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Finite Element Modelling of UHPC Beams under Pure Torsion

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***Abstract*—This paper presents finite element modelling of Ultra High Performance Concrete (UHPC) beams subjected to pure torsion. The beams have two cross sections (180 mm * 180 mm) and (280 mm * 280 mm). Different combinations of traditional bar reinforcement (longitudinal and transverse) and steel fibers have been used in the test program. The nonlinear cementitious material model used in the F.E package implements a combined Fracture-Plastic model to describe the material behavior which employs Orthotropic-Smeared crack formulation and Crack-Band approach in tension and Hardening/Softening plasticity model in compression. Material laws such as the tensile and postcracking softening behavior, compression behavior, effect of lateral compression on tensile strength, effect of lateral tensile strain on compression capacity and postcracking shear strength and stiffness and others have been defined. Results of axial tensile experimental tests on small notched UHPC prisms have been calibrated first. Models to describe the postcracking degradation of the shear strength and stiffness have been extracted from test results conducted for this purpose. The comparison between the test and F.E results shows very good agreement.**

Keywords— finite element, modelling, UHPC, torsion

I. INTRODUCTION

Finite element modeling has been widely used to simulate the behavior of reinforced concrete structural elements under a variety of loadings. As a new innovative structural material, UHPC – at the time being – lacks models which help practicing as well as research engineers to predict not only its bearing capacity but also its behavior during the course of loading. In this article, the development of finite element model in order to predict the full load-deformation behavior of UHPC beams with different combinations of steel fibers and traditional bar reinforcement (longitudinal and transverse) pure torsional load will be presented.

II. EXPERIMENTAL PROGRAM

The deformation behavior and torsional capacity of UHPC beams with steel fibers and with/without traditional bar reinforcement under pure torsion were investigated. The detailed experimental program is shown in Table 1. The beams had square cross section and dimensions of either (180 mm * 180 mm * 2400 mm) or (280 mm * 280 mm * 1500 mm).

III. MATERIALS

A fine-grained UHPC mix (M3Q) was used. This mix is considered as a further development of the (M2Q) UHPC mix. A detailed description of the input materials of the (M2Q) mix and notes on the production and handling can be found in the research report by Fehling et al. [1]. The average cylinder compressive strength was about 205 MPa and the average modulus of elasticity was about 48000 MPa. Steel fibers having tensile strength, length and diameter of 2500 MPa, 17 mm and 0.15 mm were used. Two volumetric ratios of the steel fibers were used within the test program, namely 0.5 % and 0.9 %. Reinforcing steel bars of the type Bst 500 having a nominal modulus of elasticity of 200 GPa was used. According to tests carried out, the yielding strength of the steel bars of 8, 12 and 16 mm diameters was approximated as 550, 570 and 570 MPa respectively and the ultimate strength as about 625 MPa. More information regarding the casting, treatment of the test beams, the test setup and instrumentation can be found in [2].

In order to determine the actual steel fiber efficiency (e.g. postcracking tensile strength), small UHPC notched prisms having dimensions of 4 cm * 4 cm * 8 cm were cut out from the test beams along the cracking surface after conducting the torsion tests. Axial tensile tests according to [3] were then carried out. The results of these tests are shown in Fig. 1.

IV. DESCRIPTION OF THE USED FINITE ELEMENT PACKAGE

A finite element package called "ATENA" (Advanced Tool for Engineering Nonlinear Analysis), which implements a nonlinear finite element analysis of reinforced concrete structures, was used [4]. ATENA can predict the behavior of the structural member not only at ultimate but also throughout the complete load history.

Unlike the normal and high strength concretes, which have well defined material models in ATENA, no standard material model for UHPC with steel fiber (as a new innovative cementitious material) is implemented in ATENA. However, ATENA allows the user to define his own material model laws using the general "CC3DNonLinCementitious2user" material model. These laws are:

- Tensile and post cracking softening behavior
- Compression behavior
- Effect of lateral compression on tensile strength

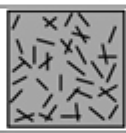
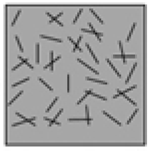
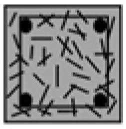
- Effect of lateral tensile strain on the compression capacity
- Post cracking shear strength
- Post cracking shear stiffness
- Other input parameters, like:
  - Tensile and compressive strength
  - Modulus of elasticity and Poisson's ratio

In general, the "CC3DNonLinCementitious2user" material model in ATENA is based on the "CC3DNonLinCementitious" material model which uses a combined "Fracture Plastic model" to describe the behavior of concrete. This model employs the "Orthotropic smeared crack formulation" and the "crack band approach" in tension and the ''Hardening/Softening plasticity model'' in compression.

The fracture part of the combined model employs the Rankine failure criterion, exponential softening and can be used as rotated or fixed crack model and the compression part employs the "Menétrey-Willam failure surface" [4].

This combined material model can handle not only cases when failure surfaces of both failure models are active, but also when physical changes such as crack closure occur. The model can be used to simulate concrete cracking, crushing under high confinement, and crack closure and it is not restricted to any particular shape of hardening/softening laws [4].

TABLE I. THE EXPERIMENTAL TEST PROGRAM

Group	No. of beams	Fiber vol. %	Longitudinal reinforcement ρ_L	Transverse reinforcement ρ_T	Beam code	Cross section
1	1	0.5	-	-	UPF(0.5)18	
	1	0.9	-	-	UPF(0.9)18	
2	1	0.5	-	-	UPF(0.5)28	
	1	0.9	-	-	UPF(0.9)28	
3	1	0.5	4Ø12 mm, 1.4 %	Ø8 mm@45 mm, 1.96 %	UL(1.4)T(1.96)F(0.5)18	
	1	0.5	4Ø16 mm, 2.48 %	Ø8 mm@45 mm, 1.96 %	UL(2.48)T(1.96)F(0.5)18	
	1	0.5	4Ø16 mm, 2.48 %	Ø8 mm@30 mm, 2.94 %	UL(2.48)T(2.94)F(0.5)18	

Legend: U = UHPC, P = Plain concrete, L = Longitudinal reinforcement, T = Transverse reinforcement, F = Steel fiber, 18 = 180 × 180 mm cross section, 28 = 280 × 280 mm cross section and ( ) = Volumetric ratio in %.

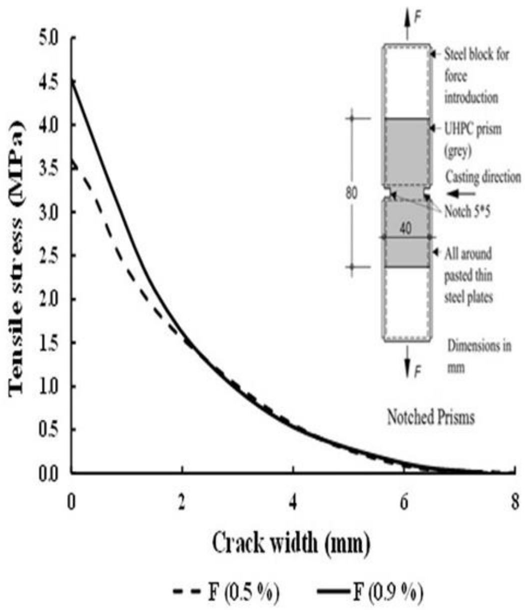


Figure 1. Average stress-crack width diagram [2]

V. MATERIAL Laws For UHPC with Steel

A. Tension law

Based on experimental tensile tests on notched prisms cut from the test beams after conducting the torsion tests, the behavior of UHPC with steel fibers is linear elastic up to cracking. Thereafter, the material shows softening behavior both for steel fiber volumes 0.5 % and 0.9 % as shown in Figure 1. In the Rankine-fracturing model for concrete cracking, the crack opening w is computed from the total value of fracturing strain multiplied by the characteristic length (crack band size) "L_t"". In ATENA, the crack band size L_t is calculated as the size of the finite element projected into the crack direction.

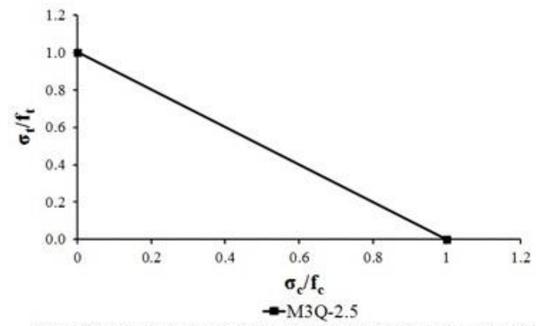


Figure 2. Reduction of tensile strength due to lateral compression [5]

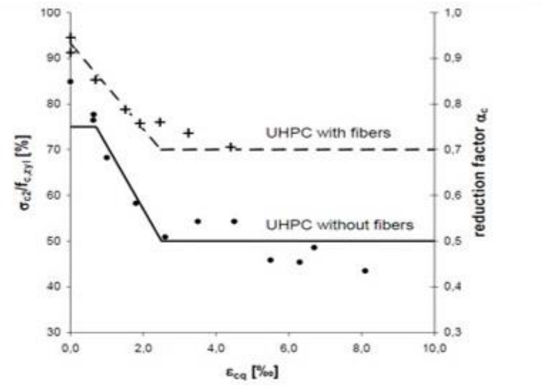


Figure 3. Reduction of the compressive strength of UHPC due lateral tensile strain [6]

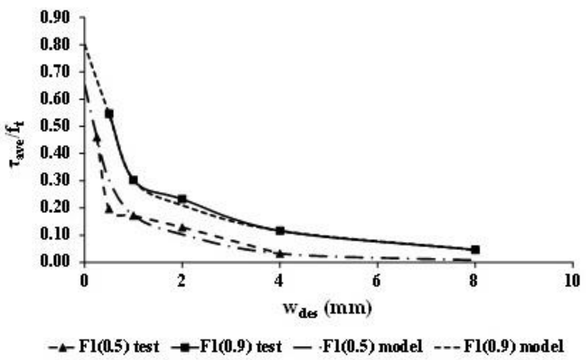


Figure 4. Degradation of the shear strength of UHPC-M3Q with steel fibers due to cracking (test results against proposed model) [2]

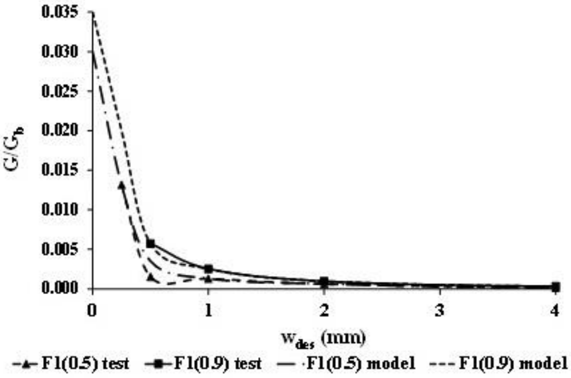


Figure 5. Degradation of the shear stiffness of UHPC-M3Q with steel fibers due to cracking (test results against proposed model) [2]

B.Effect of lateral stress/strain on uniaxial strength

The effect of lateral compression on the tensile strength of UHPC (M3Q-2.5) mix with steel fibers has been experimentally investigated by Speck [5]. Based on these experimental tests, the tensile strength was reduced due to lateral compression. The relationship which describe this behavior was estimated as shown in Fig. 2. The reduction of the compressive strength due to lateral tensile strain in the postcracking range was assumed to follow the results obtained by Fehling [6] for steel fiber UHPC as shown in Fig. 3

C. Shear stress and stiffness in cracked UHPC

The shear modulus and shear strength are reduced with growing strain normal to the crack direction. The laws for post cracking shear strength and stiffness were derived based on own series of experimental tests on UHPC prisms with steel fibers. At first, axial tensile force was applied to the prism to introduce a specific desired crack width (W_{des}). The crack width was then held constant and a direct shear force was applied to the crack faces. More details can be found in [2]. Figs. 4 and 5 show the proposed models for the degradation of the postcracking shear strength and stiffness against the test results respectively.

VI. BOUNDARY CONDITIONS AND FINITE ELEMENT MESH

In order to save calculation time and enhance the computational efficiency only part of the test beam with only 80 cm pure test length was modeled making use of symmetry as shown in Fig. 6. However, for some beams, the F.E calculations consumed very long time, hence the pure test length in the model was even reduced to 50 cm only.

Additional steel plates C, D, E and F, 20 cm in length, were added to the model to simulate the effect of the steel profiles in the test setup and to withstand the high stresses due to force introduction at one end and support reactions at the other one.

The torsional moment was generated through a couple of forces at the right end of the beam (points c and d), while the left end was fixed in the yz plane through fixing the outside surfaces of steel plates E and F in the z direction and the points e,f,i and j in the y directions (point j is hidden and located on plate E and faces point f). In the x-direction, surface A was fixed only at one point (the point at the center, a) allowing it to warp freely. Only the center point of surface B (point b hidden in figure 8 and faces point a) was fixed in the y and z directions, thus allowing the beam to elongate and warp freely.

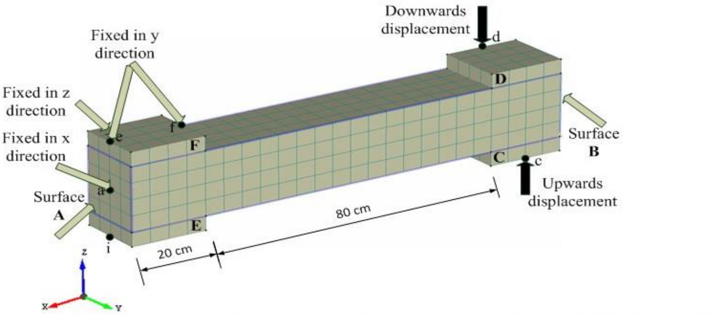


Figure. 6 Geometry, loading, supports and mesh of the finite element model of the UHPC test beams [2]

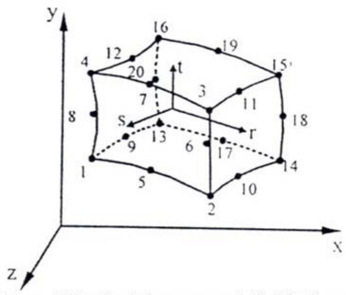


Figure. 7 Quadratic isoparametric brick element with 20 nodes

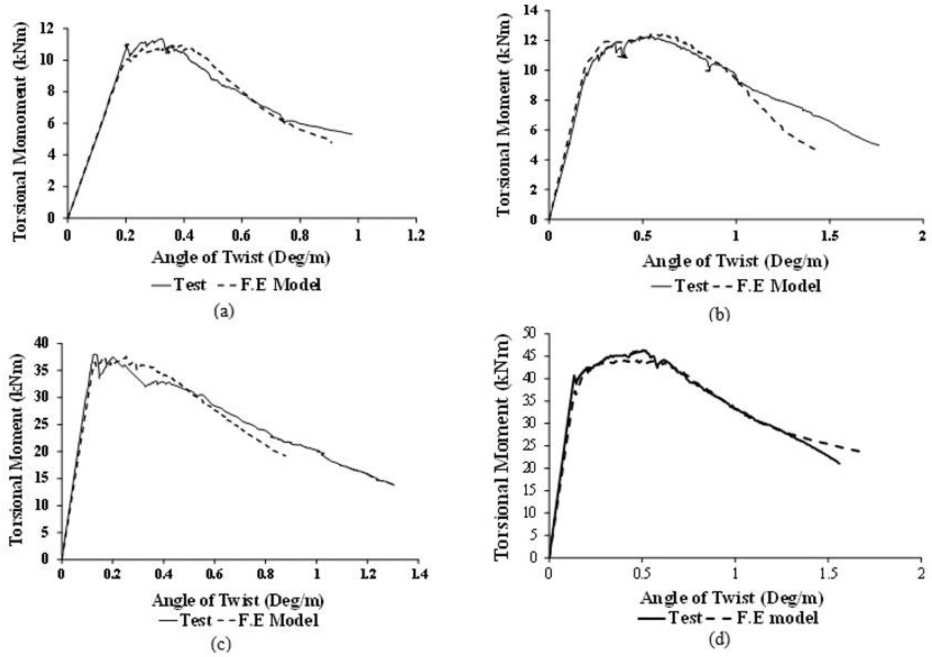


Figure 8. Comparison between test results and F.E prediction for the test beams: a) UPF(0.5)18, b) UPF(0.9)18, c) UPF(0.5)28 and d) UPF(0.9)28 [2]

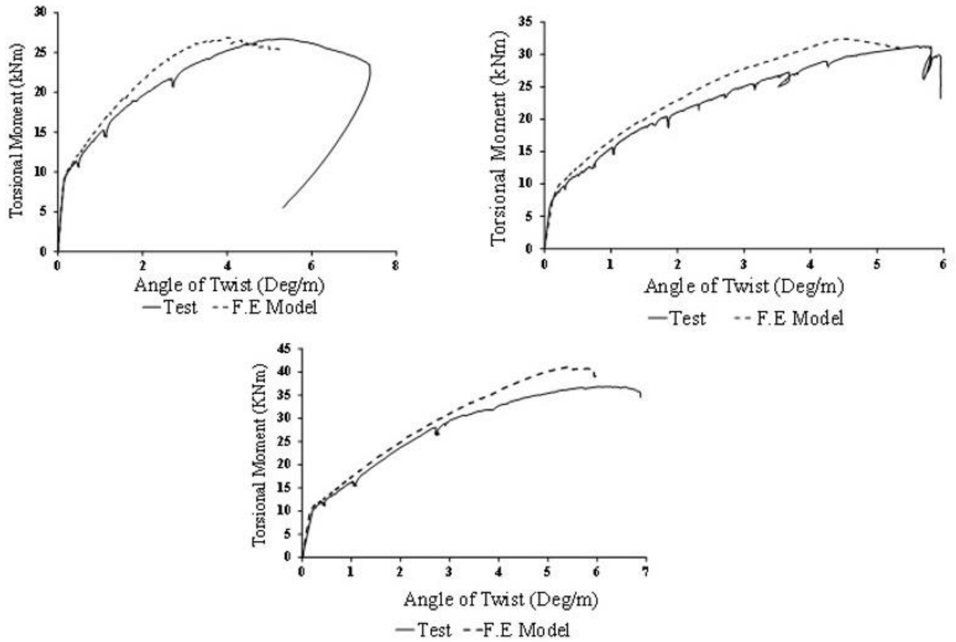


Figure 9. Comparison between test and F.E prediction for the test beams: a) UL(1.4)T(1.96)F(0.5)18, b) UL(2.48)T(1.96)F(0.5)18 and c) UL(2.48)T(2.96)F(0.5)18

In this model, the loads applied were increased simultaneously by displacement control at points c and d. The nonlinear solution procedure used was the standard Newton-Raphson iteration method.

The numerical model used three-dimensional isoparametric Brick element with 20 nodes and quadratic shape functions as shown in Fig. 7. The beam cross section was covered by a total of 16 elements, with an element length of 45 mm.

VII. Finite Element Model Predictions

Figs. 8 and 9 show the comparison between the test results and the Finite Element model predictions. Very good agreement was obtained for all beams.

VIII. Conclusion

A Finite Element model was developed using F. E. Package ATENA for the simulation of the full load-deformation behavior of UHPC beams with different combinations of steel fibers and traditional longitudinal and transverse reinforcement. The comparison of the own test results and the simulation predictions shows very good agreement.

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