Numerical Investigation of RC Beam Strengthened with UHPFRC Layers Using Cohesive Surface Bonding Method

Mohammed AL-HURI[1], Shamsad AHMAD[1], Mohammed AL-OSTA[1], Ali AL-GADHIB[1], Muhammad KALIMUR RAHMAN [2],

[1]Department of Civil Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

[2]Center for Engineering Research, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

Contact e-mail: shamsad@kfupm.edu.sa

ABSTRACT: Ultra high performance fiber reinforced concrete (UHPFRC) is a smart concrete material that possesses very high strength, modulus of elasticity, ductility, and excellent durability characteristics because of its very dense homogenous microstructure. Due to the excellent performance of UHPFRC, it can be used as an alternative material for strengthening and retrofitting of the partially damaged or undamaged reinforced concrete (RC) structures for restoration or augmentation of the load-bearing capacity. In the recent years, several experimental and numerical investigations have been carried out pertaining to strengthening of RC beams using UHPFRC as retrofitting layers. Most of the researchers simulated the rebars in their finite element models (FEMs) using a 2-noded linear 3D-truss element and considered the contact between steel and concrete as perfect bond. In this study, an alternative 3D finite element model was developed using ABAQUS and the bond between the rebars and concrete was modeled using cohesive surface interaction method, which was found to be a better approach for bond simulation. The results obtained using the 3D finite element models developed in this study were matched well with the experimental and numerical data obtained from the previous studies.

1 INTRODUCTION

Reinforced concrete (RC) is the most widely used material for construction. RC structures are designed to perform its functions effectively over a specific designed service life. Nevertheless, due to deterioration and/or over loading, the structural members might lose their load-bearing capacities leading to the damage before completion of their designed service lives. Therefore, RC structures might need repairing and strengthening to enhance their capacities over their service lives. A relatively new concrete material, named ultra-high performance fiber reinforced concrete (UHPFRC), has emerged with added advantages that may be used for repairing and strengthening of the RC structures.

Hakeem (2011) reported compressive strength and elastic modulus of UHPFRC as 163 MPa and 57000 MPa, respectively. As compared to high performance concrete (HPC), the flexural and compressive strength of UHPFRC could be 2 to 6 times and 2 to 3 times higher, respectively (Lubbers 2003). A study was conducted by Al-Osta et al. (2017) on experimental and numerical investigations to evaluate the effectiveness of strengthening of RC beams using UHPFRC layers.

Results of their study have shown the enhancement and efficacy of this strengthening approach at both serviceability and ultimate limit state.

To model the steel-concrete bond for simulating the RC beams using finite element analysis, three different methods have been reported in the literature. First method uses the spring element, which can transfer the stresses between concrete and the rebars. This method is suitable for the 2D modeling in which reinforcement bars are modeled by two nodes truss elements and the nonlinearity of spring element can be prescribed by entering the experimental relationship of load versus displacement (Li et al 2014) ; (Xiaoming and Hongqiang 2012). However, some researchers have used 4-noded interface elements to simulate the bond in ABAQUS software (Murcia-Delso and Benson Shing 2014); (Val and Chernin 2009). In the second method, the bond behavior between the bars and surrounding concrete is simulated by modifying the steel or concrete properties (Ziari and Kianoush 2013); (Dehestani and Mousavi 2015). The third method consists of simulating the bond as an interaction between two 3D surfaces. This approach can be used in ABAQUS software for 3D model of both steel bars and concrete (Amleh and Ghosh 2006). Al-Osta et al. (2018) explored the possibility of using various approaches to simulate the bond behavior between rebars and normal concrete in a 3D finite element modeling of RC beams. Among these three methods, the cohesive surface interaction method was found as the most suitable for simulating the bond behavior between rebars and surrounding concrete.

In the present work, simulation of RC beam, strengthened by UHPFRC layer on the bottom face, was carried out by adopting 3D nonlinear finite element analysis using ABAQUS software. The model simulates the bottom steel rebars as 3D elements while 2-nodded linear elements were used for simulating stirrups and top bars. In addition, two different bond approaches were considered in this model including 3D tied perfect bond and 3D cohesive surface interaction method.

2 EXPERIMENTAL BEAM DETAILS

Geometry and details of the experimental beam studied by Al-Osta et al. (2017) is shown in Figure 1. The concrete specimen was reinforced by two bars of 10 mm-diameters at the bottom and top of the beam and 8 mm-diameter have been used as stirrups placed at a space of 50 mm center/center.

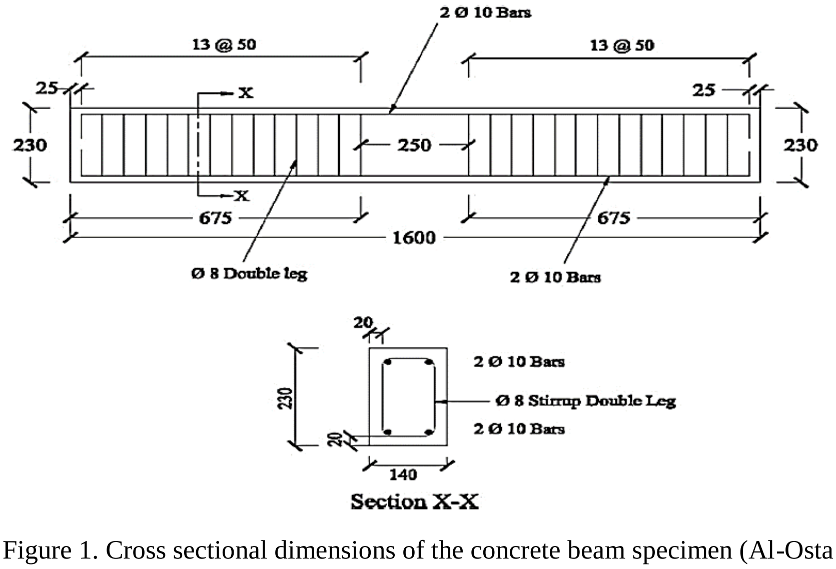


Figure 1. Cross sectional dimensions of the concrete beam specimen (Al-Osta et al. 2017).

The simply supported RC beam was tested in flexural by four-point bending test method. The Experimental instrumentation and flexural test setup are shown in Figure 2 and 3 respectively.

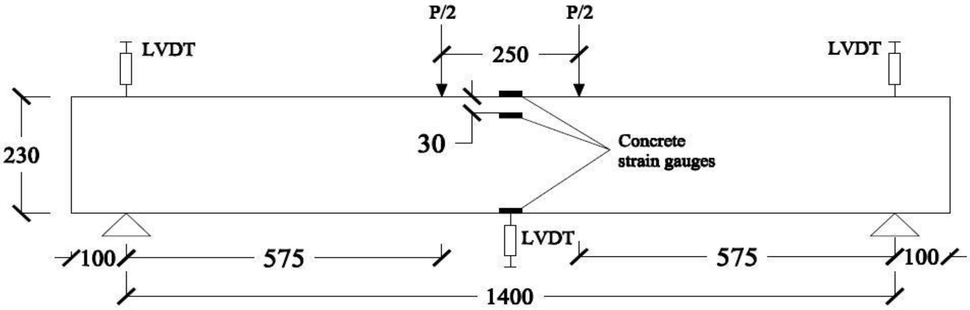


Figure 2. Experimental instrumentation for the beam flexural test (Al-Osta et al. 2017).

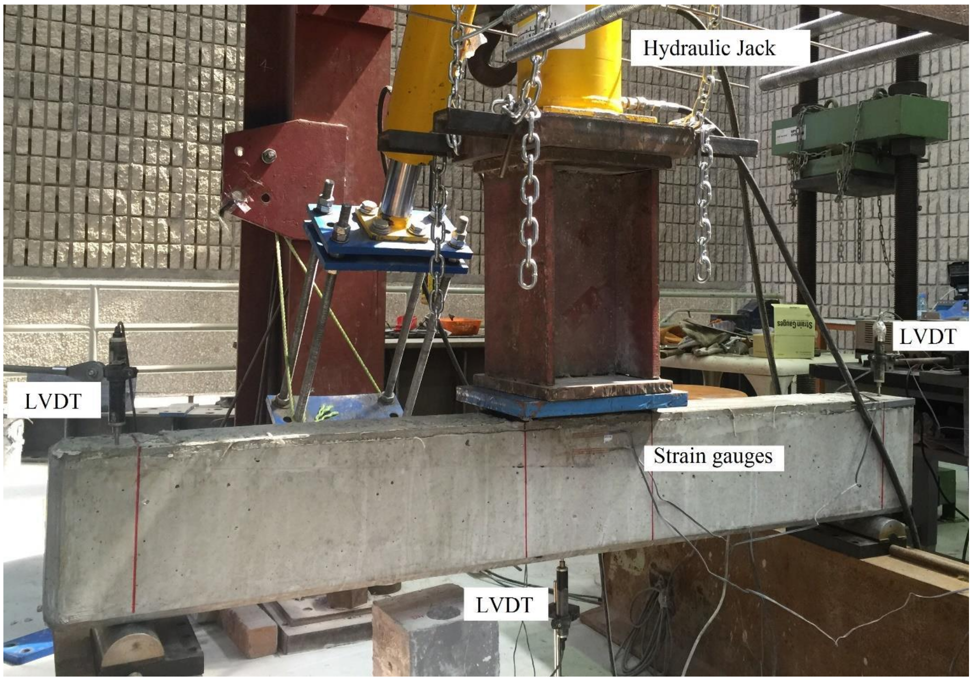
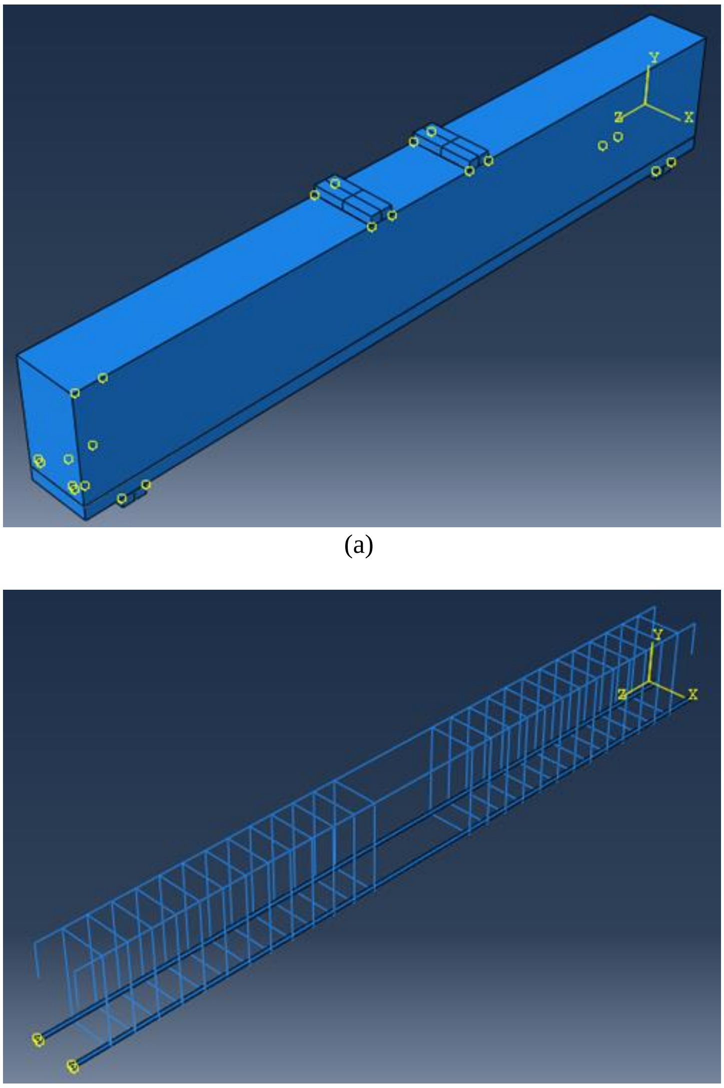


Figure 3. Flexural test setup of the experimental beam (Al-Osta et al. 2017).

3 FINITE ELEMENT MODEL OF STRENGTHENED RC BEAM

A 3D finite element modeling (FEM) of the RC beam specimen was carried out using the non-linear finite element software (ABAQUS) to predict the flexural behavior of the beam specimen. UHPFRC and normal concrete were simulated in the FEM using the concrete damage plasticity model (CDPM). All the material behaviors needed for the simulation were introduced directly into the selected models using the stress-strain experimental results.

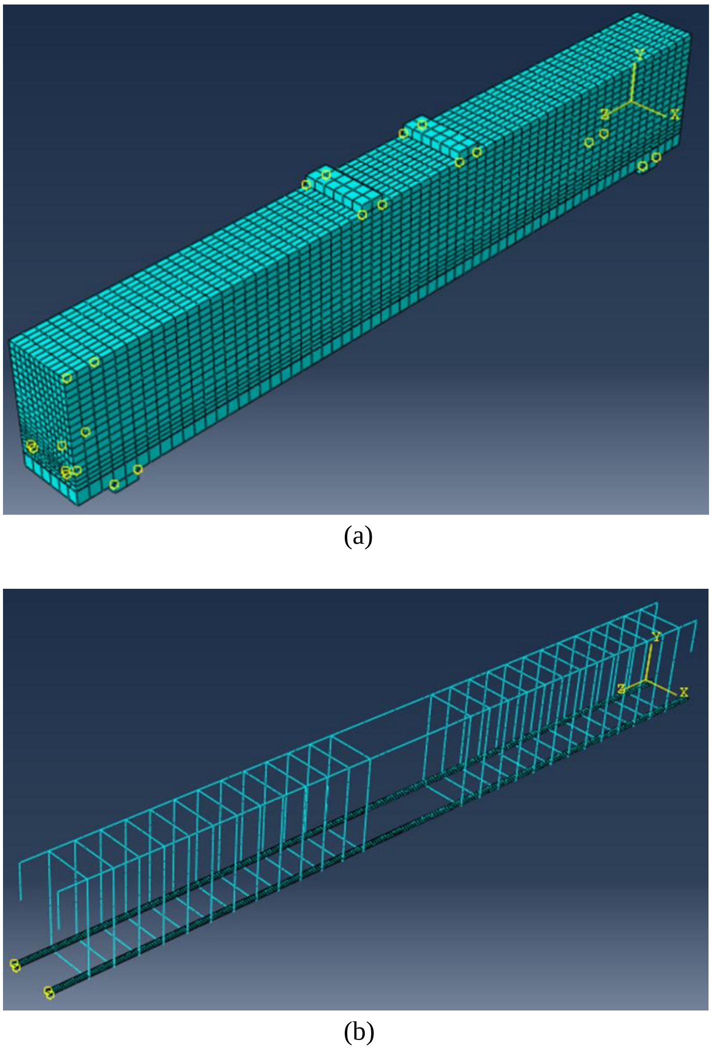
Three-dimensional eight-nodded linear brick element (C3D8R) was used to model concrete and bottom longitudinal steel bars while two-nodded element (T3D2: A 2-nodded linear 3-D truss element type) was used for the stirrups and top steel bars simulation as shown in Figure 4. Moreover, steel plates at loading points and supports have been modelled to prevent any stress concentration. These plates were modelled using C3D8R elements and perfect bond was considered between concrete and these plates. The discretized beam elements for concrete and steel bars are shown in Figure 5.



(a)

(b)

Figure 4. Finite element model of the RC Beam in ABAQUS (a) 3-D concrete beam simulation (b) steel reinforcement cage modeling



(a)

(b)

Figure 5. Discretization of the RC beam (a) concrete elements (b) steel reinforcing bar elements

The CDPM was used for simulating the nonlinear behavior of both UHPFRC and normal concrete. This model requires the values of modulus of elasticity, Poisson’s ratio, the description of compressive and tensile stress-plastic strain behavior, and five plastic damage parameters. Table 1 shows the required parameters needed for CDPM simulation in ABAQUS as reported by Al-Osta et al. (2017). The remaining parameters were taken from the experimental results shown in Figure 6 (Al-Osta et al. 2017).

Table 1. The CDPM parameters for both normal concrete and UHPFRC (Al-Osta et al. 2017).

$\Psi(^\circ)$	$\in$	$\frac{\sigma_{b0}}{\sigma_{c0}}$	K	Viscosity Parameters
Normal Concrete (NC)				
36	0.1	1.16	0.667	0
UHPFRC				
36	0.1	1.16	0.667	0

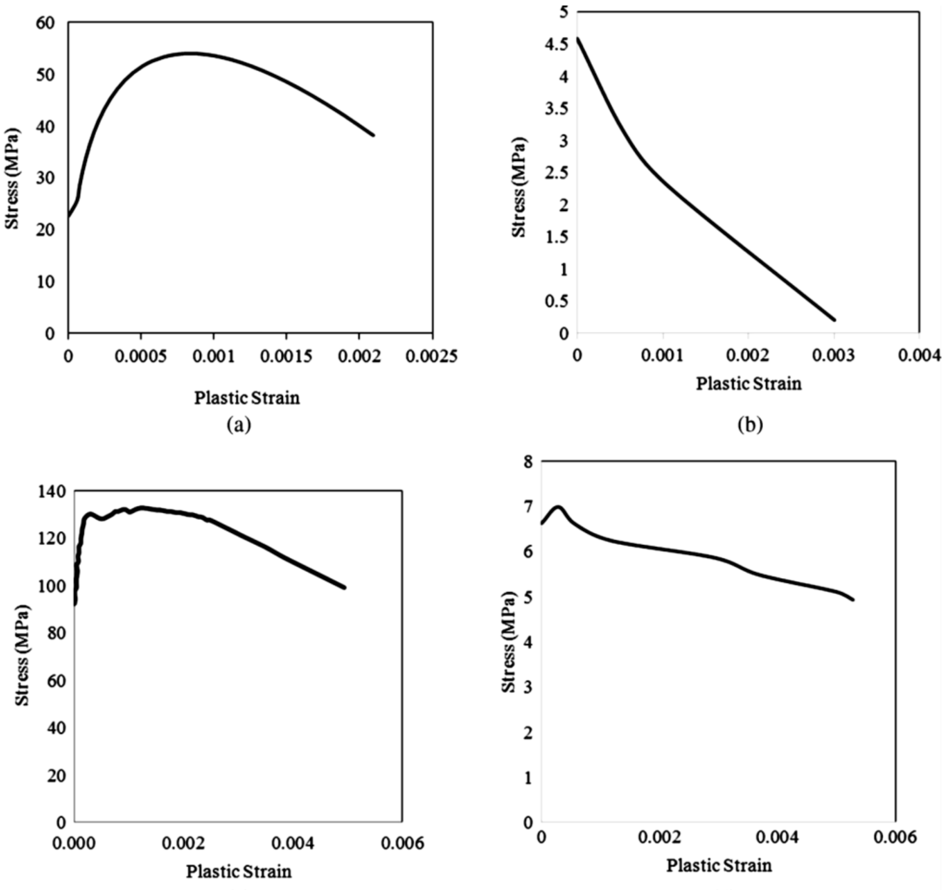


Figure 6. The nonlinear behaviour of (a) compression in normal concrete (b) tension in normal concrete (c) compression in UHPFRC (d) tension in UHPFRC (Al-Osta et al. 2017).

Perfect bond was assumed between concrete and UHPFRC, as reported by Al-Osta et al. (2017). They did not observe any deboning between UHPFRC and concrete during experimental testing.

An elasto-plastic response was considered for modelling the steel reinforcement behavior. The stress-strain curve for the steel rebar is shown in Figure 7. Linear-isotropic behavior was used for steel plates modelling. The modulus of elasticity, Es, and the Poisson's ratio, ν, of steel bars and steel plates were considered as 200 kN/mm2 and 0.3, respectively (Al-Osta et al. 2017).

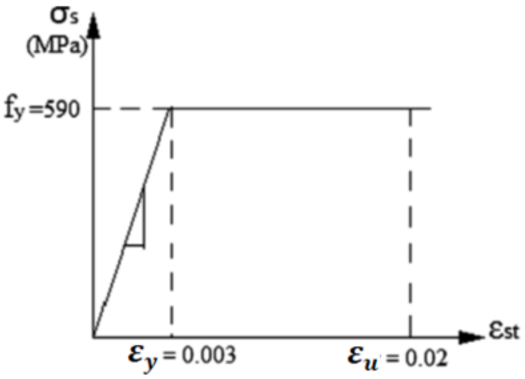


Figure 7. Tension behaviour of steel reinforcement rebar (Al-Osta et al. 2017).

In order to simulate the bond between two surfaces in ABAQUS using the cohesive surface-bonding model, parameters, which define the interaction response, were selected to reflect the exact response of bond slip relation between steel bars and normal concrete. There are several models reported in literature for modelling the concrete-steel interface for RC members. The approximations used in ABAQUS by expressions for the shear and normal stiffness's are given by Eqs. 1 and 2:

$$k_{ss} = k_{tt} = \frac{\tau_{\mathrm{max}}}{\mathrm{S}_1} \tag{1}$$

$$k_{nn} = 100\, k_{tt} \tag{2}$$

Where:

k_{nn} = stiffness in the normal direction

k_{ss} = stiffness in the shear direction

k_{tt} = stiffness in the tangential direction

τ_{max} = bond strength of steel bar

S_1 = slip at maximum bond stress

The τ_{max} and S_1 values can be calculated using Eqs. 3 and 4. Eq. 3, which is suggested by (EL Maaddawy et al. 2005), is used to calculate the bond stress τ_{max} of corroded and non-corroded rebar in the reinforced concrete structures in MPa. It includes two main terms, the first term is the influence from normal concrete, whereas the second term is influence from stirrups.

$$\tau_{\mathrm{max}} = \mathrm{R}\left(0.55 + 0.24\ \frac{C_{\mathrm{c}}}{\mathrm{d}_b}\right) \mathrm{fc}' + 0.191\ \frac{\mathrm{A}_t\ \mathrm{f}_{yt}}{S_S \mathrm{d}_b} \tag{3}$$

Where:

R = the bond loss reduction factor, this value is taken equal to 1

c_c = smaller of clear cover of RC or one-half clear spacing between rebar

d_b = steel reinforcement bar diameter

S_{S} = spacing between the stirrup

A_t = total cross sectional area of stirrup within Ss space

f_{yt} = stirrups yield stress.

To calculate the slip at maximum bond stress, S_1, a model for slip values which is proposed by (Kallias and Rafiq 2010) was adopted. The value of S_1 is equal to S_{max} given by Eq. 4 and maximum slip $S_2 = 0.35\ C_0$, where C_0 = rib spacing = 8 mm (assumed by Kallias and Rafiq 2010).

$$\mathrm{S}_{\mathrm{max}} = 0.15\mathrm{C}_0 \mathrm{e}^{\frac{10}{3}\ln\left(\frac{\tau_{\mathrm{max}}}{\tau_1}\right)} + S_0 \ln\left(\frac{\tau_1}{\tau_{max}}\right) \tag{4}$$

Where:

τ_1 = bond strength in well confined concrete = $2.57\sqrt{\mathrm{fc}'}$

S_0 = 0.15 and 0.4 mm for plain and steel confined concrete, respectively.

4 RESULTS AND DISCUSSIONS

The load-displacement behavior of the proposed finite element model developed in this study was plotted and compared with the experimental and numerical results reported by Al-Osta et al. (2017) for the strengthened RC specimen by using different simulation technique for the bottom steel bars. Comparison of the load deflection behavior of experimental, numerical and the proposed FEM show that the developed model can capture both load development and stiffness of RC beam with high precision as shown in Figures 8. Although, both 3D-tied and 3D- cohesive models showed a perfect matching with the experimental results, the surface cohesive model is recommended since the interaction between rebars and concrete can be controlled and adjusted.

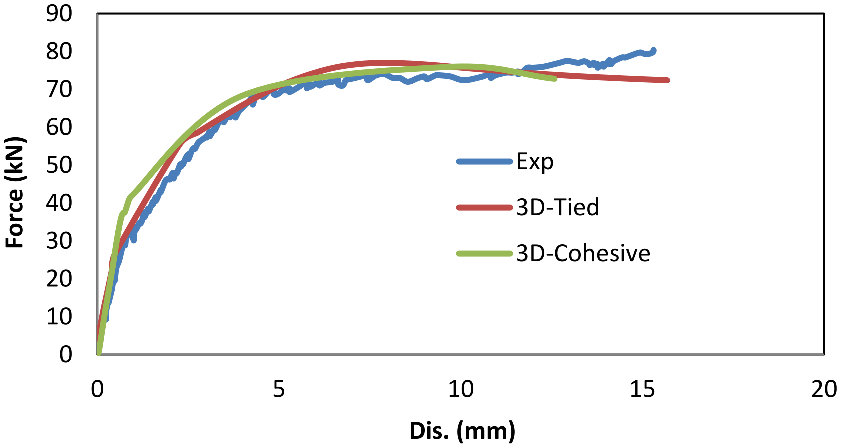


Figure 8. Load-Displacement behavior for the strengthened RC beam

The experimental crack pattern shows high resemblance with that obtained from finite element simulation using 3D- cohesive model, as shown in Figure 9. This matching between the experimental and numerical results indicates the adequacy of the proposed model to predict the behavior of the RC specimen with high accuracy.

(a) (b)

Figure 9. Crack pattern for the strengthened RC beam (a) experiment (b) 3D-Cohesive FEM

5 CONCLUSIONS

A 3D finite element modelling of a reinforced concrete beam strengthened by UHPFRC layer was carried out using the explicit dynamic approach in ABAQUS and CDPM for UHPFRC and normal concrete. The surface-based cohesive interaction technique was used to model the bond between the 3D- element steel bars and normal concrete.

Based on the results of the present study, following conclusions can be withdrawn:

- The damage-plasticity simulation for concrete in FE software ABAQUS has been found to model accurately the response of the RC beam.

- Validation of the proposed 3D finite element modelling using experimental and numerical data showed a very good matching of the experimental and predicted data.
- The alternative technique of using cohesive surface bonding method to simulate the bond between the steel bars and concrete can predict the behavior of RC beams with a good degree of accuracy.

6 ACKNOWLEDGMENTS

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