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Sectional analysis for design of ultra-high performance fiber reinforced concrete beams with passive reinforcement

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ABSTRACT

Sectional flexural analysis, as performed in normal strength concrete design, requires uniaxial constitutive models. For ultra-high performance fiber reinforced concrete (UHPFRC), the constitutive model tensile backbone varies with section heights for different flexural members, due to the size-dependent stress-crack opening relation used to derive it. In this paper, several simplified size-independent constitutive models were investigated. For unreinforced sections with heights between 51 mm and 1067 mm, the elastic-perfectly-plastic tension model leads to conservative ultimate moment prediction (or results within 5%) when compared to that obtained by the size-dependent model. For reinforced sections, the difference between the two models is affected by the reinforcing condition and is even smaller than the unreinforced cases. By assuming an elastic-perfectly-plastic tension model, the flexural strength of rectangular or T section UHPFRC beams was estimated analytically. The flexural strengths are greatly influenced by the reinforcement ratio and yielding strength of the longitudinal reinforcement. Including shear strength predictive equations from past research, the load capacity and failure mode for rectangular and T beams are presented in a design chart. The impact of several factors on UHPFRC beam flexural responses were investigated, such as different compressive strength, curing conditions, and anisotropic fiber orientation distributions. The load-deflection relationships generated from beam flexural analysis were compared to experimental results for both unreinforced and reinforced beams, with or without fiber alignment. Factors affecting the first crack strength in tension (i.e., fiber orientation distribution) had greater impact on the flexural strength of UHPFRC beams than the effect of using a size-dependent model.

1. Introduction

Ultra-high performance fiber reinforced concrete (UHPFRC) commonly refers to concrete materials with a compressive strength higher than 150 MPa and exhibiting tensile strain hardening behavior under uniaxial tension. The high compressive strength of the matrix is achieved by using only fine aggregates that ensure good homogeneity and compactness [1]. The appropriate granular mixture also reduces the entrapped air and creates a rigid structural skeleton. There are various types of UHPFRC materials. The water-binder ratio for one particular category is less than 0.2 and as reported in Appendix I of the French code [2], it reaches an average compressive strength of 228 MPa determined from 197 7 cm diameter, 14 cm long cylinders with both ends ground. Its modulus of elasticity was in the range of 57–61.4 GPa. The stress-strain curve exhibited nearly linear behavior until failure. This highly linear stress-strain relation on the compressive side was also observed by Graybeal [3], who performed a series of compressive tests on cylinders and cubes with different dimensions. The difference of compressive strength due to geometry of the specimen was within 8%.

The fiber volume fraction (FVF) is about 2% for typical UHPFRC mixtures. The short fibers, usually round 12 mm long, are added into the cement matrix as micro-reinforcement. In order to achieve high bond strength between fibers and matrix, fibers are usually surface treated. The good ductility of UHPFRC comes from the bridging effects of fibers and leads to a strain hardening response with high pre- and post-crack tensile strength. The existence of fibers also changes the brittle compressive failure mode to a more ductile type and prevents sudden explosive compressive failures [4].

To ensure the high quality and high compressive strength of UHPFRC, hot water bath curing at 90 °C and 95% humidity for 48 h is usually required [2] to accelerate the hydration process. However, for the case of large-scale UHPFRC specimens, this heat curing process is

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difficult to implement. Therefore, untreated UHPFRC structural members are also of interest, particularly given that the strength of untreated UHPFRC is in the range of 120–160 MPa, which is still higher than traditional high strength concrete. According to previous experimental results [3], UHPFRC cured under room temperature will still reach much higher compressive strength than normal strength concrete. However, at 28 days, its compressive strength is usually lower than the samples with heat treatment. The 28 day compressive strength of 76 mm diameter cylinders with both ends ground were around 190 MPa and 120 MPa for the steam treated specimens and untreated specimens, respectively [5].

Vodicka et al. [6] suggested that the critical FVF to achieve a homogeneous distribution is about 0.4–0.5%. The homogeneous distribution can be achieved for up to 8% FVF when using short steel fibers [7]. Therefore, 2% of steel FVF falls within the range where a homogeneous distribution can be assumed along with acceptable workability of the cement paste. However, the assumption of random orientation distribution of individual fibers is usually violated due to the flow casting method. This casting method is widely used with or even without external vibrations by taking advantage of the self-consolidation property of UHPFRC.

By casting UHPFRC in a specially designed U-shaped sag box, image analysis of the fiber orientation showed the fibers tend to align with the cement paste flow direction, and the degree of alignment is related to the flow ability of the cement paste [8]. The influence of form boundaries on fiber alignment was utilized by Bernier and Behloul [9] to create prisms with fibers aligned at a particular orientation. The anisotropic distribution of fiber orientation was also confirmed by non-destructive electrical resistivity measurements on two slabs with different casting procedures [10]. The flow directions matched the pattern of the measured anisotropic axis. In the current French design guideline [2], the effect of adverse fiber orientation distribution was considered by introducing a reduction factor K on the post-crack strength at all strain levels. For common scenarios, $K = 1.25$ is used. This method is insensitive to the level of anisotropy and aims to provide a conservative estimation for design purposes. However, this method does not provide a direct link between the level of anisotropy and the mechanical responses, and can underestimate the adverse effects if the fibers are highly aligned. Xia and Mackie [11] developed a framework to quantify the degree of anisotropy for axisymmetric distributions of fiber orientation.

Due to the brittle nature of cementitious materials, concrete beams usually exhibit a size effect under flexural loading. For UHPFRC, the size effect is reported to be less severe than normal strength concrete due to its high ductility [12]. Yoo et al. [13] state the size effect is potentially related to the anisotropic fiber orientation distribution. To characterize the properties of UHPFRC, many mechanical experiments have been performed, including uniaxial compressive strength tests, first-crack strength tests, modulus of rupture tests, etc. Several uniaxial constitutive models were developed based on the experimental results, e.g., by Graybeal [3] and Steinberg [14]. A bilinear size-dependent material model was proposed for strain hardening materials, while a four segment piecewise material model was proposed for strain softening and low strain hardening materials [15]. For strain hardening materials, the elastic tensile strength can be calculated based on the linear portion of the load versus deflection curve from un-notched flexural tests. The maximum cracking stress can be obtained through back analysis based on the post-cracking load deflection curves. The ultimate strain is determined by the length of fiber and characteristic length, which is related to the section height. Therefore, the proposed strain hardening relation is by nature size dependent. The size effects also exists in the material model for strain softening and low strain hardening materials. The material constitutive model changes with respect to sectional dimensions, which is usually not considered by structural designers, particularly during preliminary design.

One of the modified versions of the French model is size independent and has been used for structural optimization purposes [14]. A simplified uniaxial stress-strain curve was also developed by Graybeal [16] based on experimental observations from test results at the material level and on prestressed UHPFRC girders. It has been used to predict the structural responses of waffle-shaped bridge decks [17]. The model has a simplified stress-strain relationship with elastic-perfectly-plastic segments. The flat portion begins at a stress level of 9 MPa and remains constant until reaching the ultimate tensile strain at 0.007. However, the applicable range of section heights for different size-independent models still requires investigation.

This paper proposes a uniaxial constitutive model for UHPFRC, and verifies its effectiveness through comparison with experimental results for both unreinforced and reinforced beams. The model can consider various factors that affect the flexural behavior, such as different curing conditions, fiber orientation distributions, and different reinforcing ratios. The applications of a size-independent model were verified by comparing flexural responses with the equivalent results obtained from the size-dependent model. Design equations are derived based on the simplified size-independent model for both rectangular and T-section beams reinforced with normal and high-strength steel.

2. Uniaxial constitutive model

The main compression parameters are characteristic compressive strength f_c' and modulus of elasticity in compression E_c. Tension parameters are characteristic first crack strength f_t and modulus of elasticity in tension, with the assumption $E_t = E_c$.

2.1. Stress-strain backbone and parameter characterization

The tensile responses of the size-dependent French model can be generalized as shown in Fig. 1 with seven characteristic stress and strain values as shown in Eq. (1). The subscripts of '0.3', '1%', and 'lim', represent the crack widths of 0.3 mm, 1% of the total section height h, and the limiting or maximum value, respectively. The term $w_{\lim} = l_f/4$ is the maximum crack width.

$$\sigma_{t0} = f_t \sigma_{t1} = \sigma(w_{0.3}) \quad \sigma_{t2} = \sigma(w_{1\%}) \quad \sigma_{t3} = 0$$
$$\varepsilon_{t0} = f_t/E_t \quad \varepsilon_{t1} = \varepsilon_{t0} + w_{0.3}/l_c \quad \varepsilon_{t2} = \varepsilon_{t0} + w_{1\%}/l_c \quad \varepsilon_{t3} = \varepsilon_{t0} + w_{\lim}/l_c \tag{1}$$

The characteristic length l_c is usually equal to two-thirds of the total section height h, which means that the stress-strain relation is size dependent. Considering a common fiber used in UHPFRC has a length $l_f \approx 12$ mm, the value of ε_{t3} may be smaller than that of ε_{t2}. Therefore, for sections with height larger than 300 mm, the tensile strain-stress curve degenerates to a three-segment model with a linear degradation between strains of ε_{t1} and ε_{t3}. The parameters that define the tensile responses are usually obtained via either direct tensile tests or flexural tests. By applying back analysis to the load-displacement relation, the

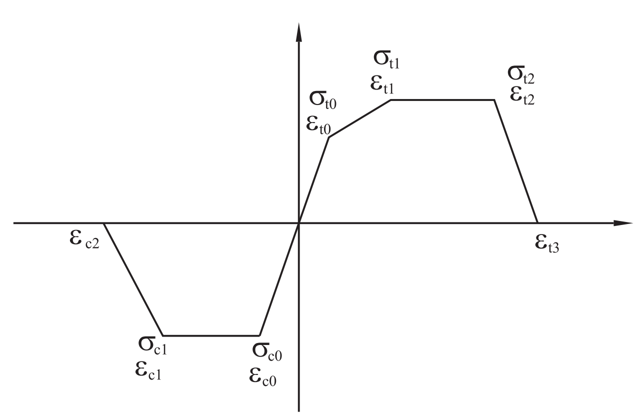

Fig. 1. Generalized uniaxial constitutive model.