International Journal of Impact Engineering 114 (2018) 20–31

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Applicability of damage plasticity constitutive model for ultra-high performance fibre-reinforced concrete under impact loads

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ARTICLE INFO

Keywords:
Concrete damage plasticity
Ultra-high performance fibre reinforced concrete (UHP-FRC)
Drop-weight impact
Strain rate effect
Strain-hardening response

ABSTRACT

This paper presents a numerical investigation on assessing whether the concrete damage plasticity (CDP) constitutive model can be used to simulate new ultra-high performance fibre reinforced concrete (UHP-FRC) material under impact loading rates at different damage stages. The performance of the numerical models is verified by comparing numerical results to the experimental data that were previously tested by the authors. This paper also presents experimental tests that aimed to characterize the strain rate effect on UHP-FRC. The numerical simulations have been performed using ABAQUS/Explicit. CDP parameters are identified based on impact test results of a control specimen. Subsequently, the predictive capability of calibrated model has been investigated by simulating two UHP-FRC plates with varied steel reinforcement ratios tested under repeated drop-weight impact loads.

It has been found that compressive and tensile strength enhancement predicted using CEB-FIP Model Code (1990) fits well with test results of the strain rate effect on UHP-FRC material. The numerical results demonstrate the feasibility of the CDP constitutive model for analyzing UHP-FRC under dynamic loading rates. Computed responses are sensitive to CDP parameters related to the tension, fracture energy, and plastic volumetric change. The effect of tensile strain hardening response could be ignored in the nonlinear finite element (FE) analysis of UHP-FRC materials with low strain-hardening behaviour.

1. Introduction

UHP-FRC is a relatively new generation of cementitious material that is consisting an optimum combination of cement, fine sand, silica fume, superplasticizer, very low water-to-cementitious materials ratio, and fibres [1]. UHP-FRC exhibits exceptional mechanical and durability characteristics in comparison to its traditional counterparts. UHP-FRC has an unconfined compressive strength of greater than 150 MPa [2], tensile strength in the range of 8–15 MPa, high elastic modulus, strain hardening in tension [3], outstanding post-cracking capacity [4], enhanced dynamic properties, especially impact resistance, and superior damage control characteristics [5]. UHP-FRC can be considered a promising way to innovate in a wide spectrum of applications where the static, dynamic, and durability properties are required, such as nuclear waste containers, offshore platforms, protective structures, transportation structures, etc.

Despite the obvious advantage of UHP-FRC, its structural application is not widespread. One of the main reasons that has delayed the extensive use of UHP-FRC has been the lack of widely accepted and reliable UHP-FRC constitutive law and/or design guidelines. In addition, limited numerical studies have been performed on modelling the structural responses of the reinforced UHP-FRC members (e.g., [6–8]). Several experimental investigations have been conducted with an aim of characterization UHP-FRC mechanical properties under uniaxial state of stress. Such investigations have shown that the mechanical properties of UHP-FRC material are different from traditional concrete, in particular, the tensile response [2,4], fracture energy [1,4], and strain rate effects [9,10]. These differences in material behaviour might result in more complexity to the analysis and design of UHP-FRC.

Generally, the post-peak tensile response of concrete has a significant effect on the accuracy of numerical results of FE modelling when compared to the post-peak compressive response [11]. The tensile post-peak regime of UHP-FRC is different from normal- (NSC) and high-strength concretes (HSC). Fig. 1 illustrates the difference between the tensile response of traditional strain softening concrete and UHP-FRC. The uniaxial tensile response of UHP-FRC is characterized by linear-elastic up to matrix tensile strength, followed by strain hardening behaviour associated with several micro-cracks distributed in the entire volume of the bulk material until the tensile strength is reached and a macro-crack is localized. Across this macro-crack the force is still

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https://doi.org/10.1016/j.ijimpeng.2017.12.013
Received 3 August 2017; Received in revised form 6 November 2017; Accepted 14 December 2017
Available online 15 December 2017
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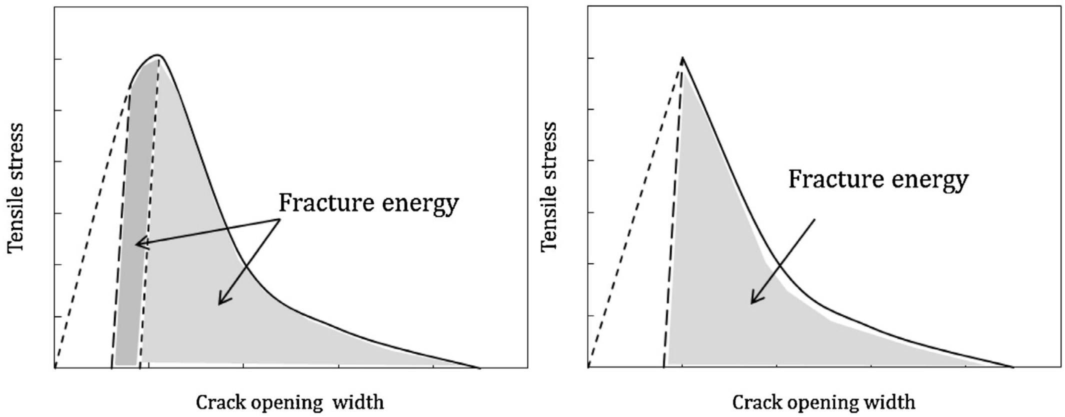

Fig. 1. Uniaxial tensile behaviour for (left: UHP-FRC; right: conventional concrete).

transferred by fibres and the stress decreases until full pull-out of fibres. Fracture energy (G_F) is another important parameter defining the cracking and post-cracking behaviour of concrete and it is significant for any accurate FE analysis [12]. According to fictitious crack model, fracture energy is defined as the area under the stress-crack opening curve and represents the energy required to produce a continuous crack of an unit area within the damage zone. UHP-FRC is characterized by fracture energy of several orders of magnitudes of NSC and HSC [4]. The tensile post-peak law of UHP-FRC still a challenging topic for researchers and such model has not been fully established. Graybeal [13] adapted a simple elastic perfectly plastic uniaxial tensile model based on material test results. This simple model was used successfully to predict the quasi-static response of UHP-FRC I-Girders using ABAQUS software [7]. On the other hand, several researchers developed tensile models to accurately capture the tensile response of UHP-FRC, including strain hardening (multiple cracking) and softening (crack opening) behaviour. Man and Wille developed a fracture tensile model consists of linear strain hardening and exponential softening curve [8]. Sadouki et al. adapted a piecewise linear function to describe tensile hardening and softening [14]. It should be pointed out that there is still a lack of agreement as to which tensile curve is adequate for modelling UHP-FRC. It is worth mentioning that the significance of modelling strain hardening on the numerical results is not clear.

Several experimental investigations have demonstrated that the mechanical properties of concrete and steel are enhanced significantly under high strain rates corresponding to dynamic loads. Commonly, strain rate effects incorporated in the numerical analysis by defining the dynamic increase factors (DIF) at different strain rates. The behaviour of UHP-FRC at high strain rates is not well addressed. French standard recommends DIF for UHP-FRC in compressive and tensile strength of 1.5 and 2, respectively, for an impact loading strain rate range of 10^{-3} to 1 s^{-1} [2]. The testing results of Ngo et al. showed that UHP-FRC is less strain-rate sensitive than NSC and HSC [15]. On the other hand, Pajak carried out an extensive review of experimental data for all concrete classes, including UHP-FRC under a wide range of strain rates [16]. Pajak concluded that the values of DIF obtained from testing UHP-FRC materials are same as NSC tests. Based on contradictory information in the literature and the lack of data for UHP-FRC, the strain rate effect on UHP-FRC is in need to be experimentally investigated.

In general, there is a distinct lacking of comprehensive test data that can be used to develop a constitutive model for UHP-FRC under various confining pressure levels. Previous multiaxial tests on UHP-FRC have revealed that: compressive strength and deformation capacity are enhanced by lateral confinement [17,18]; multiaxial strength is related to the uniaxial strength [17,19]; the yield surface (i.e., compression and tension meridians) can be described by parabolas opened in the direction of increasing hydrostatic pressure [20,21]; the yield surface on the deviatoric planes changes from triangular at low confinement stress to nearly circular with increasing hydrostatic pressure [20]; UHP-FRC has an uniaxial compressive-to-tensile strength ratio similar to NSC [21]; and the yield surface of UHP-FRC in the plane stress can be modelled using Kupfer's failure criteria [22]. Based on these limited experimenral results, UHP-FRC can be modelled in three-dimensional state of stress using classical plasticity-based models (e.g., Drucker-Prager) or combined damage-plasticity models (e.g., CDP model) [23]. However, under dynamic loading conditions (i.e., under high confining pressures), combined damage-plasticity models are more accurate in describing the yiled surface and flow rule of concete [24]. The main objective of this research is to assess whether the existing CDP constitutive model with adjustable material parameters can predict the dynamic response of UHP-FRC structural members by collaborating the aforementioned new characteristics. A second objective is to address the significance of including such characteristics on the numerical results. This numerical investigation is carried out using ABAQUS/Explicit, version 6.14 [23]. CDP model is used to define the complete behaviour of UHP-FRC material. The classical metal plasticity model is used to describe nonlinearity of the steel reinforcement. Two experimental tests have been associated with the current research to facilitate the numerical investigation. The first testing program is material investigation aims to generate accurate input data for new UHP-FRC and steel reinforcement constitutive models. The second testing program focuses on the dynamic response of reinforced UHP-FRC specimens tested under repeated drop-weight impact. A brief description of the experimental tests is provided, published in more detail elsewhere [5,25], followed by a detailed description of the numerical investigation.

2. Concrete damage plasticity model

Concrete damage plasticity model, also known as Bacelona model, was firstly introduced by Lubliner et al. [26] for monotonic loading, and later was adopted by Lee and Fenves [27] to consider the cyclic and dynamic loadings. The default flow potential eccentricity is $\epsilon = 0.1$. The mathematical formulation of the CDP model can be found in [23,26,27]. CDP model is a continuum, plasticity-damage based model that allows for separate input of stress-strain relations, damage parameters, and strain rates in tension and compression. CDP model can represent various types of concrete using a set of adjustable input parameters that can be measured experimentally. Such input parameters are well defined for NSC and HSC. However, the performance of CDP model for defining UHP-FRC behaviour remains unclear.

The CDP model is a two-invariant plasticity model, where the yield surface is a modified Drucker–Prager strength hypothesis [27]. The yield surface of CDP model in the deviatoric stress plan is not a circle to allow for different yield triaxial tension and compression stresses (Fig. 2a). This noncircular yield surface is governed by shape parameter (K_c). Physically, parameter K_c is interpreted as a ratio of second stress

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