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Experimental and numerical study of the flexural behaviour of ultra-high performance fibre reinforced concrete beams

M. Singh [*], A.H. Sheikh, M.S. Mohamed Ali, P. Visintin, M.C. Griffith

School of Civil, Environmental and Mining Engineering, The University of Adelaide, Australia

HIGHLIGHTS

- UHPFRC mix with conventional aggregates is used to manufacture beams.
- Stress-strain behaviour of UHPFRC under compression and tension is presented.
- Flexural behaviour of large-scale UHPFRC beams is presented.
- Finite element analysis of beams is conducted using concrete damaged plasticity model.

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ABSTRACT

The development of standard analytical procedures and design guidelines for concrete requires extensive tests at material and structural level. For ultra-high performance fibre reinforced concrete (UHPFRC) this task is even more complicated than that of conventional concrete due to the potential range of fibre types and volume fractions. The experimental task of large scale structural members to develop the design procedures can be reduced by adopting an alternative way in which the concrete material model available in finite element packages are validated with the limited number of tests conducted on material and structural members. The validated numerical models can further used to study the effect on the structural behaviour due to change in geometry, loading conditions and reinforcement. Therefore the objective of the present study is to investigate the efficacy of the hybrid approach of validating the existing concrete model to study the behaviour of large-scale structural members made up of UHPFRC. For this four full-scale beams with varied spans and cross-sections were fabricated with the indigenously developed UHPFRC using conventional materials and mixing methods and tested under different loading conditions until failure. Numerical models were developed and validated with the test results of the beams for which the concrete damaged plasticity (CDP) model was adopted to characterize the behaviour of UHPFRC material. The material parameters required to define the constitutive model were identified by conducting direct/uniaxial tension and compression tests. The results obtained from the numerical models shows that the CDP model can accurately predict the load/moment carrying capacities of the UHPFRC beams. The results also show a good capability of the numerical models to predict the overall load deflection behaviour of the UHPFRC beams.

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1. Introduction

Ultra-high performance fibre reinforced concrete (UHPFRC) is an advanced cement composite material, which is characterised by high strength, ductility, durability and fracture toughness [1–4]. UHPFRC is generally characterized as the reactive powder concrete with compressive strength exceeding 150 MPa containing sufficient fibre content to achieve strain hardening under tension [1]. Since its conception, various proprietary UHPC mixes have been developed such as: SIFCON, Ductal, CARDIFRC and CEMTEC, however due to the cost and specialist curing requirements of these materials use in practice has been limited to several landmark structures. In an attempt to further expand the usage of UHPC by simplifying manufacture techniques and reduce costs recent research has aimed to develop in-house UHPFRC mixes using indigenously available materials [5,6].

Most of the reported studies on UHPFRC focus on the characterization of material properties [7–10] with a few considering the

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[*] Corresponding author at: School of Civil, Environmental and Mining Engineering, The University of Adelaide, South Australia 5005, Australia.

E-mail address: manpreet.singh@adelaide.edu.au (M. Singh).

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behaviour of full-scale structural members especially with indigenously developed mixes [11,12,40]. Notable examples of investigations at a member level include that of Graybeal [13] who investigated the potential of constructing of prestressed bridge girders from UHPFRC designed by Ductal. It was reported that the fibre pull out lead to the failure of the girder. At fibre pull out, the flexural stress carried by fibres transferred to the prestressing strands that lead to increase of tensile stresses in strands due to which the prestressing strands ruptured and the girder collapsed. Yang et al. [14,15] investigated the effect of reinforcement ratio and concrete placement methods on the flexural strength of UHPFRC beams. It was found that the method of placement of UHPFRC in the beams has considerable effect on the ultimate moment capacities. Recently, Yoo et al. [34] investigated effect of using different fibres on the flexural behaviour of reinforced UHPFRC beams. It was found that the ultimate moment capacity was not influenced by the fibre geometry whereas the post peak response and ductility was considerably improved by long steel fibres.

The flexural behaviour reinforced concrete (RC) beams constructed with normal strength concrete (NSC) is well understood. The analytical models and standard procedures are also developed for the analysis of such NS-RC beams. However, the analytical procedures developed for the analysis of NS-RC beams cannot be straightforwardly adopted for the beams made up of UHPFRC materials. For the fact that UHPFRC has substantial tensile strength and strain capacity that cannot be neglected in the analysis procedure. The extensive test regimes are needed to capture the material characteristics such as tensile characteristics, bond-slip and tension stiffening characteristics. The full-scale structural tests are also required to study the effect of varying geometry, material properties and loading conditions on the structural behaviour. The task of empirically developing the analytical procedures for UHPFRC is even more complicated than that of conventional concrete due to the potential range of fibre types and volume fractions. Such extensive testing regimes will entail time and cost that constraint the adoption of UHPFRC in real life structures. An alternative way is to conduct a well formulated but limited tests on material and structural level to develop the numerical models using commercially available finite element (FE) software packages [38]. The FE software such as Abaqus is equipped with concrete constitutive models developed for normal strength concrete (NSC). It is well understood that the material behaviour of UHPFRC is substantially different from NSC hence the adoption of such concrete constitutive models may not be reliable. The number of material parameters are also required to define the material model which also needs to be obtained for UHPFRC material through the experimental tests. The objective of present study is to validate the concrete constitutive model by conducting the material tests on UHPFRC and to adapt the material model for the analysis of the flexural behaviour of UHPFRC beams.

The concrete damaged plasticity model is based on the classical theory of plasticity. The degradation to the stiffness is modelled by defining the damage variables for tension and compression. The isotropic damage to the elasticity is considered to model the inelastic behaviour of concrete. Previous studies have shown that the use of concrete damaged plasticity (CDP) constitutive models available in finite element (FE) software such as Abaqus, to be a powerful and reliable predictive tool for the analysis of normal strength concrete. Recently, Mahmud et al. [16] tested unreinforced notched UHPFRC beams to study the size effect on the flexural strength of UHPFRC. The two dimensional plane stress FE analysis of beams was conducted using a CDP model for UHPFRC. The overall load versus crack mouth opening displacement (CMOD) captured by the model was in good agreement with an error ranged from 11.8% to 1.2%. Tysmans et al. [17] adopted a CDP model to simulate the behaviour of high performance fibre reinforced concrete composite under biaxial tension. It was reported that the model accurately simulated the strain hardening behaviour of fibre concrete but with reduced stiffness. It should be noted that in the above-mentioned studies, only small-scale specimens without internal reinforcement are considered and only 2D finite element models are developed.

In this investigation an UHPFRC mix developed with conventional materials, normal mixing and curing regimes is considered to study the material characteristics and structural behaviour in full-scale beams. The materials characteristics such as stress strain behaviour under uniaxial tension and compression is studied for the developed mix. The uniaxial stress strain data from the tests is used to calibrate the parameters of concrete damaged plasticity (CDP) model. The calibrated CDP model is adapted for the FE analysis of the full-scale beams. The FE models of the beams are validated with the experimental data of the full-scale beam tests obtained from this study. Further the efficiency of the finite element models is verified with the beam tests conducted by other researchers [14]. The methodology of conducting limited but well formulated material and structural tests to validate the numerical models in available finite element packages can expedite the task of development of design guidelines facilitating the adoption of UHPFRC in construction industry.

2. CDP model – theoretical background

The damage-plasticity model used for the concrete is based on a plasticity-based continuum damage model [24]. The model uses a scalar (isotropic) damage parameter as an internal variable for the characterisation of the damage model which is combined with the elasto-plastic behaviour under tensile and compressive stresses to represent the inelastic behaviour of the material [23]. It uses a non-associated flow rule with the help of a plastic potential. Formation of tensile micro-cracks is captured macroscopically with a softening stress-strain relationship whereas its plastic response in compression is typically represented by strain hardening followed by strain softening behaviour. The evolution of the yield (or failure) surface is controlled by two hardening parameters (equivalent plastic strains), which are linked to failure mechanisms under tension and compression loading, respectively. The uniaxial stress strain data in compression and tension data is required by the model to evaluate the hardening/softening behaviour of the concrete. In addition, five parameters are required to define the yield function, plastic potential and visco-plastic regularization that are explained in the following paragraphs.

The damage-plasticity model uses the yield criteria proposed by Lubliner et al. [24] along with the modifications proposed by Lee and Fenves [25] to account for different evolution laws of the strength under tension and compression. The two main parameters required to define the shape of the yield surface are; the ratio of initial biaxial compressive strength to initial uniaxial compressive strength σ_{bo}/σ_{co} and parameter k_c is used to define the shape of the failure surface in the deviatoric plane. Fig. 1 shows the shape of the yield surface under plane stress condition while the yield function is defined as

$$f = \frac{1}{1-\alpha}\left(\bar{q} - 3\alpha\bar{p} + \beta\left(\tilde{\varepsilon}^{pl}\right)\left\langle\hat{\bar{\sigma}}_{\max}\right\rangle - \gamma\left\langle-\hat{\bar{\sigma}}_{\max}\right\rangle\right) - \bar{\sigma}_c\left(\tilde{\varepsilon}^{pl}\right) \leqslant 0 \qquad (1)$$

where α and γ are dimensionless material constants controlled by the parameters σ_{bo}/σ_{co} and k_c defined below, $\bar{p}$ is the hydrostatic pressure based on effective stresses, $\bar{q}$ is the effective von Mises equivalent stress, $\hat{\bar{\sigma}}_{\max}$ is the effective major principal stress, and $\bar{\sigma}_c$ is the effective cohesive stress in compression, function of the

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