The trend is to replace clinker by limestone filler, replace steel fibers by high modulus PE-fibers.
6) The aim of all future investigation is to overcome the challenges related to the composition and technology of preparation of UHPFRC and its in-situ application.

7) It is necessary to develop a local national regulatory framework /recommendations for design and/or to adapt existing recommendations [10] to the specifics of UHPFRC in Bulgarian conditions.
8) Due to the higher cost of UHPFRC, the use for the complete construction of structures of buildings and facilities in Bulgaria will probably be difficult to access for investors at the actual moment, but in the activities of rehabilitation and strengthening, as well as for special purposes, the application of UHPFRC is one sustainable and effective solution.
9) It is necessary to make serious efforts to conduct long-term monitoring of the behaviour of the already strengthen elements.

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