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STATIC AND DYNAMIC PERFORMANCE OF A NEWLY DEVELOPED STEEL FIBRE-REINFORCED SELF-COMPACTING CONCRETE

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ABSTRACT

Ultra-high performance concrete (UHPC), such as steel fibre-reinforced self-compacting concrete, is of high strength, high deformation and high toughness in comparison with conventional concrete, making it ideal material to resist blast loading. In this paper a series of static tests has been conducted to study the performance of newly developed steel fibre-reinforced self-compacting concrete specimens. The quasi-static compressive tests and direct tensile tests were conducted for determination of the compressive strength and direct tensile strength of the specimens with/without steel fibres and four point bending tests were conducted to obtain the flexural tensile strength of the steel fibre-reinforced self-compacting concrete specimens. The stress–strain relationships, the flexural tensile strength of steel fibre-reinforced self-compacting concrete tested were compared and discussed. Then a moment-rotation model developed based on the static testing was applied in this study and afterwards, this material model is incorporated into a numerically efficient one dimensional finite element model, utilizing Timoshenko Beam Theory, to determine the flexural response of steel fibre reinforced concrete slabs subjected to blasts and the model is then validated with the real blast testing results. The results show that the developed material model is able to predict the moment curvature relationship with reasonable accuracy and the advanced FEM based model can be used to simulate the dynamic response of ultra-high performance reinforced concrete (UHPRC) specimens against blasts efficiently.

KEYWORDS

UHPC, static Tests, material model, finite element method, dynamic response.

INTRODUCTION

There has been a continuous interest in the modelling structural responses under high intensity dynamic loads such as impact and explosions due to the phenomenon of more and more people concerned about the industrial accidents and terrorist attacks. The research into this area is having great importance because of its practical real world significance. Ultra high performance reinforced concrete (UHPRC) has been shown to perform better under blast loading than normal strength concrete. This study will consider ultra-high performance concrete with steel fibres to increase the ductility of this material to better enhance its resistance to blast loading. In order to produce a simple, reliable and accurate model for simulating the response of structural members against blast loading, three essential research components are required for achieving the prediction. Basically, with a given blast charge weight and stand-off distance, the blast loading which in the form of a pressure-time history acting on the member needs to be calculated. Secondly, the structural response mechanism which describes the ultimate resistance deflection relationship is essential for the analysis. Finally, the blast loading and structural behaviour must be incorporated into the dynamic response system, this dynamic model will analyse the response of the structural member against blast in terms of deflection-time history.

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In order to determine the structural response mechanism of UHPRC members, a number of studies, including Habel et al. (Habel, et al. 2006), Habel and Gauvreau (Habel and Gauvreau 2008), Astarlioglu and Krauthammer (Astarlioglu and Krauthammer 2014), Bindiganavile et al. (Bindiganavile, et al. 2002), Yi et al. (Yi, et al. 2012), Habel et al. (Habel, et al. 2007) have been conducted to investigate the mechanical properties of UHPRC. These studies have all indicated that UHPRC enhances the compressive strength and a compilation of the stress-strain model which was comprised by three linear branches to representing the elastic, flat peak and post peak descending behaviour proposed for UHPRC members. However, the stress-strain model proposed for UHPRC was obtained by fitting the experimental results proposed by Ngo et al. (Ngo, et al. 2007) and Wu et al. (Wu, et al. 2009), therefore this model can used for typical UHPRC mixes and fibres ratio only, otherwise the key stress-strain values from this model need to be determined experimentally (Astarlioglu and Krauthammer 2014). Therefore, a moment-rotation model which developed based on a partial interaction linear displacement profile method was employed into the dynamic analysis in this study.

Furthermore, considering using the dynamic system to simulate the flexural response of UHPRC member against blasts, SDOF models and some commercial simulation software are commonly used as analysis tools to find out the structural response against to blast scenarios. The assessment of flexural behaviour of UHPRC slabs, especially specimens used to investigate the flexural relationship based on the finite element method, has not been attempted thus far in the research communities. It is unknown whether finite element model can accurately capture this type of behaviour/failure. Thus in the current study, the experimental results for UHPRC slab subjected blast loads, will be used to compare with the results obtained with the Finite element method.

EXPERIMENTAL TESTING

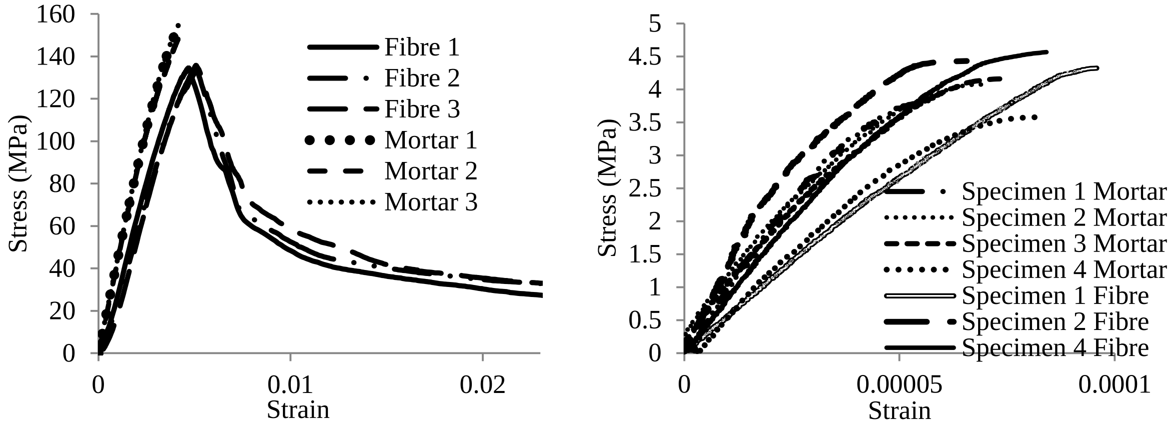
To determine a moment-rotation relationship for UHPC, it is needed to ascertain certain material properties such as the compressive, tensile and bending behaviour. To obtain these properties, material testing was conducted on UHPC specimens.

Compression Tests

Compression testing for 28 day strength was conducted on an Amsler compression testing machine with maximum load of 5000kN. Data from the 28 day tests was recorded using 2 axial and lateral strain gauges on each specimen, 4 axial LVDTs located at each corner of the loading platen and 2 lateral LVDTs to record dilation of the specimen. 28 day compression tests were conducted on two types of specimens, plain mortar and specimens with 2.5% by volume content of steel fibres. Figure 1(a) shows the plot of the average stress strain curves of both types of specimens. There was an average increase in the peak stress of approximately 13% from the fibre specimens to the plain mortar specimens, and an average increase of 22% in the peak strain. However, the plain mortar specimens displayed a very brittle explosive behaviour with a catastrophic failure after the peak load was reached. The steel fibre specimens however displayed a very ductile behaviour post peak as can be seen in Figure 1(a) by the long descending branch post peak where the specimen continues to carry load up to strains far greater than the peak strain.

Tension Tests

To gain important information on the tensile properties of UHPC direct axial tension tests were conducted as part of this research. Tests were conducted on 150x150mm specimens that had been cut down from 150x300mm specimens and were notched to a diameter of 100mm at the centre of the specimen. The deformation of the specimens was measured using 3 axially oriented LVDT's located at 120 ° around the specimen that were glued to specimen on either side of the notch so that the crack opening of the notch could be accurately measured. A total of 8 specimens were tested as part of this investigation, 4 plain mortar specimens and 4 fibre-reinforced specimens. The stress-strain plots prior to cracking for both the fibre and mortar specimens are presented in Figure 1 (b).The fibre specimens generally provided a greater tensile strength than the plain mortar specimens, however, the strain at peak stress varied quite a bit between all the specimens and there is no significant difference between the strain at peak stress of the fibre specimens as compared to the mortar specimens. The most marked difference between the fibre specimens and the plain mortar specimens was in the post cracking behaviour. The plain mortar specimens could carry no further stress once the cracking strain in the material had been reached and the specimens failed in tension. However, once the cracking strain was reached in the material the stress that the specimen could carry initially dropped as a major crack formed across the specimen. After the initial drop in stress with the formation of a major crack the fibres are activated and the stresses that the specimen can carry increases again as the fibres pick up the load. The stress then slowly decreases with increasing crack width as the fibres bridging the crack slowly pull out. As the fibres are 12mm long we would expect the maximum crack width to be approximately 6mm as having half a fibre embedded on either side of a crack would be the optimum configuration.



(a) Compression test results (b) Tension test results prior to cracking

Figure 1. Stress-strain relationship of compression and tension tests

Four Point Bending Tests

Four point bending tests were conducted on small unreinforced and un-notched beams. The beams had dimensions of 100x100x500mm and were only reinforced with 2.5% by volume of steel fibres. The beams were tested under 4 point bending to obtain a region of zero shear in the centre third of the beam to ensure that flexural failure would occur in this region. As can be seen from Figure 2 the three specimens had a similar response in terms of the shape of the load deflection curve, however they all reached quite different peak loads. A typical example of the failure of the specimens is shown in Figure 2 as well.

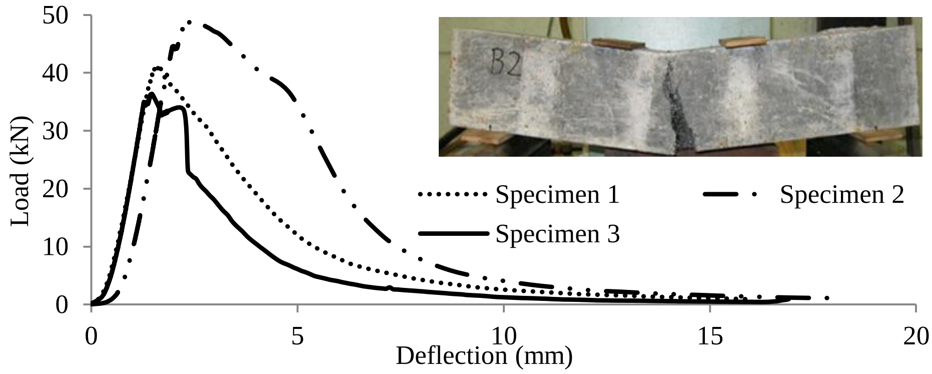


Figure 2. Load-deflection relationship of four point bending tests

MODELLING THE STATIC SECTIONAL BEHAVIOUR

A moment-rotation model developed based on a partial interaction linear displacement profile method developed by Visintin at al. (Visintin et al. 2011) was applied in this study. It uses the principle of a linear displacement profile at the face of a crack in a member. A member can be divided into segments of length which is the crack spacing of the member. An effective linear strain profile can then be determined from the deformation profile where the calculated strain is the deformation from the profile divided by the half segment length over which the deformation occurs. To find the forces in the member several regions within the member are considered. These include the uncracked and cracked tension regions, as well as the compression ascending and softening regions. To be able to produce an accurate moment-rotation model requires accurate material properties. That the reason why material testing of UHPC specimens in both tension and compression need to be conducted.

Once the material properties had been ascertained, the experimental data could be used as an input into the moment-curvature model to determine the forces in the uncracked and cracked tension regions, as well as the ascending compression region. Shear friction properties were used to determine the force in the compression softening region which account for the formation and slipping of wedges within the member.

Figure 3 shows the typical moment curvature relationship from the test plotted against the results obtained by the modeling. The experimental and modeling moment curvature curves both exhibited the same two stages of behavior. In the first portion of the curve, all of the materials remained elastic; the concrete began to crack in tension. As shown that the model does predict the peak load very well, with a slight over estimation of approximately 1.5%. The model also matches the shape of the elastic and plastic branch very well. The major difference between the two curves is in the rising branch, particularly in the pre-cracking region shown as the region before point A, but the ultimate result conditions are very reasonable. The post cracking shape predicted by the model, shown as the region after point A fits the shape of the experimental curve also quite well. These validation results indicated that the modeling results can be used to simulate the moment curvature relationship of UHPRC and the results should be acceptable, thus this modeling will be used in the further dynamic analysis.

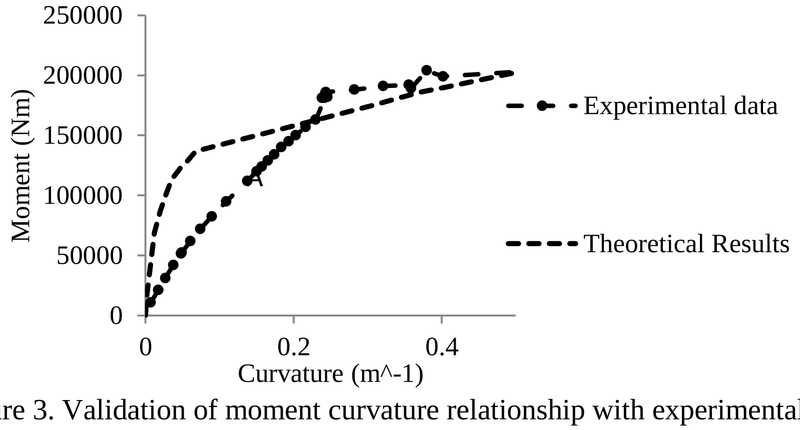


Figure 3. Validation of moment curvature relationship with experimental data

STRUCTURAL RESPONSE USING A FINITE ELEMENT MODEL

A self developed coding of finite element model (FEM) has been developed to simulate the blast test is presented in this section. The structural response along the beam was modelled by considering the beam to be comprised of a series of beam elements to which based on the Timoshenko's beam theory. Unlike Solutions obtained by the application of classical theory of plate flexure, Timoshenko's theory considers both shear deformation and bending deformation as well as rotational inertia, as shown in Equations (1) and (2) and this theory has been demonstrated as useful for blast loading problem by some previous researchers (Dragos, et al. 2014) (Wu, et al. 2013).

$$\frac{\partial M}{\partial x} - Q = -\rho m I \frac{\partial^2 \rho}{\partial t^2} \quad (1)$$

$$\frac{\partial Q}{\partial x} + q + P_0 \frac{\partial \beta}{\partial x} = \rho_m A \frac{\partial^2 v}{\partial t^2} \quad (2)$$

Where M =the applied bending moment, Q = the applied shear force, q = the distributed blast loading acting transverse to the beam, P0 = the column axial load, A = the cross sectional area, ρ_m = the mass density of the beam, β= the rotation and ν = the transverse displacement. The FE method solves Eqs.(1) and (2) in their weak forms. The governing weak form equation can be expressed in matrix form as:

$$K\delta + M\ddot{\delta} = P \quad (3)$$

Where [K] is the stiffness matrix, [M] is the mass matrix, {δ} is the displacement vector, { $\ddot{\delta}$ } is the acceleration vector, and {P} is the load vector. Eq. (3) is solved using the Newmark method at each time interval.

COMPARING THE FEM WITH EXPERIMENTAL DATA

Prior to modeling the deflection time histories for the blast scenario, the finite element model need to be validated against previous test data so that it could be used with confidence. The experimental data that was used in the validation process was a blast test which was conducted on a 2000 x 1000 x 100 mm UHPRC slab, in a free air environment, the details of the test set up can be found in Wu et al. (Wu, et al. 2009). The pressures acting on the slab were determined from the TM5-1300 prediction for the equivalent charge weight and distance.

The predicted and experimental maximum deflections were calculated and summarized in Figure 4. As can be seen the predicted plots that the finite element method follows the experimental plot very closely. The maximum deflection predicted by FEM is approximately 1.8 mm (with 4.5% error) less than the maximum deflection measured experimentally. The period of oscillation predicted by FEM also matches the period of the slab determined from the experimental program. This indicates that FEM has modeled the structural dynamics of the slab very well.

Table1. UHPC Slab and charge Properties

Material Properties								
	Reinforcing Steel				Concrete		steel fibre	
Slab No.	steel diameter (mm)	Reinfo rcing ratio	yield strength (MPa)	Young's modulus (MPa)	compressive strength	tensile strength	fibre length	volum e %
D3B	15.2	1.81	1750	200000	150	22	13	2.5

Charge properties					
Event No.	Slab No.	Stand-off distance (m)	Scale distance (m/kg^(1/3))	explosive used (g)	charge shape
7	D3B	1	0.5	8076	cylinder

CONCLUSIONS

This study achieves the aims of characterizing the material through three different static tests, analyzing the sectional behavior of UHPC by using a mechanical based material model, and determining the structural response of UHPRC slabs for dynamic blast loads by using finite element method. This was achieved through the use of experimental testing results, sectional UHPC model, and dynamic member response models.

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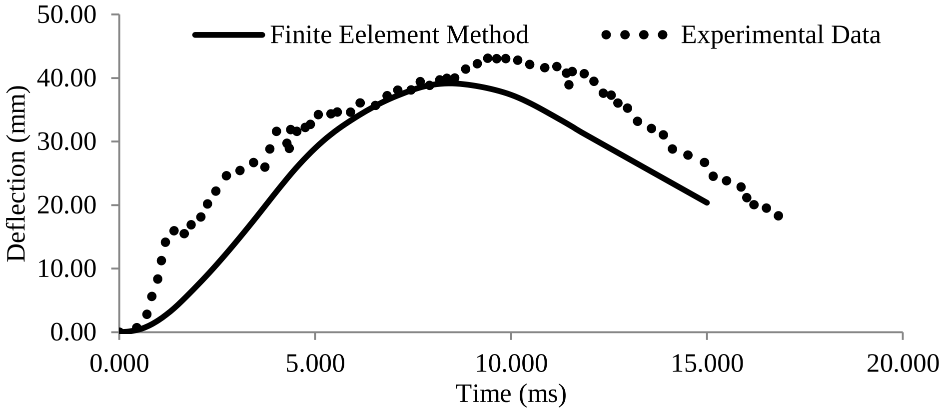

Figure 4. Comparison between the predicted plots by using different methods

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