THREE-DIMENSIONAL FINITE ELEMENT MODELING OF UHPC USING TOTAL STRAIN CRACK MODELS

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Abstract

The use of UHPC is currently expanding worldwide from bridge deck joints and connections to full components and larger applications. To improve structural design of UHPC and accurately estimate sections capacities for ultimate design conditions, a better understanding of the damage mechanism of the material is needed. Only few studies investigated the behavior of full UHPC structural elements at failure, which are mainly experimental studies. This study aims at extending the use of computational methods by investigating the validity of Total Strain Crack model for capturing the behavior of UHPC until failure. This model, as readily implemented in DIANA FEA software, is used to study the 3D behavior of UHPC under pure tension and compression. The total strain crack model allows independent user-defined stress-strain relationships input in tension and compression, while incorporating sustained tensile strength and strain hardening for UHPC. Published material tests were utilized to develop the finite element model and check analysis results.

Résumé

L'utilisation des BFUP est actuellement en expansion dans le monde, depuis les joints et connections de pont jusqu'à des pièces complètes et des applications à grande échelle. Pour améliorer la conception structurelle des BFUP et estimer précisément les capacités des sections à l'état limite ultime, une meilleure compréhension des mécanismes d'endommagement du matériau est nécessaire. Seulement quelques études, qui sont essentiellement expérimentales, ont étudié le comportement à la rupture d'éléments de structures en BFUP. La présente étude vise à étendre l'utilisation des méthodes de calcul en analysant la validité du modèle de fissuration en déformations totales (*Total Strain Crack Model)* pour l'étude du comportement du BFUP jusqu'à rupture. Ce modèle, déjà implanté dans le code aux éléments finis DIANA, est utilisé pour étudier le comportement tridimensionnel du BFUP en traction pure et en compression. Le modèle de fissuration en déformations totales permet à l'utilisateur de définir indépendamment les relations contrainte – déformation en traction et en compression, tout en intégrant pour le BFUP le maintien de capacité résistante en traction et l'écrouissage. Des résultats d'essais publiés ont été utilisés pour développer le modèle aux éléments finis et vérifier les résultats de l'analyse.

1. INTRODUCTION

In the recent decades, Ultra High Performance Concrete (UHPC) has attracted worldwide attention of the industry and academia, due to its significant features, compared to conventional concrete. Based on Russel and Graybeal [1] definition, UHPC is a cementitious material, reinforced by fiber, which has compressive and tensile strength more than 150 MPa (21.7 ksi) and 5 MPa (0.72 ksi), respectively. Note that compressive strength of regular concrete is in the range of 28 to 55 MPa (4 to 8 ksi). Strain-hardening behavior of UHPC in tension along with its pre- and post- cracking tensile strength, are of its unique characteristics associated with the fiber bridging effects. High ductility, energy absorption capacity, considerable shear resistance, self-consolidation, reduced section sizes and low cost of maintenance are other features of UHPC, which make it a desirable candidate in the construction industry despite its high initial costs. These outstanding physical and mechanical characteristics stem from the UHPC mix design, including: very low water-to-cementitious material ratio (about 0.2) and optimized granular mixture with minimal or no coarse aggregate [1]. The resulting very low porosity of UHPC lead to increased durability, especially for construction in harsh environments. Hence, structures built by UHPC can be much lighter (due to the high strength that lead to smaller cross-sections) and can have longer service life (due to the high durability) than those built by regular concrete. UHPC is currently used in relatively small-scale applications, such as bridge deck joints and connections. However, there is great potential in extending the use of UHPC to larger applications and full structural elements to realize a new generation of resilient and almost maintenance-free structures.

Despite all the progress occurred in the UHPC industry, its high price tag still limits its application. Accordingly, UHPC behavior is still not thoroughly understandable at larger structural applications, especially for design and reinforcement optimization. More experimental tests and numerical finite element (FE) studies at both material and large-scale structural elements level are needed. In particular, a comprehensive constitutive model, capturing the UHPC complicated behavior is needed. Such model will make it more feasible to examine larger applications and help optimize design of structural elements made of UHPC. Previous researchers mostly used existing constitutive models commonly used for modeling of conventional concrete, to model UHPC. For instance, Chen and Graybeal [2] used concrete damage plasticity model to study structural performance of UHPC I-Girders. They considered elastic-perfectly plastic relations for strain-stress curves in tension and compression, and, therefore, ignored hardening and softening properties of UHPC. However, strain-hardening behavior of UHPC, both in tension and compression, plays a crucial role in overall material behavior of UHPC. Fiber bridging effect in UHPC, leads to enhancement of material behavior after cracking, compared to conventional concrete. After first cracks, tensile load transfers from concrete to fibers which results in higher tensile strength.

This study aims at investigating the validity of a readily available predefined material model to model the UHPC macro material behavior using the FE method. Total strain crack model, which is based on smeared crack approach, as readily available in the commercial FE software DIANA FEA [3] is used in this study. Available pure tension and compression material tests data from the literature are used for FE models development, calibration, and validation. Details about the material characterization, FE model development, and tension and compression analysis results are discussed in the following sections.

2. MATERIAL CHARACTERIZATION

In the recent years, a number of researchers have carried out several experimental tests and numerical studies to better understand the behavior of UHPC. For example, Wille *et al.* [4] and Graybeal and Baby [5] investigated the tensile behavior of UHPC with focus on characterizing strain hardening, while Graybeal [6] studied the compressive behavior. All used comprehensive experimental programs. Chen and Graybeal [7] extended the application of UHPC to bridge girders, and Xu and Wille [8] presented a three dimensional fracture model for UHPC under tensile loading. More details on the tensile and compressive behavior of UHPC based on the aforementioned sample studies are presented here for completeness.

2.1 Tensile behavior

UHPC is especially prominent for the hardening behavior it shows, after the first cracks appearing in tension. Given this outstanding feature, the proper consideration of the tensile strength of UHPC in design calculations can lead to a more economical design. Tensile behavior of UHPC have been investigated based on two different kinds of tests: direct tension tests and flexure-based tests. Each test has it particular pros and cons. Even though three point flexural or wedge splitting tests present information about tensile behavior of material, they need some extra calculation for determination of tensile properties of UHPC. On the other hand, there is also adversity in conducting direct tensile test because of dependency of results on the specimen shape, controlling the stability of force-displacement response, and uniform distribution of stress through the section. However, direct tensile tests still provide the most reliable data on UHPC actual behavior [2].

Based on the carried-out experiments, tensile behavior of UHPC is typically defined by three different parts: 1. elastic, 2. strain hardening, and 3. softening part (Fig. 1, after Wille et al. [4]). Commonly, UHPC behave elastically until the first cracks appear. After first cracks generated, multiple-cracks propagates between the existing ones till a single crack reaches it limit. At that point, fibers start working to the point that material completely loses its strength.

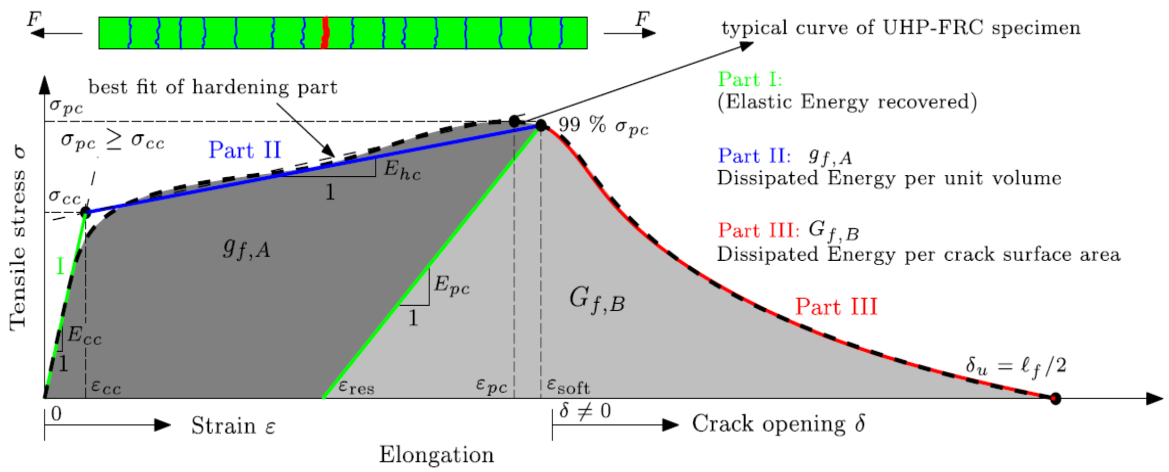

Figure 1: Strain hardening tensile behavior of UHPC and idealized modeling approach (excerpt from Wille et al. [4])

2.2 Compressive behavior

Compared to the regular concrete, UHPC has much higher compressive strength and modulus of elasticity in compression. Previous studies (e.g. [6]) provides equations to estimate the UHPC modulus of elasticity based on compressive strength. Most of the studies used force-controlled tests to estimate the peak compressive stress and associated strain, which resulted in a good understanding of the UHPC compressive behavior until peak (e.g. [6, 9]). However, only few studies used proper displacement-controlled loading protocols to capture the entire stress-strain response of UHPC including the post-peak behavior. More extensive experimental tests are needed to fully characterize the compression behavior of UHPC especially under different confinement levels.

3. FINITE ELEMENT MODEL DEVELOPMENT

Accurate modeling of a non-homogeneous material such as concrete has always been challenging. It becomes more complicated when macro modeling of overall behavior of reinforced concrete or fiber concrete at the structural element level is aimed. It is obvious that for advanced modeling of UHPC, accurate constitutive models are crucial. One of the most comprehensive studies that aimed at developing such models is the study by Xu and Wille [8], who developed a fracture 3D model for UHPC under tension. Engineers and researchers can choose the appropriate constitutive model based on the desired level of complexity and accuracy as needed for the design. Thus, this study aims at investigating the validity of an existing popular damage model used for conventional concrete if properly calibrated for UHPC. The focus of this paper is on the macro tensile and compressive material behavior of UHPC with a short term goal of extending this work to the structural element level. Details about the utilized constitutive model and the FE model development in DIANA [3] are presented in this section.

3.1 Constitutive Model

UHPC, similar to regular concrete, is a complex material with different tensile and compressive behavior, which depends on cracking and confinement, respectively. Confinement effects on UHPC has not been the focus in any of the past or ongoing computational modeling efforts, and in turn, has not been thoroughly examined as the tensile behavior. Tensile cracks are geometrical discontinuities that separate concrete or UHPC, with UHPC having a better performance due to the effect of fibers. To model the cracking behavior of materials, there are two basic approaches, the discrete crack approach and the smeared crack approach [10, 11]. The discrete crack approach reflects the final damaged state most closely. It models the crack directly via a displacement-discontinuity in an interface element that separates two solid elements. The discrete approach does not fit the nature of the FE displacement method. In addition, it is computationally more convenient to employ a smeared crack approach. In this latter approach, a cracked solid element can be still considered a continuum but requires proper account of the stiffness change according to certain stress-strain relationships. This second approach is the one utilized in this study in an attempt to capture the macro behavior of UHPC under tension.

Furthermore, cementitious materials behavior using the smeared crack approach can be modeled using either a multi-directional fixed-crack method or a total strain rotating-crack method. The multi-directional fixed-crack method considers that the orientation of the cracks remain constant, and in turn, the stress-strain relationships are evaluated in a fixed coordinate system that is set once cracking initiates. On the other hand, the total strain rotating-crack method considers that the orientation of the cracks rotates with the directions of the principal strains. Only the total strain method, which was developed along the lines of the 2D modified compression field theory [12] and extended to 3D by Selby and Vecchio [13], is utilized in this study. The total strain formulation follows the coaxial stress-strain concept, which is also known as the rotating crack model, where the stress-strain relationships are evaluated in the principal directions of the strain vector. The basic concept of the total strain-based crack models is that the stress is evaluated in the directions given by the crack directions.

The total strain crack model, as implemented in DIANA [3], describes independently the tensile and compressive behavior of a material using their stress-strain relationships. DIANA provides different approaches to model each of the tensile and compressive nonlinear behavior. Some of the available options to define the compression behavior are ideal elastic-perfectly plastic or multi-linear user-defined input for instance. Similarly, in tension, the input behavior can vary from brittle with sudden drop in strength to again a multi-linear user-defined input. The idea of this study is to input a macro UHPC behavior, i.e. the overall behavior given the interaction between the cementitious paste and fibers at the different stages of behavior (e.g. Fig. 1). The multi-linear user-defined input was elected for both tension and compression stress-strain relationships as illustrated in Fig. 2. Note that enough stress and strain input values are used to define the elastic, strain hardening, and strain softening behavior in tension. Similarly, enough points are used to approximate the compression behavior. While Fig. 2 is just a schematic representation of multi-linear input in DIANA, Table 1 provides the actual stress and strain values used in defining the model. These values are based on the studies by Wille et al. [4] and Graybeal [6], which are further used for model and analysis verification and comparison. Moreover, to consider mesh size effects, the default value of *h* (crack band-width), calculating by DIANA [3], was accepted. This value is calculated based on the area (in 2D modeling) or volume (in 3D modeling) of the elements. In the present 3D model in DIANA [3], crack bandwidth default is defined as cube root of V, where V is the volume of the element.

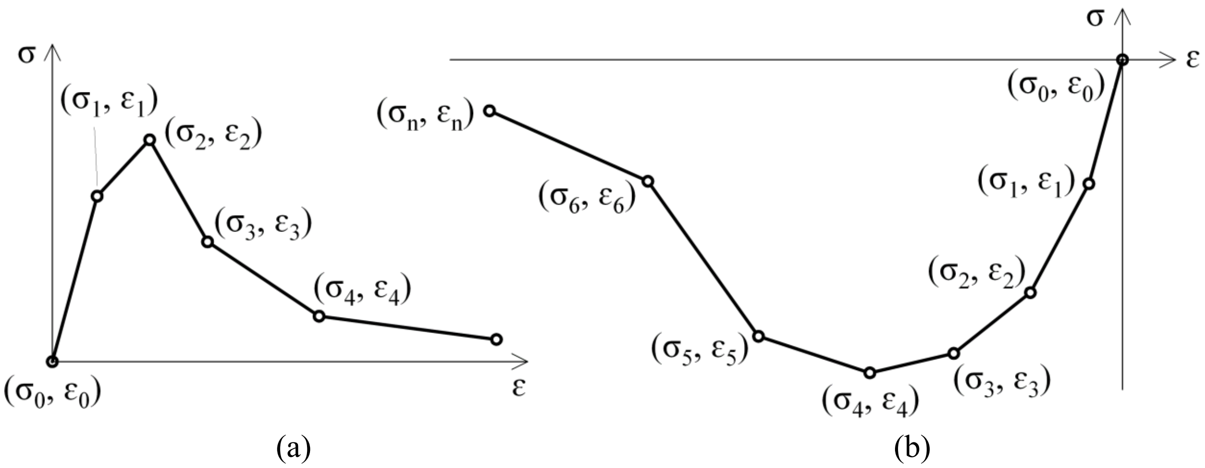

Figure 2: Multi-linear user-defined stress-strain relationships used for Total strain crack model definition in DIANA in: (a) tension, and (b) compression

Table 1: Material properties for multi-linear DIANA model input in tension and compression

	Tension	Compression	
	Wille et. al., 2014	Graybeal, 2007	Wu, et. al., 2017
Modulus of Elasticity, E (MPa)	56,000	34,000	40,000
Poison Ratio, υ	0.2	0.2	0.2
Density, γ (kg/m^3)	2500	2500	2500
ε_1, σ_1 (MPa)	0.000211, 11.8	-0.0030, -110	-0.00118, -90.2
ε_2, σ_2 (MPa)	0.004800, 15.1	-0.0035, -120	-0.00275, -150.8
ε_3, σ_3 (MPa)	0.010000, 15.1	-0.0040, -120	-0.00389, -174.6
ε_4, σ_4 (MPa)	0.080000, 12.1	-	-0.00459, -177.3
ε_5, σ_5 (MPa)	-	-	-0.00528, -174.6
ε_6, σ_6 (MPa)	-	-	-0.00822, -120.2
ε_7, σ_7 (MPa)	-	-	-0.00970, -104.3
ε_8, σ_8 (MPa)	--	-	-0.02020, -33.5
ε_9, σ_9 (MPa)	-	-	-0.04503, -27.4
ε_{10}, σ_{10} (MPa)	-	-	-0.07463, -20.5

3.2 Meshing and Boundary Conditions

Three different 3D FE solid models were developed in DIANA to model two direct tension test specimens and one compression cylinder specimen. For all models, brick elements (element HX24L as designated in DIANA) were used to generate the mesh. A brick element is an eight-node isoparametric element that is based on linear interpolation and Gauss integration, and features a constant stress and strain formulation over the element volume. Mesh refinement was also carried out to find the best fit to the experimental values.

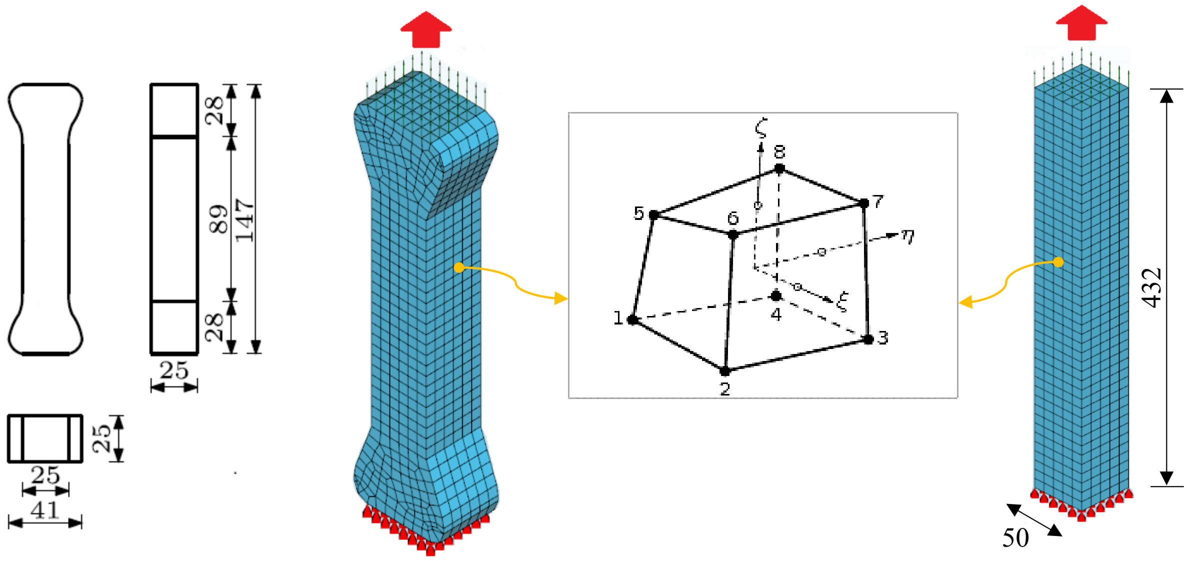

Figure 3: Geometry and dimensions (in millimeters) of dog-bone and uniform direct tension test specimens and their DIANA FE models. The models illustrate the boundary conditions, applied load, and the utilized HX24L brick element

Fig. 3 shows the geometry, dimensions, and FE mesh for the two direct tension test specimens used in this study. To define the boundary conditions, all the specimens' models are vertically restrained at all of the nodes at the bottom face, both in tension and compression (see Fig. 3). However, only two nodes in the center are laterally restrained in the two other directions. All constraints are translational only, i.e. pinned with no moment constraints applied. For the nonlinear analysis conducted in this study, a secant-stiffness approach is adopted given that this approach has been proven to be robust and stable in concrete structures with extensive cracking.

4. TENSION TESTS RESULTS

Two different direct tension tests from the literature were used in this study to examine the capability of the total strain rotating-crack model in simulating tensile behavior of UHPC. The first test by Wille et al. [3] used a dog-bone specimen, and the second set of tests by Graybeal [9] used uniform prism specimens (see Fig. 3 for dimensions and geometry).

Based on the previous discussion, a total strain crack model was implemented using a multi-linear tensile behavior. Fig. 4a illustrates the actual implemented stress-strain relationship for UHPC tensile behavior. This multilinear curve includes three different parts of the material behavior in tension. However, a small negative slope is considered for the softening part. This small value contributes reducing the analysis efforts in big-scale structures, while can simulate post-peak softening behavior to the strain of 0.7%, which is an acceptable value for UHPC itself. Apparently, UHPC is designed as a reinforced material; thus, reinforcement bars may tolerate the main portion of the tensile load after peak tensile strength of UHPC. In this condition, normally UHPC does not experience strain as large as 1.5%.

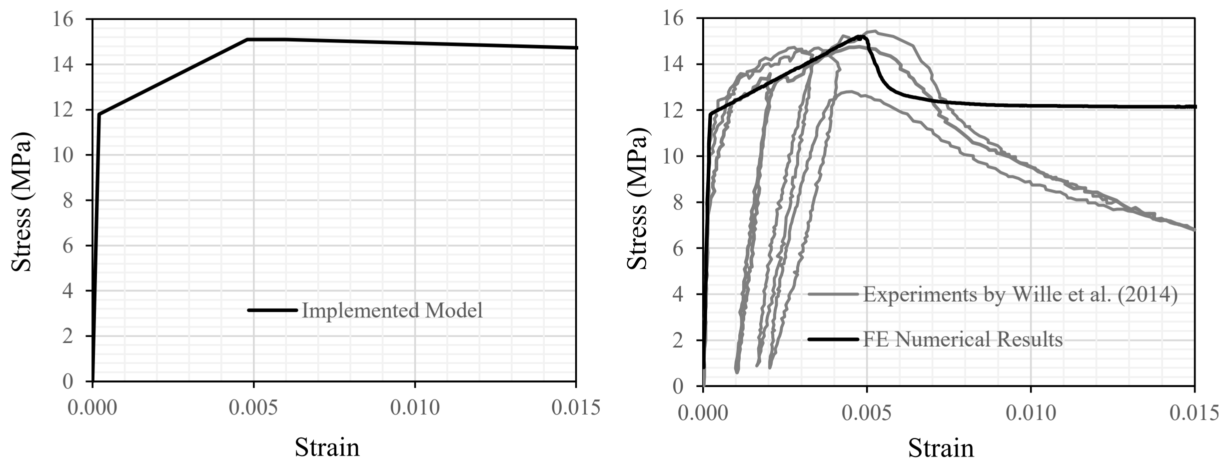

Figure 4 Actual implemented constitutive model in tension (left); and comparison of stress-strain relationships from the FE analysis and experimental results under pure tension (right)

The FE dog-bone specimen model was subjected to displacement-controlled pure tension and different results were obtained. Fig. 4b shows the stress-strain relationship obtained from the FE analysis as compared to the experimental results. Note that the shown stress and strain results in Fig. 4b are deduced from the obtained force and displacement results. It is observed from the figure that the implemented total strain rotating-crack model is accurately capture the elastic and strain hardening regions of behavior, but only capture softening to some extent. The crack propagation and corresponding strain distribution as captured from the FE analysis at the three different stages of behavior is illustrated in Fig. 5. The uniform strain distribution along the neck of dog-bone specimen and the location of crack initiation can be observed from the figure.

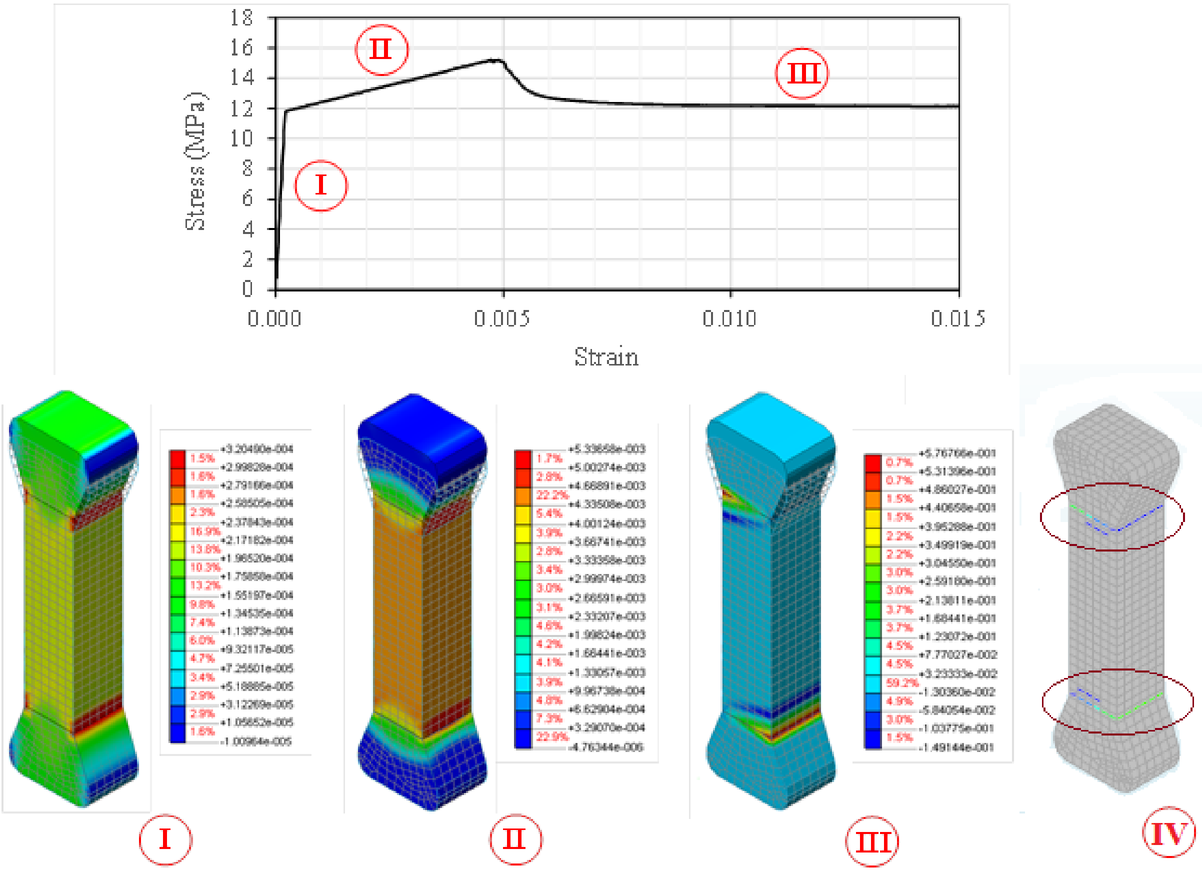

Figure 5: Stress-strain relationship of FE model under pure tension (top); and strain distribution along the dog-bone specimen at three stages: (I) elastic, (II) strain hardening; and (III) softening after the loss of strength, (IV) Crack pattern.

To further check and verify the capability of the total strain rotating-crack model in modeling tensile behavior of UHPC, a set of four direct tension tests conducted by Graybeal [9] for specimens with different tensile properties were used for FE simulation. The dimensions of all tests specimens were 50.8×50.8×431.8 mm (2×2×17 in.) as shown before in Fig. 3. The stress-strain relationships obtained from FE analysis for the four specimens are shown in Fig. 6 and compared to the test results. Again the comparison shows that the elastic and strain hardening can be well captured numerically with even a better softening behavior representation (no sudden drop was observed as the dog-bone tests).

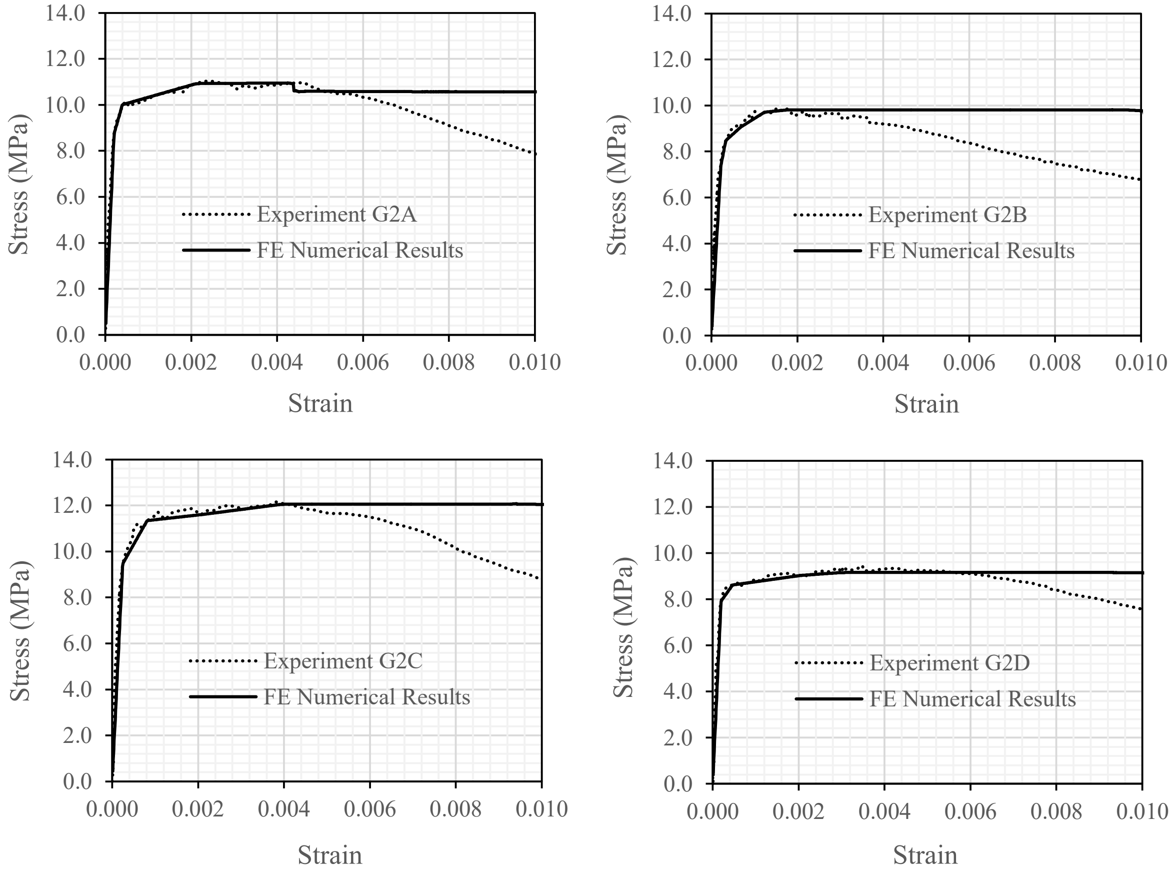

Figure 6: Comparison of stress-strain relationships from FE numerical and the pure tension tests results by Graybeal [9] for four specimens with different tensile behavior

5. COMPRESSION TEST RESULS

Similar to tension, two validity tests were conducted to verify the total strain crack model in compression using experimental data. First, a compression test conducted on a cylinder of 76 mm (3 in.) diameter and 150 mm length (6 in.) by Graybeal [6] was used in this part of the study. Then, another compression test on prism specimen of 40×40×40 mm^3 by Wu *et al.* [14] was modeled to examine the ability of the total stain model in predicting the overall behavior of UHPC in compression. A schematic view of the developed DIANA model meshes, boundary conditions, and applied loads is shown in Fig. 7. A typical strain distribution due to compression loading is shown in Fig. 7 and Fig. 8 as well. The obtained stress-strain relationship from the FE analysis are shown in Fig. 9 and Fig. 10 and compared to the test results. Note that most of conducted compression tests in literature used force control and hence, data for the post peak behavior of UHPC under compression is not very common. However, the model reasonably captured the compression behavior of UHPC from elastic part to the end residual strength. Based on what shown for tension and compression, the total crack model has a great potential to be further investigated and extended to simulate the behavior of UHPC at larger applications and structural elements level.

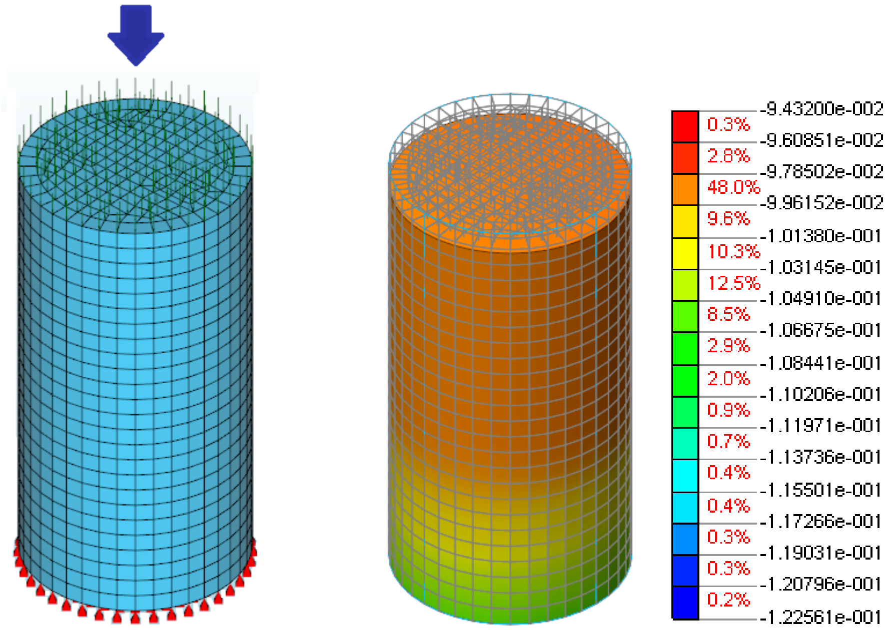

Figure 7: FE model for compression cylinder test specimen (left); and typical strain distribution under loading

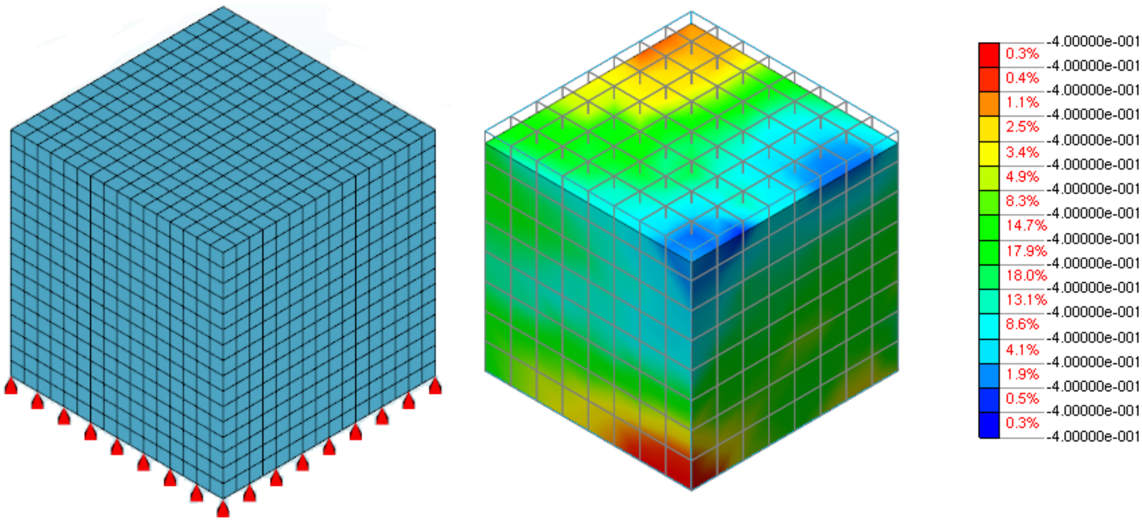

Figure 8: FE model for compression prism test specimen (left); and typical strain distribution under loading

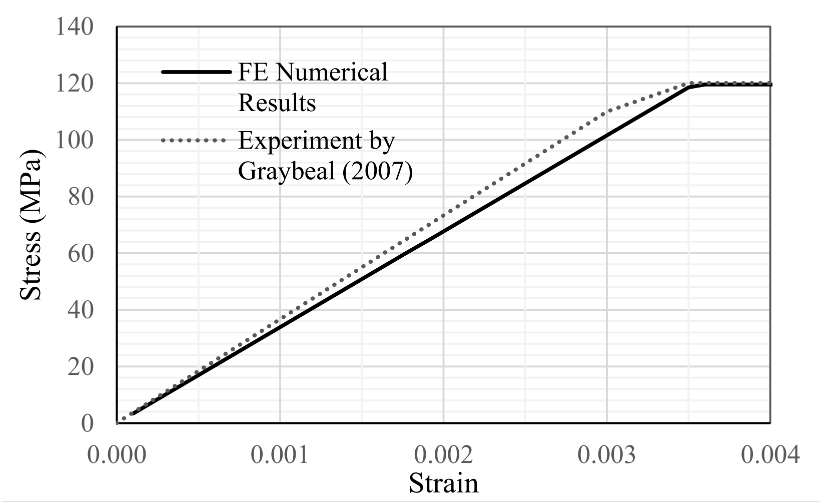

Figure 9: Comparison of stress-strain relationship obtained from FE numerical results and experimental data by Graybeal [6] under pure compression

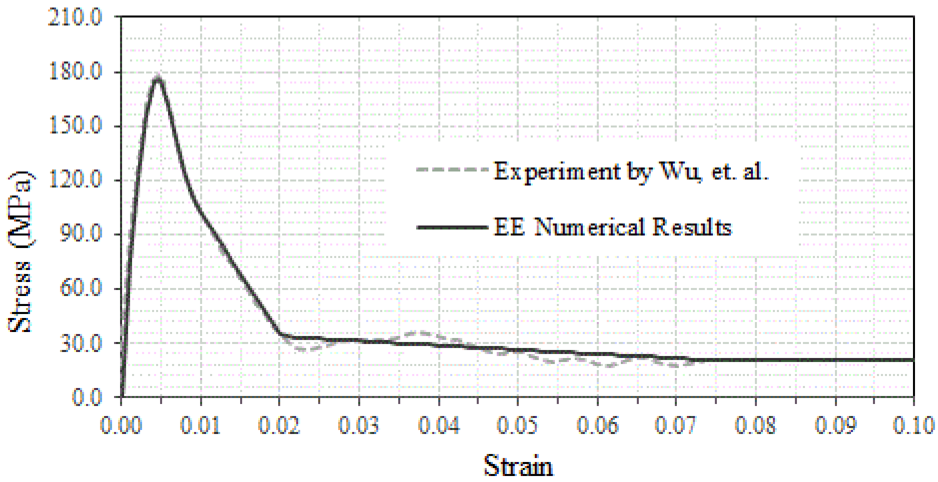

Figure 10: Comparison of stress-strain relationship obtained from FE numerical results and experimental data by Wu *et al.* [14] under pure compression

6. CONCLUSION

In this study, the capability of a multi-linear predefined constitutive model in a commercial FE software, DIANA, to capture UHPC behavior was investigated. The total strain rotating-crack model was used to model UHPC behavior in tension and compression. To verify the implemented input models, experimental tests from the literature were used to develop the FE model and define the material input. Overall, a very good agreement between the numerical and experimental results was observed for the elastic, strain hardening and softening parts of the compression behavior. There was a very good agreement, as well, in pre-peak tensile behavior. The peak (ultimate) strength and corresponding strain was accurately captured by the FE model in both tension and compression. Although, the stress value in softening part of tensile curves was overestimated, in relatively large tensile strains, it matches to the experimental results approximately to the strain of 0.7%, which is an acceptable value with the approach of analysis of UHPC reinforced elements. The models can be further refined and verified for other loading cases, such as flexural testing, and has the potential to be extended to larger application for full structural elements with reinforcing bars. The total strain crack model can also be used for design purposes where ultimate sections capacities can be determined, given the accurate definition of both tensile and compression strength. Future work planned by the authors will continue to explore the capabilities of the proposed model for different applications and extend it to larger scale at full elements or structures level.

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