Numerical Modeling for Flexural Behavior of UHPC Beams Reinforced with Steel and Sand-Coated CFRP Bars

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Abstract. Many properties of advanced materials need to be studied, including ultra high performance concrete (UHPC) as well as the Carbon Polymer Reinforcing Fiber (CFRP) rods of sand coated surfaces. The combined action of (UHPC) with (CFRP) is of constructive importance for researchers to know the behavior of the structural members in different loading stages. Eight samples were prepared with dimensions of 2.4 meters in length, 0.25 meters in depth, and 150 mm in width. The compressive strength of 110 MPa was selected after preparing many trail mixes. A computer model by ANSYS 11 program was made for the representation of all inputs, including steel fibers. All parts of beams, testing accessories, and loads were simulated with adequate elements. The study examined the effect of the orientation of steel fibers on the flexural capacity in terms of load-deflection response. It was concluded that the distribution of the steel fibers plays a fundamental role in the behavior of the models, and thus the optimal distribution was found to be orthogonal distribution to the longitudinal direction of UHPC beam in equal ratios.

Keywords: Ultra high-performance concrete (UHPC); CFRP bars; flexural strength; finite element.

1. Introduction

Reinforced polymer fibers are a successful alternative to steel reinforcement in terms of corrosion and magnetic resistance due to their polymeric properties. It generally consists of fibers immersed in a resinous substance. It can be considered as an additive method to the used methods to protect the installations in harsh environments such as protecting concrete itself, using stainless steel, or using the cathodic method to protect reinforcing steel [1], see Fig. 1. The increase in concrete strength requires an increase in the cement content and a decrease in the water content of the mixture, which causes great difficulty in workability. So, the concrete mixture by a specific manufacturing regime can be produced [2-12]. All materials for production UHPC with their proportions per cubic meter were illustrated in Table 1.

Recently, the structural problems can be numerically simplified using the Finite Element Method (FEM). The systematic procedure of computer abilities consists of assemblage and solving using a specific solver [13]. Many of the features of the available programs encouraged the researchers to simulate the UHPC material, reinforcement, stress-strain relations of different materials, concrete crack/crush, failure criterion of CFRP bars, modeling of steel fibers, ease in managing outputs, and capturing images at any time of loading step [14]. The brick elements of 20-node were used. The designed failure type was shear for all beams [15]. The reinforced bars were taken as an axial member. Empirical equations for both compressive and tensile strength were used.
Figure 1. Types of FRP Reinforcement.

Table 1. Mix Proportion for UHPC.

|                | Cement (kg/m³) | Sand (kg/m³) | Silica Fume (kg/m³) | W/C (%) | HRWRA (%) | Steel Fibers (kg/m³) |
|----------------|----------------|--------------|---------------------|---------|-----------|----------------------|
|                | 812            | 1100         | 195                 | 21      | 3         | 158                  |

A square plate with one opening and 60cm thickness was investigated by ANSYS software [16]. The utilized element for simulation of the plate was a 4-noded thick element. By making use of symmetry, one part of (L shape) was chosen. The nonlinear analysis for UHPC beams was performed by selecting the quadrilateral parametric degenerated layer thick shell elements [17]. The twenty-four degrees of freedom were used, i.e., three DOF per node. The tensile strength was considered as an eighty percentage of characteristic compressive strength when testing the indirect tension test. The combined member of high-strength concrete and CFRP bars was numerically studied [18,19,20]. The conventional plain solid element was utilized. ANSYS program was used to achieve the analysis. The CFRP bar was simulated by a discrete bar element. The expected slip was modeled by a spring.

The numerical study by ABAQUS was utilized [21]. The model accounted for the effects of compressive strength, tensile strength. The strain hardening in tension was explicitly included. The study was covered flexural strength, shear capacity, stiffness, and modes of failure. The numerical simulation for determining the shear capacities of UHPC beams was studied in ABAQUS program for tracing the response during all stages of loading [22]. Several Parameters were included as a stress-strain response in both compression and tension, and strain hardening effect. The response parameters obtained from the model were recorded as deflections, crack propagation, and failure mode. Also, The model covered the varying shear reinforcement ratio.

2. Experimental Works

The design of the flexural strength was based on the Japanese recommendations in determining the maximum compressive stress and the distribution curve [23], while the tensile stress distribution of concrete was estimated as forty percent of the root of UHPC’s characteristic. Besides, the samples that containing CFRP bars, were designed based on ACI 440 code [24]. The information sheet of CFRP bars was included to find the maximum tensile stress because of the difficulty in obtaining it in the laboratory. Flexural strengths were similar for each section containing steel or those containing CFRP bars. All details of UHPC beams, Testing, characteristics of UHPC were mentioned in Table 2, Table 3, and Fig. 2.
Table 2. Main features of the tested beams.

| Beam ID | Load (kN) | Flexural Strength (kN.m) | Flexural Strength Ratio (Steel/CFRP) | Reinforcement Area (mm²) | Rebar | Effective depth d (mm) | Steel Stirrup |
|---------|-----------|--------------------------|-------------------------------------|--------------------------|-------|------------------------|--------------|
| FU-1    | 116.72    | 43.19                    | 0.985                               | 2∅12 mm + 1∅10 mm + 3∅6 mm (389.56) | Steel | 185.5                 |              |
| FU-S-1  | 118.42    | 43.81                    |                                     | 2∅12 mm                 | CFRP  | 201                   |              |
| FU-2    | 146.13    | 54.07                    | 1.005                               | 306 mm (84.823)         | Steel | 185.5                 |              |
| FU-S-2  | 145.34    | 53.78                    |                                     | 2∅16 mm                 | CFRP  | 201                   |              |
| FU-3    | 158.85    | 58.77                    | 0.982                               | 1∅6 mm (486.95)          | Steel | 183.5                 |              |
| FU-S-3  | 161.74    | 59.84                    |                                     | 4∅6 mm (113.09)         | CFRP  | 201                   |              |
| FU-4    | 177.6     | 65.71                    | 1.01                                | 1∅10 mm + 4∅6 mm (593.76) | Steel | 183.5                 |              |
| FU-S-4  | 175.67    | 65                       |                                     | 5∅6 mm (141.37)         | CFRP  | 201                   |              |

Table 3. Experimental compressive and tensile strengths of UHPC.

| Sample No. | Compressive strength ($f_c'$) (MPa) | Splitting Tensile Strength (MPa) | Modulus of Rupture (MPa) |
|------------|-------------------------------------|---------------------------------|--------------------------|
| 1          | 108.31                             | 7.55                            | 20.361                   |
| 2          | 111.74                             | 7.08                            | 19.824                   |
| 3          | 104.51                             | 7.17                            | 22.021                   |
| Average    | 109.4                              | 7.27                            | 20.74                    |

Figure 2. Testing UHPC beam.
3. Finite Element Analysis

All parts of the beam must be properly represented in order to perform numerical analysis. Concrete, support's plate, loading's plate, and longitudinal reinforcement all of which a specific element was used to simulate it. The summarized types of elements are mentioned in Table 4.

| Material Type          | Element     |
|------------------------|-------------|
| Concrete               | SOLID 65    |
| Steel plates and Support| SOLID 185   |
| Steel Reinforcement    | LINK 180    |
| CFRP Reinforcement     | LINK 180    |
| Stirrups               | LINK 180    |

3.1 Real Constants

One of the inputs necessary to achieve a correct representation in the ANSYS program is the Real Constant for each individual element. All real constants are mentioned in Table 5 and Table 6.

| Real constant set | Element type | Real Constants | Diameter (mm) | Area (mm²) |
|-------------------|--------------|----------------|---------------|------------|
| 1                 | LINK180      |                | Ø 6 mm        | 28.27      |
| 2                 | LINK180      |                | Ø 10 mm       | 78.54      |
| 3                 | LINK180      |                | Ø 12 mm       | 113.1      |
| 4                 | LINK180      |                | Ø 16 mm       | 201        |
| 5                 | LINK180      |                | Ø 25 mm       | 409.87     |
| 6                 | LINK180      |                | Ø 6 mm-CFRP   | 28.27      |

| Real constant set | Element | Characteristics | Real constants for rebar |
|-------------------|---------|-----------------|--------------------------|
| 7                 | SOLID65 | Number of materials | examined examined examined |
|                   |         | Ratio of Volume  | examined examined examined |
|                   |         | Horizontal angle (THETA) | examined examined examined |
|                   |         | Vertical angle( PHI) | examined examined examined |

3.2 Steel Fiber Model

One of the most influential aspects of the simulation process for steel fibers is the issue of distribution of these fibers. In this study, the fibers will be modeled by several representations as lumped distribution of smeared bar's field in the characteristic screen of Solid 65 and then, compared with the experimental results of each model. The total percentage of steel fibers was selected in horizontal, vertical, inclined 45° counter clockwise. Two equal distribution in the orthogonal direction (x and z-direction) were used. Distribution in horizontal, vertical, and inclined of counterclockwise 45° were also proposed.
3.3 Simulation of Loads and Boundaries

Two boundary conditions were utilized in the current model. The first one was at support by applied zero displacements and allowed the rotational movement to complete roller support. All nodes in the plane of symmetry in mid-span were constrained in orthogonal direction relative to transverse direction (UZ = 0 and UX = 0). The transverse movement was free as shown in Fig. 3. The lumped applied load was placed at the steel plate on two external nodes and half-value for other internal nodes. The half beam was selected for all models.

![FE mesh diagram](image)

**Figure 3.** Typical details of FE mesh.

3.4 Analysis Performance

The linear static analysis was used. The small deformation was considered while the large deformation effects were neglected. Generally, the time denotes to load, in other words, the time at the ending load step refers to the ending load.

4. Results and Discussion

When looking at the UHPC beam having steel bars, Fig. 4 to Fig. 7, the increase in stiffness is clear when the rebar ratio is increased. Also, the deflection in the middle of the space decreases with the increase of the reinforcing steel bars of UHPC beam. The numerical representation using equal distribution of the steel fiber ratio as smeared bars in the two orthogonal directions on the longitudinal direction approaches greatly and is almost identical with the practical results. This gives an impression of the importance of representing the distribution of fibers and their effect on the behavior of the structural members. The linear behavior for pre-crack and post-crack stages was noticed for both the experimental and 2-way proposal models.

As for beams containing CFRP bars, Fig. 8 to Fig. 11, the stiffness increases when the proportion of the polymer fiber is increased with decreasing in the mid-deflection. In this type of beam, the stiffness is lower if compared to samples that reinforcing with steel bars due to the lower stiffness of the polymer fibers originally. The same as previous behavior of steel bars reinforced models with respect to pre-crack and post-crack behavior as well as numerical analysis about steel fibers distribution was noticed.
Figure 4. Mid-deflection vs Loads, FU-1

Figure 5. Mid-deflection vs loads, FU-2

Figure 6. Mid-deflection vs loads, FU-3.

Figure 7. Mid-deflection vs loads, FU-4.

Figure 8. Mid-deflection vs loads, FU-S-1.

Figure 9. Mid-deflection vs loads, FU-S-2.
5. Conclusions

The ANSYS program can perform the representation of UHPC by using the options in the Solid 65 window, as well as the ability of the program to represent CFRP bars by entering the yielding stress in Link 180, which both give it preference in representing such structural elements. Several proposals were studied for representing the distribution of steel fibers and comparing the results with their practical counterparts. It was found that the optimal distribution is when the ratio of the fibers will be divided into two equal parts in the two orthogonal directions perpendicular to the longitudinal direction of beams. The numerical representation was very suitable for both pre-crack and post-crack behavior. The results revealed that there was no need for slip representation between UHPC and CFRP bars due to the breakdown of the surface layer of the fibers in the last loading stages. Also, the ductility ratio for beams containing CFRP is higher than those having steel bars.

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