

Numerical Simulation Study On Load Deflection Of Reinforced Ultra High Performance Fiber Reinforced Concrete And Normal Concrete Beams Under Static Load

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Abstract: *One of the biggest obstacles that prevents emerging concrete types to become widely adopted in construction is the deficiency of standardization background in practice codes for these materials, despite the fact it possess superior properties, such as Ultra-high Performance Fiber Reinforced Concrete (UHPFRC). In this study, Finite Element Analysis (FEA) is utilized to simulate the behavior of UHPFRC and Normal Concrete (NC) simply supported beams under static flexural loading. Abaqus software has been used in which a simplified version of the Concrete Damage Plasticity Model (CDPM) was chosen as a non-linear constitutive model. The model has been validated against conventional CDPM at global (load-deflection) and local (load-stain) levels. Reinforced UHPFRC beam models showed clearly matching response with the validity research paper (reference study) experimental findings. The response of UHPFRC beams has been compared to NC beams. This comparison has been explained in detail and checked with similar material comparisons in the literature. The proposed study has revealed and compared the distribution of cracks in the form of tension and compression damage for both materials. As a conclusion, modelling is an effective way to predict the behavior of concrete beams in which the relative local response was captured in reinforcement bars.*

Key words: *Finite Element Method (FEM), steel, Flexure, UHPFRC, Concrete, Load, deflection, strain.*

1. INTRODUCTION

One of the modern concrete classes recently discovered (mid of 1990s) is the UHPFRC, a new material with superior properties. Likewise all new concrete types, it was developed due to the need of concrete with improved quality. When compared to conventional concrete, UHPFRC has different characteristics like high content of binder, fine aggregate size, presence of fibers and the use of large amount of super-plasticizers. It was developed by relying on the advanced material technologies in which the fine weak spots like pores and micro-cracks are minimized to increase the load carrying capacity of the material [1]; this was achieved due to the high binder content and low W/B ratio which leads to the absence of capillary porosity. Whereas the fibers are introduced to improve the tensile strength of the cementitious material as well as to enhance the ductile behavior. Although it has unique properties, UHPFRC is not widely used in construction due to high cost of the material itself and the lack of practical design code regulations along with the high testing costs.

Abaqus/CAE, or "Complete Abaqus Environment" (a backronym with an obvious root in Computer-Aided Engineering) is a three-dimensional finite element (FE) package with advanced modelling capabilities which is mostly utilized as a research tool [2]. It has many commands to create variety of elements and wide range of material constitutive models to simulate the behavior of most typical materials. Simulation using such models plays an important role in minimizing the number of experimental tests needed to establish accurate response of the materials [3]. As a consequence, the ultimate benefit of any simulation research will be in terms of saving time, money and effort especially when the material under consideration or testing machine needed are not available or require huge budget. Even one can avoid doing any checking tests by referring to test results of previous studies. The practice is changing towards focusing on the numerical model only and not to perform any experimental testing; since many tests are already done in the past. In case of new material, only few tests are necessary for the identification of constitutive model parameters [4].

Several laboratory investigations on the behavior of UHPFRC beams under load were conducted. These tests came out with a conclusion stating that higher fiber content will increase the beam flexural and shear capacities. Only few numerical simulation studies have mentioned the structural behavior of UHPFRC beam. Studies that simulated the response of UHPFRC members using finite element based numerical method have indicated that the prediction of allowable load capacity by relying on the finite element model can give results with a high degree of accuracy. However, these studies has performed experiments to a small extent and accounts only for global response of UHPFRC without considering the local response (strain and cracking). Finite element based numerical modelling was conducted in the research paper by (Solhmirzaei & Kodur, 2017) [5] to overcome this deficiency of numerical studies on UHPFRC beams, in which the paper is focusing on the structural member response globally and locally. The local behavior was taken as the overall strain in steel reinforcement at mid-span although experimental results have shown obvious difference between center bars and corner bars. It was unclear whether Abaqus software is able to capture this difference based on FEM, so it is required to find out the local response of center bars relative to corner bars. In addition, the advantage of UHPFRC over the NC was evaluated as a ratio of load capacity and then the obtained proportions are related to proportions from previous studies in flexure.

(Shafieifar, Farzad, & Azizinamini, 2017) [6] have already compared between the two materials experimentally and numerically but in terms of testing that is performed on small specimens for the purpose of getting the mechanical properties.

Emerging materials such as UHPFRC require more investigation in order to establish the main guidelines for design and construction practice, while frequent testing on such material is not feasible due to the variety of its specifications in terms of fiber detailing (Singh, Sheikh, Ali, Visintin, & Griffith, 2017) [7]. An alternative approach is necessary to deal with this lack of material standardization. With the aid of FE package such as Abaqus, it is possible to predict precisely the behavior of concrete not only in a cost effective way, but it reduces time and effort as it will replace the conventional material testing [2]. This investigation will go further by studying the behavior of structural element itself instead of small specimens and then check simulation output with experimental data available in the literature.

2. LITERATURE REVIEW

Simulation researches became a trend in most of the educational institutions around the world, especially in engineering applications. The literature provides many researches on the modelling of concrete using Abaqus software or other software programs. Herein we are going to refer to some of the published papers related to this project. Only studies of the flexural response with CDPM are included in a chronological order with some investigations on UHPFRC compared with NC.

(Wahalathantri, Thambiratnam, Chan, & Fawzia, 2011) [8]: CDPM was used to compare the non-linear behavior of reinforced concrete elements experimentally and numerically. 3 point, 4 point and un-symmetric 3 point bending tests are modeled and compared with real test results. The model shows very good agreement with the test results, namely the accuracy of displacement values was in the range of 95% to 98%.

(Deng, Qie, & Wang, 2015) [9]: Simply supported reinforced concrete beam was modeled with CDPM using Abaqus. Through steel bar embedment and concrete failure definition by damaging, the model showed similarity to a large extent in mid-span deflection when compared with testing deflection. It was stated that Abaqus is precise but more investigations are needed to avoid small differences in the results.

(Singh, Sheikh, Ali, Visintin, & Griffith, 2017) [7]: Due to the urgent need for a methodology that saves the amount of testing required for materials having no background and due to the variety of UHPFRC specifications and detailing, it is necessary to rely on FE models. The study focused on the flexural behavior of steel reinforced UHPFRC beams under 3 and 4 point bending tests and models were developed using CDPM. The results showed very good agreement in terms of load carrying capacity and load-deflection curve with ability to capture the entire load-deflection response from the start of loading until failure.

(Hafezolghorani, Hejazi, Vaghei, Jaafar, & Karimzade, 2017) [10]: Behavior of simply supported partially pre-stressed beams was modeled with Simplified Concrete Damage Plasticity Model (SCDPM) for grades B20, B30, B40 and B50. The mid-span displacement was compared with empirical deflection formulation and with the conventional CDPM. The clear correlation between the suggested SCDPM and the other two approaches led to describe simplified model as "realistic" due to its ability to detect the damage in tension and

compression of concrete along with the mid-span displacement.

(Solhmirzaei & Kodur, 2017) [5]: The response of UHPFRC beams under flexural and shear loading was modeled using CDPM. The response of UHPFRC beam obtained from the numerical model was compared to virtual test results. In conclusion it was stated that the model was able to capture the overall experimental response during all stages of loading. Results agreement was proven globally through load-displacement curve and locally through load-strain curve on rebar at mid span. This is the only paper was found in which the local behavior is taken into account.

(Shafieifar, Farzad, & Azizinamini, 2017) [6]: A general comparison between Ultra-high Performance Concrete (UHPC) and NC in terms of mechanical properties and behavior in order to demonstrate the superior characteristics of UHPC over the NC. Compression and tension tests were conducted on specimens of both materials. FE numerical model was utilized using Concrete Damage Plasticity (CDP) to simulate the behavior of same materials. Compressive strength of UHPC was three to four times the strength of NC, tensile strength was two to four times and flexural strength was 4.5 times. Material parameters obtained from numerical modeling have good agreement with the actual properties.

(Pourbaba, Sadaghian, & Mirmiran, 2019) [11]: Experimental investigation was done for the flexural and shear behavior of five UHPC beams. Four point bending test was performed on concrete specimens, compared with laboratory results of five Normal Strength Concrete (NSC) beams. The analysis of failure mechanisms and crack distribution pointed out that bending caused the failure in UHPC beams while NSC beams failed by shear. Results showed that the experimental flexural and shear capacities of UHPC specimens are greater than NSC specimens up to 3.5 times. Comparison of experimental values with theoretical values represents moderate estimation for low reinforcement ratios in most of the models.

3. METHODOLOGY/MATERIALS

3.1 Experimental Details

The beam was tested in flexure in which four-point bending test has been modeled when a static load is applied, then model results were compared with data provided by (Solhmirzaei & Kodur, 2017) [5] from which same test layout has been followed with similar UHPFRC properties. Also beams are introduced with two configurations, either 3 or 4 tension bars, so that two models are made for each concrete type as shown in Table-1. The units of quantities in all four models are in Millimeters for length, Newton for force and Mega pascal for stress [3]. In simulation, force has to be applied by rigid surface [12]. To satisfy this condition, the model includes two plates with dimensions of 180×60×20 mm as shown in Figure 1. The load which was applied on both plates is a pressure load with a total force of 107.7 kN for U-B3 and 126.6 kN for U-B4 (half load magnitude on each plate). Moreover, the beam is simply supported with other two plates, one is pinned (or hinged) and other is roller support. For the material nonlinearity, elastic properties has been considered for liner stage and plastic properties for non-liner stage when all the parameters of concrete and steel are fed into Abaqus program [4].

Table-1: Concrete material and bar description for each beam model

Beam designation	Dimension (mm)	Type of concrete	No. and dia. of bars
U-B3	4000 × 270 × 180	UHPFRC	3Ø13 mm
U-B4		UHPFRC	4Ø13 mm
N-B3		NC	3Ø13 mm
N-B4		NC	4Ø13 mm

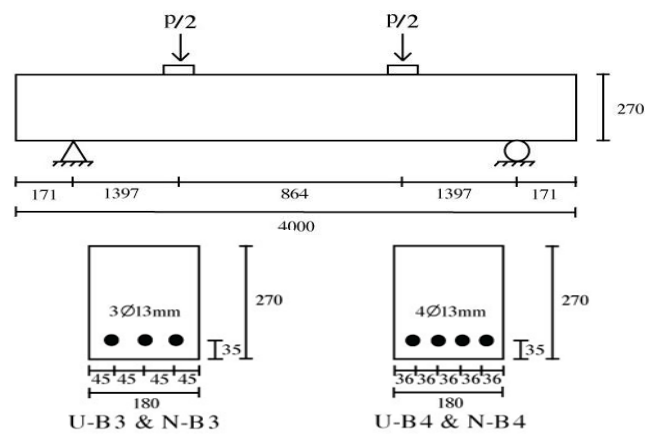
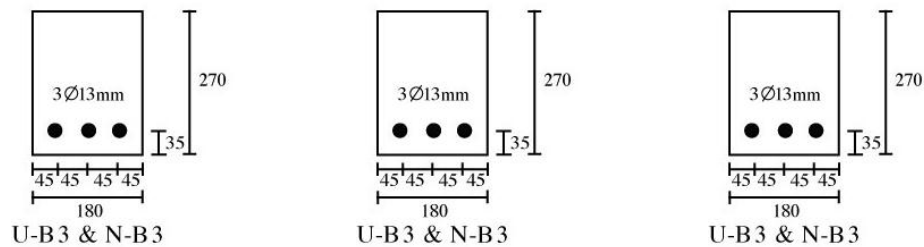


Figure 1: Loading condition, test layout and beam cross-section. (All dimensions are in mm)

3.2 Numerical Model



Simply supported beam layout as proposed by (Solhmirzaei & Kodur, 2017) [5] has been followed throughout all the four models with total span of 4 m and cross-section of 0.18 m by 0.27 m. Four-point bending test arrangement was introduced in which two plates with half load

magnitude is being applied on each plate. Two different reinforcement layouts have been simulated with concrete cover in the longitudinal direction of 45 mm. Cover to reinforcement in other directions, beam dimensions and rebar detailing are shown in Figure 1. During model formation, for both concrete and steel bars, the 3D 8-Node Solid Brick Element with Reduced Integration (C3D8R) has been selected [2]. The bonding between the reinforcement bars and beam has been formed by introducing embedded region constraint for the bars inside the beam (host region) from the interaction section in Abaqus [3], [4].

In Abaqus analysis user guide, section 2.2.4 (Defining rebar as an element property) which is linked to section 23.6.3 (Concrete damaged plasticity), it was stated that the definition of rebar layer emended in solid element has to be as a Continuum (Solid) Element (C3D8). Also it is mentioned that beam element cannot be used for steel reinforcement as it include shear stress caused by torsion. Based on these two statements, both material elements (concrete and steel) are set as 3D 8-Node Solid Brick Element with Reduced Integration (C3D8R) [3], [4].

3.3 Material Properties

The ultimate compressive strength f_{cu} for UHPFRC is 193 MPa and tensile strength is 7.11 MPa. The properties of NC are taken from numerical simulation study by (Hafezolghorani, 2017) [10] with concrete grade of B50 (50 MPa) and tensile strength of 5 MPa. Even though it was used with partially pre-stressed beam, in this study 50 MPa strength has been selected as the maximum strength of NC. UHPFRC yield strain is 0.0044 while ultimate strain is 0.008. All other parameters are shown in Table-2 including elasticity and concrete damage plasticity parameters. Steel properties are as shown in Table-3. Stress-strain response of UHPFRC material in Table-4 is necessary to calculate the damage plasticity parameters using the Simplified Concrete Damage Plasticity Model (SCDPM) [10] including inelastic (or crushing) strain, cracking strain, compression damage and tension damage.

Table 2: Material properties of UHPFRC and NC

Concrete Property		UHPFRC	NC
Elasticity parameters	Young's Modulus, E	43970 MPa	33400 MPa
	Poisson's ratio, ν	0.2	0.2
Concrete damage plasticity (CDP) parameters	Dilation angle, ψ	39°	31°
	Eccentricity, ξ	0.1	0.1
	Biaxial stress ratio, σ_{b0}/σ_{c0}	1.16	1.16
	Second stress invariant ratio on tensile meridian, k_c	2/3	0.67
	Viscosity parameter, μ	0.0001	0

Table 3: Material properties of steel reinforcement

Elasticity parameters	Young's Modulus, E	207000 MPa
	Poisson's ratio, ν	0.3
Plasticity parameters	Tensile yield strength, f_y	435 MPa
	Tensile yield strain, ϵ_y	0.0021
	Tensile ultimate strength, f_u	700 MPa
	Tensile ultimate strain, ϵ_u	0.12

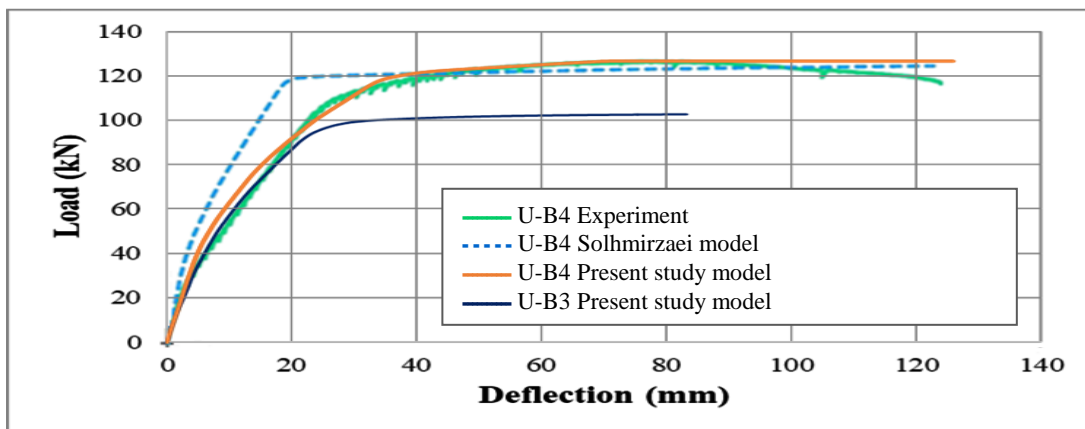
Table 4: Uniaxial stress-strain response of UHPFRC in compression and tension

Compressive response				Tensile response	
Stress (MPa)	Strain			Stress (MPa)	Strain
0	0.00000	187	0.00510	0.001	0.00000
100	0.00230	118	0.00600	7.110	0.00033
150	0.00350	77	0.00640	7.110	0.00200
167	0.00390	33	0.00700	6.110	0.00830
193	0.00490	9	0.00820	0.100	0.01800

4. RESULTS AND FINDINGS

Four models have been developed based on one complete model. After getting first model results, the model assembly is modified to form the other steel bar configuration and then material properties are changed to model the other material. When analysis results are shown, a variety of visual outcomes (e.g. stress, strain, displacement, reaction force...etc.) will appear on the beam deflected shape and expressed by a range of colors and each color refers to a certain value as proposed by the legend. Numerical values for each result (outcome) are taken using Output Database (ODB) command and all the values are transferred to an excel sheet to represent the tabular format values as graphical curves. In addition, the extracted results were illustrated as visual images and comparison tables.

4.1 Load vs. Deflection of UHPFRC



Figure

2: Load-deflection curve comparison for U-B4 and U-B3

As Figure 2 demonstrates, the load-deflection curve obtained for U-B4 is quite satisfactory when compared to experimental data. It can be seen that the response of the two beams has different stages starting from linear elastic stage until crack initiation in tension followed by post-cracking stage with linear response for rebar until steel yielding then finally plastic deformation until peak load with continuous curve up to the stage of approaching failure with fully plastic response. For U-B4 beam in Figure 2, the three curves have exhibit almost the same behavior in plastic stage but for the elastic stage there are three distinct paths. This difference can be explained by referring back to the test arrangement. The breadth of the spot (plate) at which the load is applied will affect the load intensity and hence the slop of the elastic linear curve will be inversely proportional to the load spot breadth. U-B4 beam gives higher deflection than U-B3 due to the occurrence of concrete failure while the steel reinforcement is

in its plastic stage. The ability of U-B4 to carry the load is greater than U-B3; since neutral axis depth is more in the former with larger area of concrete in compression and hence the plastic elongation in steel bars will be increased accordingly with higher loads resulting in more deflection. The load at failure for U-B4 beam is almost equal to the experimental load at failure which was 126.6 kN while the load from numerical model obtained by (Solhmirzaei & Kodur, 2017) [5] was 124.6 kN. For U-B3 beam the load at failure is 102929.3 N \approx 102.9 kN compared to 107.7 kN as obtained from (Solhmirzaei & Kodur, 2017) [5] modelling and 97.1 kN from test results of the same study.

4.2 Load vs. Deflection of NC

As shown in Figure 3, the load at failure for N-B3 beam is 32094.98 N while the load at failure for N-B4 beam is 32661.44 N. From the study done by (Shafieifar, Farzad, & Azizinamini, 2017) [6] who has mentioned in his study that the UHPC flexural strength is up to 4.5 times the flexural strength of NC. Considering the flexural strength equation for 4-point bending test:

$$\sigma = 3 P (L - L_i) / (2 b d^2) \quad (1)$$

where P is the load at failure, L is the span, b is the beam width, d is the beam depth and L_i is the distance between the two loads applied in 4-point bending test. Obviously, all terms in the previous equation are equal in beams N-B4 and U-B4 except the load at failure (P). Hence the ratio of the load at failure will give the ratio of flexural strength of the two beams. When dividing the load capacity of U-B4 by the load capacity of N-B4 the result equals 3.876 and this value is in agreement with the statement by (Shafieifar, Farzad, & Azizinamini, 2017) [6] where 4.5 is the maximum ratio limit. The statement is applicable also for N-B3 beam against U-B3 beam as the ratio of the load carrying capacity for UHPFRC beam to NC beam is 3.206.

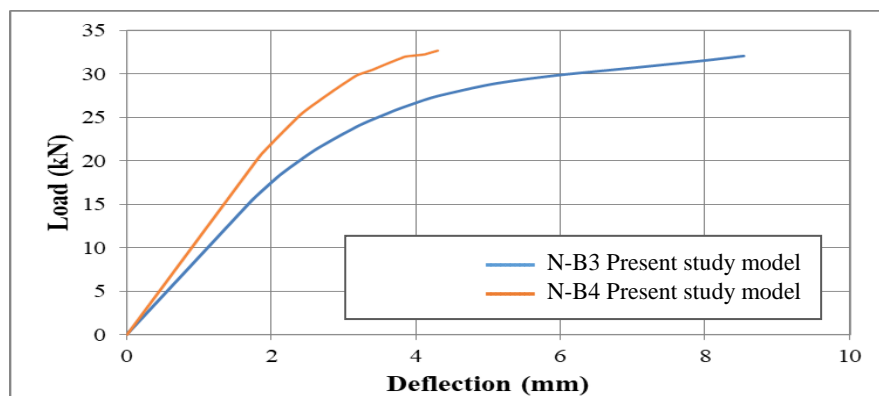


Fig Load-deflection curve comparison for N-B3 and N-B4 **ure 3:**

4.3 Load vs. Strain of UHPFRC beam reinforcement

In the strain experimental results, the higher strain magnitude in middle bars (Figure 4) can be explained by what is called anticlastic bending effect. In the rectangular beam section shown in Figure 5(a), the direct stress distribution due to bending in the vertical direction varies from maximum compression in the upper layers of the beam to tension in the lower layers of the beam as in Figure 5(b).

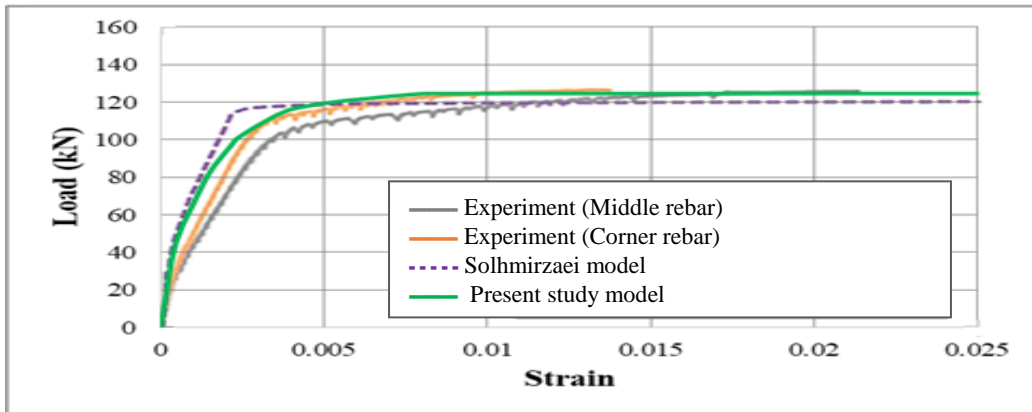


Figure 4: Load-strain curve comparison at mid-span of rebars for U-B4 beam

Due to the Poisson effect, the compressive stress results in a lateral elongation of the uppermost fiber of the beam cross-section while the tensile stress results in a lateral contraction of the lowest fiber (soffit) of the beam cross-section. The section does not therefore remain rectangular but deforms as shown in Figure 5(c); this effect is known as anticlastic bending [13].

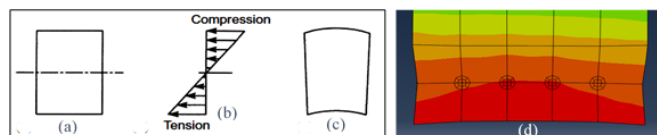


Figure 5: Anticlastic bending illustration and its effect on strain distribution in U-B4 beam cross-section

Anticlastic bending will result in a curved shape in traverse direction for both top surface and bottom surface of the beam so that when considering the lower surface it can be noted clearly that the two bars at the center will be exposed to a higher strain; since they are more confined near to the peak of the soffit curvature while corner bars have deformed inwards due to lateral contraction. Strain distribution at mid-span cross-section for U-B4 beam model is illustrated in Figure 5(d) where the curved shape due to lateral contraction is clearly formed at beam bottom surface. The model cross-section is emphasizing the deformed shape proposed by the anticlastic bending effect.

Both curves in Figure 4 and Figure 6 are in agreement with experimental and modelling results of (Solhmirzaei & Kodur, 2017) [5]. Sharper deviation is observed in (Solhmirzaei & Kodur, 2017) [5] curvature transition from elastic to plastic behavior similar to load-deflection graph in Figure 2. In addition to pressure load intensity, this can be justified by the rate at which the load is applied. From Figure 6, it can be seen that full strain magnitude has not been reached as the analysis job stopped with a message of increment (convergence) error. In some modelling situations, the analysis job will terminate at certain stage and this is the case in U-B3 beam (Figure 6). This may happen due to the high distortion of the model elements or any kind of instabilities so that the program is not able to proceed the analysis. To solve this issue it is required to introduce a sort of stabilization to the model which can be done by different techniques and options such as hourglass section control, dissipated energy fraction, element viscosity and "Nlgeom" (geometric non-linearity).

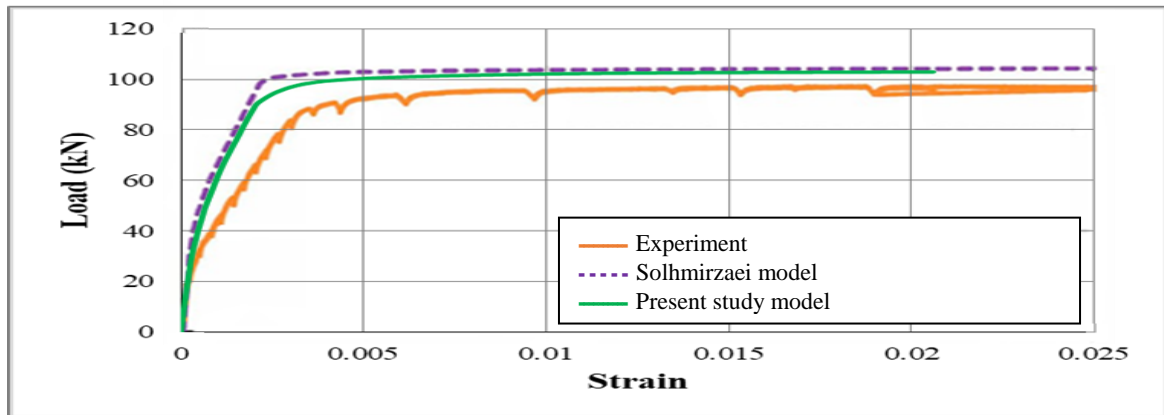


Figure 6: Load-strain curve comparison at mid-span of rebars for U-B3 beam

4.4 Visual Damage

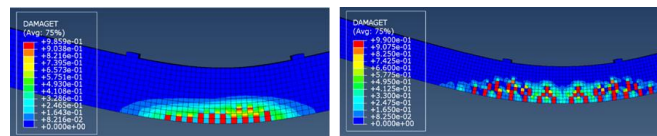


Figure 7: Side view of tension damage distribution for U-B3 and N-B3 beams

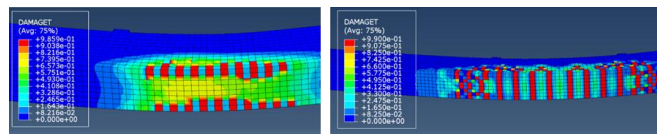


Figure 8: Bottom view of tension damage distribution for U-B3 and N-B3 beams

From Figure 7, it can be seen that longer cracks are formed in NC beams up to the beam mid-height starting from the bottom as discrete tension cracks. Whereas the UHPFRC beam has shown limited crack length in the tension zone and cracks at the beam soffit are not continues through the beam width as shown in Figure 8. When referring back to the composition of the two materials, it can be inferred that the fibers in UHPFRC beam act as a bridge for the cracks with strong interlocking to the concrete matrix and therefore severe crack propagation is prohibited. This explains the observations of damage in which the damage in UHPFRC beams is smooth and gradually distributed in limited areas, whereas in NC beams separated cracks have taken place within larger range around the weak spots of the beam mass. There is no compression damage in N-B3 and N-B4 beams because the failure in these beams was in the tension zone only.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The numerical model (CDP) was used to get the behavior of UHPFRC and NC beams under static loading. It captured the structural response from the moment of applying the load until failure. The load at failure is near to the load obtained by experimental test. In general, the results of the two UHPFRC models are matching with the experimental findings in both: global (load-deflection) and local (load-strain) levels. Furthermore, damage expectations, cracking patterns and failure modes are quite satisfactory for the two materials. The main comparisons and observations in this study are:

- Load capacity of UHPFRC beam is around 3 to 4 times the load capacity of NC beam when both beams are steel reinforced.
- The beam deflection is reduced as more reinforcement bars are added only when the concrete fails while bars are still in the elastic stage and this is the case in NC due to its brittleness. On the other hand, more bars in UHPFRC beam can result in higher deflection as bars are in plastic stage at the point of beam failure and hence more bars will undertake plastic elongation resulting in additional deformation. Since UHPFRC is ductile rather than brittle, it has the opposite behavior of NC beam.
- At high concrete grades, adding one rebar has more effect than the addition of the same bar at lower grades. The load carrying capacity difference between 3 bar and 4 bar beams in UHPFRC is 23.7 KN (see Figure 2), while this difference in NC beams is 0.566 KN (see Figure 3).

Abaqus software assumes that all test elements and arrangements are ideal including geometry, material properties, load application and beam supporting conditions. Due to software idealization, FE model showed stiffer behavior when compared to experimental test response. This can be seen clearly in Figure 2 where a horizontal (fully plastic) curve represents the numerical model response but the experimental result was different with a dip in load value after reaching the maximum value (load at failure). Concrete and steel material properties with the associated geometry and test circumstances are unideal in virtual test but they are not in the FE model. Different assumptions regarding test idealization gave two different curves. Load-deflection and load-strain curves are influenced by the load intensity mostly in the elastic stage in which different slopes are observed for model and experiment. Load applied on wider element will give less intensity and vice versa. Load application rate has also an important role in beam behavior. It can be stated that load application in real flexural test was more gradual when compared to numerical model.

SCDPM has proven its reliability for a wide range of concrete classes including high strength concretes such as UHPFRC. Fibers action in UHPFRC which enhance the material ductility was captured clearly when the damage of UHPFRC and NC beams was compared. Considering UHPFRC model outcomes, CDPM was able to imitate the behavior of quasi-brittle material effectively even though it is used mainly to model brittle materials such as concrete and concrete like materials. It offers the ability to define failure mechanisms in any element of concrete structure.

5.2 Recommendations

As SCDPM has few parameters to be defined compared to other constitutive models, it is recommended to adopt this simplified model when making several simulation models of different conditions. The simplified model is showing a quite satisfactory degree of accuracy.

It is possible to improve the simulation results of existing modeling studies in the literature by using different modelling techniques. Also when creating new models, other assumptions can be made like reducing the load intensity instead of using line load on the beam (ideal case).

Checks on both global and local levels are necessary when using the same constitutive model

with two or more different materials. Comparative experimental or numerical simulation studies can support the model results and emphasize the proposed constitutive model validity.

During beam model establishment, some details may differ likewise the type of steel rebar element. Depending upon the modelling technique, some scholars used to assign steel reinforcement as truss or beam element while others set the same bars as solid element. Consequently, it seems there is no clear and detailed rules to be followed when creating a numerical model but there is an agreement about the main formation steps. A clear criteria is required to assist the usage of element types in reinforcement bars.

High distortion of model elements or any other unstable condition may occur in some situations when the model analysis (while job is running) is not converging to the solution. For that, model stabilization options in Abaqus can resolve this issue.

Similar to concrete smeared cracking model or other cracking model, CDP is able to predict crack propagation patterns. However, crushing and cracking are defined by compression and tension damage respectively. These cracking models are not able to predict the non-linear behavior in compression so that CDP has to be followed for any kind of non-linearity.

It is recommended to imitate the same experimental test circumstances in the numerical model. For example, the supports fixation manner and its contact area with the beam in addition to the contact area of the loading object and beam's top surface. Also loading rate must be taken into account. The ideal condition for load and supports is taking a linear shape in simulation but this is not the case in real flexural test. Beam behavior is affected by the contact widths especially for loading in which small widths will give higher load intensity.

Numerical simulation can give the guidelines to obtain properties and behavior of emerging concrete classes. In addition to the long-term behavior, more experimental and numerical data for concrete elements are expected to be available in the future to formulate standards and codes of practice for these types of concrete.

List of abbreviations

– UHPFRC	Ultra-high Performance Fiber Reinforced	Concrete
– FEA	Finite Element Analysis	
– NC	Normal Concrete	
– CDPM	Concrete Damage Plasticity Model	
– CAE	Complete Abaqus Environment	
– FE	Finite Element	
– FEM	Finite Element Method	
– SCDPM	Simplified Concrete Damage Plasticity Model	
– UHPC	Ultra-high Performance Concrete	
– CDP	Concrete Damage Plasticity	
– NSC	Normal Strength Concrete	
– C3D8R3D	8-Node Solid Brick Element with Reduced	Integration
– C3D8	Continuum (Solid) Element	
– ODB	Output Database	

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