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BEHAVIOR OF RC BEAM RETROFITTED USING ULTRA HIGH-PERFORMANCE CONCRETE UNDER IMPACT LOADS

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Several new types of materials have recently been used as retrofitting materials for structural elements such as ultra-high performance concrete with steel fiber reinforcement (UHPFRC). These materials are used as jacking to enhance the strength and ductility reinforced concrete (RC) beams. Considerable attention has been focused on the response of retrofitted RC beam under static loads but the behavior of such beam under impact loading is somewhat lacking. Therefore, in this study, a 3-D finite element model (FEM) of retrofitted RC beams under impact loading using non-linear finite element software (ABAQUS) was investigated. Since experimental work on this topic is scarce, the FEM is validated using the results of retrofitted RC beam under static loads. The impact load was applied in ABAQUS as equivalent to an initial velocity of 2500 mm/s. A parametric study was carried out to study the flexural response of RC beams retrofitted with different thicknesses and strengthening configurations of UHPFRC under impact loading.

Keywords: UHPFRC, Finite element model, ABAQUS.

1 INTRODUCTION

Several techniques have been reported in the literature for the strengthening of reinforced concrete (RC) elements. Some of the conventional methods of strengthening and retrofitting of damaged RC beams include removal or replacement or RC jacketing, the addition of fiber reinforced polymer composites and external steel elements. Recently, several new techniques for the repairing of RC beams have been reported including using Carbon Fiber Reinforced Polymer (CFRP). Some of these techniques are labor-intensive and require a different level of artful detailing, high cost, disruption of building occupancy in terms of considerable loss of floor space and limited range of applicability. A major inadequacy of CFRP sheets is its early brittle failure due to the loss of bond. Mechanical anchorage was provided to fully enhance the bond of CFRP layers, by avoiding the early failure. The use of anchoring the FRP sheets in concrete may damage the anchorage zone and it will result in stress concentration zone and early brittle failure. Therefore, an ultra-high performance fiber reinforced concrete (UHPFRC) repairing system is another technique to strengthen or restore the damaged RC beams. Recently, Martinola *et al.* (2007) studied the use of a precast layer with a thickness of 40 mm and made of high-performance fiber reinforced concrete (HPFRC) to enhance RC beams. In order to overcome the above-mentioned issues and shortcomings, the non-seismically designed joint will be repaired and strengthened by using the UHPFRC jacket. Mahmud *et al.* (2013) studied the size effects of

UHPFRC on the flexural response of the beams. These researchers developed a numerical modeling using ABAQUS software. Both the experimental and numerical results showed that the size-effect in the flexural strength of the beams is almost negligible. Chalioris *et al.* (2014) investigated the use of thin reinforced self-compacting concrete (SCC) for the strengthening of conventional RC beams. Their results showed an increase in the strength with improved ductility and favorable failure behavior. It was concluded that the high strength self-compacting concrete (SCC) is a quick option for rehabilitation or strengthening the existing RC beams. Ruano *et al.* (2015) carried out an experimental work and a numerical modeling of the behavior of RC beams strengthened in shear with high-performance self-compacting concrete. Both studies from the experimental work and numerical simulation demonstrated that the fiber content not only prevented debonding from the concrete substrate but also enhanced the failure load of strengthened RC beams. Lampropoulos *et al.* (2016) investigated the efficiency of using UHPFC for strengthening of conventional RC beams. Different types of configuration of UHPFC layers were used, in the tensile, in the compressive sides and with a three-side jacket. The results showed a significant moment increase when three sides jacket was used. Al-Osta *et al.* (2017) have recently studied numerically and experimentally the performance of RC beams retrofitted with layers of UHPFC that had a thickness of 30 mm only. Different types of configuration of UHPFC layers were used, bottom side, 2 sides and 3 sides. The results indicated that beams retrofitted on three-side showed the highest failure load. Nasrin *et al.* (2017) studied numerically the effect of impact load on the behavior of bridge girder made of ultra-high performance concrete (UHPC) and reinforced concrete beams strengthened with CFRP. The results demonstrated that UHPC beams showed less deflection as compared to RC beams made of normal concrete.

The need for retrofitting the existing structures has been enormous last years. The most popular technique is using CFRP laminates for upgrading the deteriorated structures. CFRP possesses desired properties such as high-strength, corrosion protection, easy to apply and minimal size change. Besides all these advantages, CFRP system has some shortcomings, which are mainly related to the bond and the incompatibility problems Al-Osta (2018). Therefore, in this study, the UHPFRC panels attached with different thicknesses to the sides of RC beams were numerically investigated under impact loads.

2 EXPERIMENTAL TEST PROGRAM

A simply supported RC beams were tested under static four-point loading as can be seen in Figure 1. The vertical deflection at the mid-span and the corresponding load were measured and plotted. The results obtained from the experimental work and the finite element models were compared to validate the developed model.

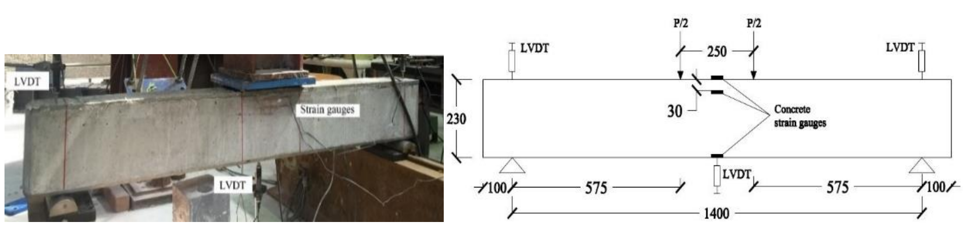


Figure 1. Beam test set-up for static load and instrumentation of beam flexural strength test.

3 FINITE ELEMENT MODELLING

The performance of normal concrete (NC) and UHPFRC is non-linear. In this study, a 3D finite element model (FEM) of beams strengthened with different configuration was developed using ABAQUS software to predict the response of the RC beams specimens under impact loads. The linear performance of materials was defined using the elastic modulus, E=34 GPa; and poisson's ratio, v =0.15 for NC and E= 46 GPa; v=0.18 for UHPFRC. The concrete damage plasticity model (CDPM) developed by Lubliner *et al.* (1989) and Lee and Fenves (1998) was utilized to capture the nonlinear behavior of NC and UHPFRC. The behavior of the materials in CDPM was defined using the parameters presented in Table 1 and nonlinear experimental data given by the author in Ref. Al-Osta *et al.* (2017). The damage parameters d_c and d_t for compressive and tension loads, respectively, in Eqs. (1) and (2) were used below Birtel and Mark (2006). The behavior of steel rebars and stirrups was modeled as an elastic-perfectly plastic with information obtained experimentally; f_y = 590MPa, E=200GPa.

Table 1. Parameters of CDPM for NC and UHPFRC Al-Osta *et al.* (2017).

Ψ (°)	*Eccentricity*	σ_{b0}/σ_{c0}	K	Viscosity parameter
NC/ UHPFRC				
36	0.1	1.16	0.667	0

where:

$\frac{\sigma_{b0}}{\sigma_{c0}}$ is the ratio of initial biaxial compressive yield stress to initial uniaxial compressive yield stress;

K is the ratio of the second stress invariant on the tensile meridian (TM) to that on the compressive meridian (CM).

Ψ is dilation angle.

$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\epsilon_c^{pl}\left(\frac{1}{b_c}-1\right)+\sigma_c E_c^{-1}} \tag{1}$$

$$d_t = 1 - \frac{\sigma_t E_c^{-1}}{\epsilon_t^{pl}\left(\frac{1}{b_t}-1\right)+\sigma_t E_c^{-1}} \tag{2}$$

where:

d_c and d_t = Damage parameters for concrete in compression and tension, respectively;

σ_c and σ_t = Compressive and tensile stresses, respectively;

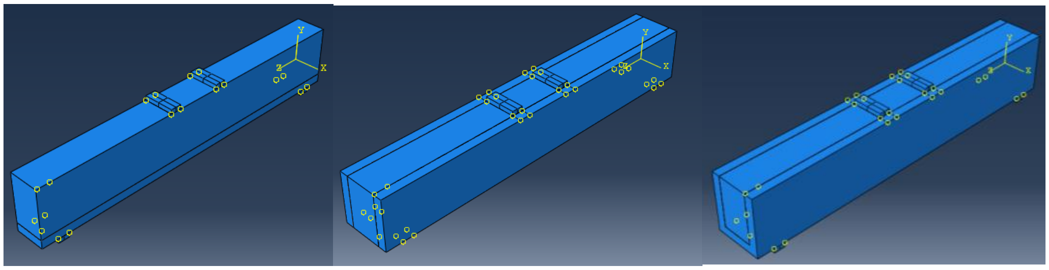
E_c = Modulus of elasticity of concrete;

ϵ_c^{pl} and ϵ_t^{pl} = Plastic compressive and tensile strains, respectively;

b_c and b_t = constant values with range 0 < b_c and b_t< 1.

3.1 Type of Element

A 3D- eight noded linear brick element was utilized to model NC and UHPFRC. The steel rebars and stirrups were modeled as 2-noded linear 3D truss element. The contact between UHPFRC and NC was considered as a perfect bond. Figure 2 shows the geometry of models.

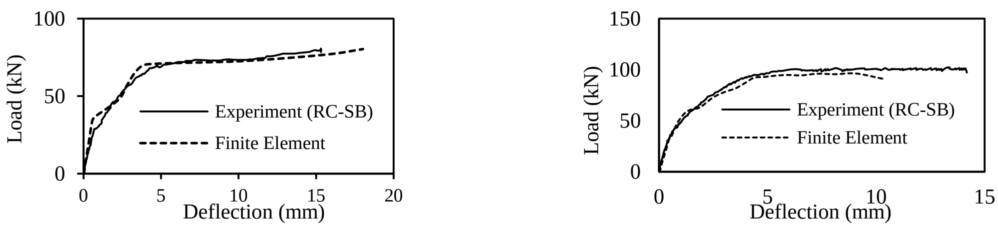


(a) UHPFRC bottom side (b) UHPFRC 2-sides (c) UHPFRC 3-sides

Figure 2. Geometry of models.

3.2 Validation of Model

The proposed FE model was validated with the results obtained from the experimental work for the beams tested under static loading. These beams were strengthened by different layers of UHPFRC (bottom, two-side and three-side). Figure 3 shows that the FEM can be used to predict the failure load and the performance of RC beams strengthened with layers of UHPFRC. More information about the validations of the FE model is available elsewhere Al-Osta *et al.* (2017).

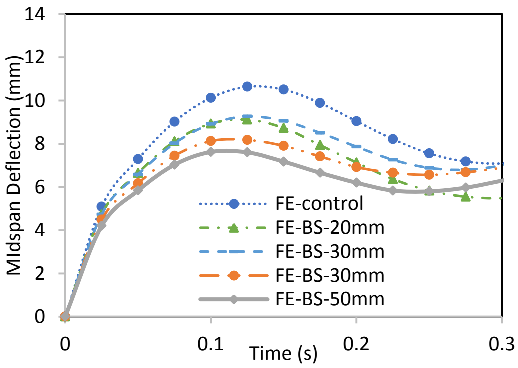


(a) UHPFRC bottom side- Static load (b) UHPFRC 2-side- Static load

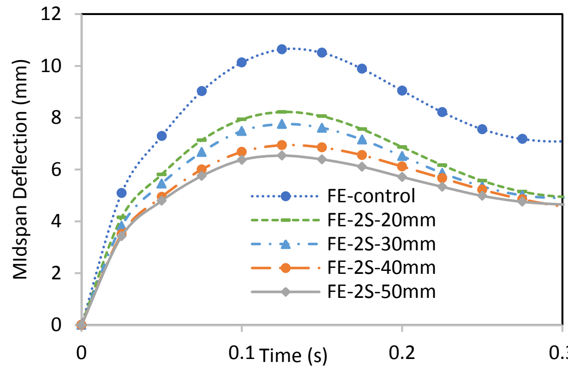
Figure 3. Experimental and FE load deflection behavior (a) RC-BS static load (b) RC-2S static load Al-Osta et al. (2017).

4 RESULTS AND DISCUSSION

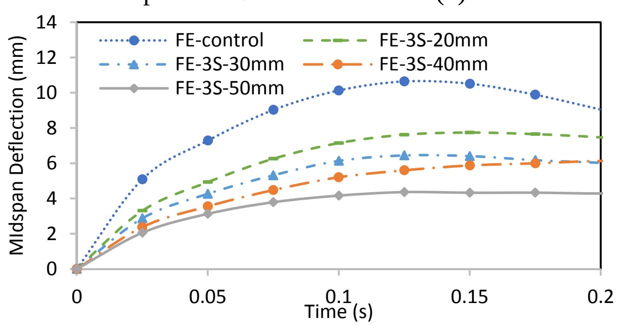
In this study, the specimens retrofitted with different thicknesses of UHPFRC layers are subjected to an impact load characterized by an initial velocity of 2500 mm/s. that was applied at the mid-span. The performance of strengthened RC beams with different configuration and thicknesses of UHPFRC layers under impact load is presented. The beams were named FE-control, FE-BS-t1, FE-2S-t1, and FE-3S-t1. For example, FE-BS-20, FE stands finite element, BS is for strengthening from the bottom side and 20 mm stands for the thickness of the layer of UHPFRC. 2S and 3S indicate the strengthening from two and three sides, respectively. Figure 4 indicates that FE-control without strengthening was subjected to more deflection than RC beam specimens strengthened with layers of UHPFRC in the bottom, two-side or in three sides under the same impact load. It can be seen from the figure that increasing the thickness of UHPFRC layers results in decreasing the mid-span deflection. This could be attributed to the dense structure and high modulus of elasticity of UHPFRC layers used as compared to NC thereby enhancing the stiffness and resisting the strengthened beams to the applied load. For RC beam, the mid-span deflection of FE-BS-20mm, FE-2S-20mm, and FE-3S-20mm decreased by 15%, 29% and 37%, respectively, compared to the FE-control. Furthermore, the beams in Figure 4 are experiencing non-linear deflection behavior of beams with the time due to impact loading. Therefore, it is evident that the impact energy is initiating/triggered the non-linear material models. Figure 5 shows the relationship between the energy and time history of FE-control, FE-BS-20mm, FE-2S-20mm, and FE-3S-20mm. It can be confirmed from Figure 5(a) that the kinetic energy is constant as expected for all beams. It is maximum when the steel block bits the concrete surface of the beams and becomes zero when it is away from the beams. Figure 5(b) shows that the total energy for all beams is almost close to the kinetic energy, which indicates the accuracy of the model according to the conservation law of energy.



(a) UHPFRC bottom side- Impact load.



(b) UHPFRC 2-side- Impact load.



(c) UHPFRC 3-side- Impact load.

Figure 4. Deflection time history at mid-span.

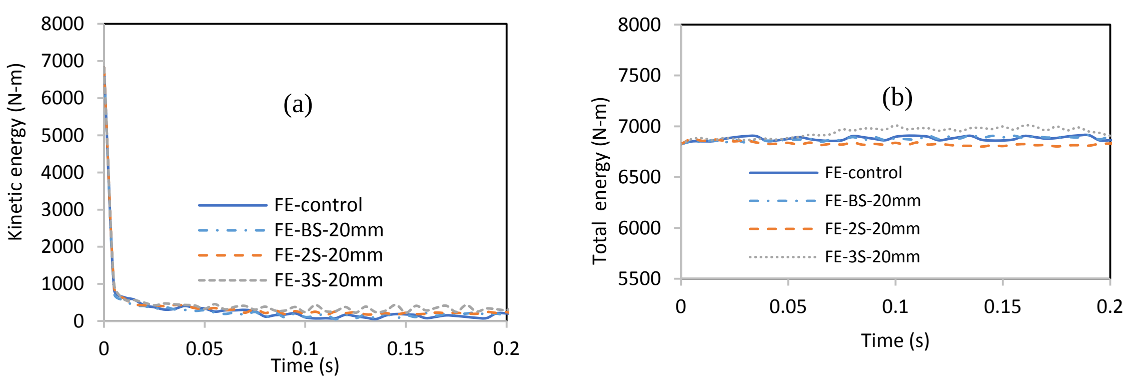


Figure 5. Energy -time relationship (a) Kinetic energy (b) Total energy in the model.

5 CONCLUSIONS

Based on the numerical simulation of the flexural performance of RC beams retrofitted with different thicknesses of UHPFRC layers under impact load, the following conclusions could be drawn:

- Since no experimental works could be found in the literature to study the effect of impact load on the performance of RC beams strengthened by layers of UHPFRC, the ABAQUS software package was utilized to preliminary investigate the effect of impact load on the behavior of retrofitted RC beams.
- It was noted that it is possible to reduce the mid-span deflections of RC beam by 15% through strengthening the beams with a bottom layer of UHPFRC with a thickness of 20 mm only. While the amount of mid-span deflection could be reduced to 37% by using layers of UHPFRC with a thickness of 20 mm that surround the beam from three sides.
- The total energy stored for all beams is almost close to the kinetic energy during the impact loading history, which indicates the accuracy of the model.

Acknowledgements

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