



# Constitutive modeling of steel-polypropylene hybrid fiber reinforced concrete using a non-associated plasticity and its numerical implementation



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## ABSTRACT

This paper presents a non-associated plasticity-based constitutive model for hybrid steel–polypropylene fiber reinforced concrete (HFRC) materials in an attempt to characterize the stress–strain responses under multiaxial loading scenarios. Together with a five-parameter loading surface and uncoupled hardening and softening regimes, a nonlinear plastic potential function is particularly introduced into the constitutive model with the material constants experimentally determined through a true triaxial compression test, which allows a more accurate estimation of the volumetric dilatancy of HFRC. The influence of fiber parameters on the plastic flow direction is also addressed. Furthermore, the developed model is implemented into ABAQUS finite element package through a User-defined Material (UMAT) subroutine that can be applicable for the convenient use in numerical simulation of HFRC materials. A substepping scheme with error control for integrating the elasto-plastic stress–strain rate equations is presented in detail. Subsequently, the proposed model is evaluated by available multiaxial compression test results of both plain concrete and FRC reported by other researchers. It is shown that the constitutive model can realistically capture the stress–strain responses as well as the volumetric deformation of HFRC having various fiber reinforcement indices.

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## 1. Introduction

Over the past few decades, considerable research efforts have been invested in the development of elasto-plastic constitutive models for plain concrete [1–5]. Some of such models [6] have been successfully incorporated into commercial finite element codes and extensively utilized for the numerical simulation of concrete structures. The achievements allow researchers to investigate the mechanical behavior of plain concrete conveniently by selecting the corresponding constitutive models.

With the rapid development of fiber reinforced concrete (FRC) theory and its applications, FRC materials such as steel fiber reinforced concrete, polypropylene fiber reinforced concrete, or hybrid steel–polypropylene fiber reinforced concrete have gained wide recognition and have become firmly established within the arsenal of existing construction materials over recent years. FRC exhibits excellent tensile, buckling and shearing strength as well as superb resistance to cracking, fracture and fatigue [7–9]. The substantial

amount of research and development in fiber reinforcing technology has led to a wide range of practical engineering applications such as in pavement design, structural repair/maintenance, shot concrete mix design, deep beams and in offshore environments (offshore foundation, condeep platform floats, support structures and storage unit for nature oil or gas) [10–13]. Nowadays, owing to the rapid improvements in numerical simulation techniques and computational capabilities, engineers have begun to simulate the behavior of FRC structures in addition to traditional concrete structures using finite element modeling (FEM) to analyze and solve various concrete problems as subjected to complicated loading conditions [14]. The analysis of an engineering problem using FEM essentially involves solving equilibrium equations with prescribed boundary and initial conditions that are linked by the material's constitutive relations [15], where the constitutive model plays a significant role in the numerical simulation. Notwithstanding that many attempts concerning on constitutive modeling of FRC materials with steel fiber reinforced concrete (SFRC) in particular have achieved certain success [16–21]. However, FRC materials exhibit complex responses in terms of strain hardening/softening, volumetric dilatancy, pressure sensitivity, etc., which

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change significantly with the varying fiber parameters, and to the authors' knowledge, the majority of the published models depend to a large degree on their particular application. Moreover, with respect to the HFRC materials, a unified constitutive model along with the incorporation into FE software package can rarely be found in the literature. As HFRC materials are typically subjected to multiaxial loadings, a more sophisticated constitutive model is imperatively required for the accurate prediction of the stress state and the deformation.

To this end, the subsequent focus of this study is to develop a constitutive model for HFRC material predicated on a non-associated plasticity which is a continuation of research [22]. In this study, a nonlinear plastic potential function is particularly introduced into the constitutive model with the influence of fiber parameter on the plastic flow addressed in detail. Furthermore, the proposed constitutive model is implemented into FE software package ABAQUS by an explicit integration method using the UMAT subroutine, of which the integration algorithm is also emphasized. Finally, the response of the developed model is validated and verified with existing experimental results in terms of stress–strain behavior and volumetric deformation under various loadings.

## 2. Constitutive modeling

### 2.1. Loading surface of HFRC

The mathematical form of the loading surface proposed in present study is developed on the basis of the Willam–Warnke (1974) (W–W) five-parameter failure model [6], the expression using the Haigh–Westergaard coordinates is shown below:

$$f(\xi, \rho, \theta) = \sqrt{2J_2} - K(\bar{\epsilon}_p) \cdot \rho^{hf}(\xi, \theta) = 0 \quad (1)$$

where  $K(\bar{\epsilon}_p)$ , ranging from  $K_0$  to 1, denotes the hardening/softening function that defines the increase of strength during hardening and the strength deterioration during softening, which is governed by the equivalent plastic strain. The parameter  $K_0$  determines the initial yield surface and limits the elastic regime. In addition, the function  $\rho^{hf}(\xi, \theta)$  describes the parabolic shape of meridians which binds the ultimate strength of HFRC (Eq. (2)). It is interpolated between the tensile meridian  $\rho_t$  (Eq. (3)) where Lode angle  $\theta = 0^\circ$ , and the compressive meridian  $\rho_c$  (Eq. (4)) where Lode angle  $\theta = 60^\circ$  as follows:

$$\rho^{hf}(\xi, \theta) = \frac{2\rho_c^{hf} \left[ (\rho_c^{hf})^2 - (\rho_t^{hf})^2 \cos \theta \right]}{4 \left[ (\rho_c^{hf})^2 - (\rho_t^{hf})^2 \right] \cos^2 \theta + (\rho_c^{hf} - 2\rho_t^{hf})^2} + \frac{\rho_c^{hf} (2\rho_t^{hf} - \rho_c^{hf}) \left\{ 4 \left[ (\rho_c^{hf})^2 - (\rho_t^{hf})^2 \right] \cos^2 \theta + 5(\rho_t^{hf})^2 - 4\rho_t^{hf} \rho_c^{hf} \right\}^{1/2}}{4 \left[ (\rho_c^{hf})^2 - (\rho_t^{hf})^2 \right] \cos^2 \theta + (\rho_c^{hf} - 2\rho_t^{hf})^2} \quad (2)$$

$$\frac{\xi}{f_{cu}} = a_2 \left( \frac{k_t \rho_t}{f_{cu}} \right)^2 + a_1 \left( \frac{k_t \rho_t}{f_{cu}} \right) + a_0 \quad (3)$$

$$\frac{\xi}{f_{cu}} = b_2 \left( \frac{k_c \rho_c}{f_{cu}} \right)^2 + b_1 \left( \frac{k_c \rho_c}{f_{cu}} \right) + b_0 \quad (4)$$

in which  $\rho_t^{hf} = k_t \rho_t$ ,  $\rho_c^{hf} = k_c \rho_c$  and  $\cos \theta = \frac{2\sigma_3 - \sigma_2 - \sigma_1}{2\sqrt{3}\sqrt{J_2}}$  for  $\sigma_3 \geq \sigma_2 \geq \sigma_1$ . In addition, the variable  $f_{cu}$  denotes the uniaxial compressive strength of plain concrete and  $k_c$ ,  $k_t$  are modification coefficients which will be discussed later on. The interpolated meridian function  $\rho^{hf}(\xi, \theta)$  forms a cone-shaped failure envelope, as schematically illustrated in Fig. 1. These equations are expressed in terms of

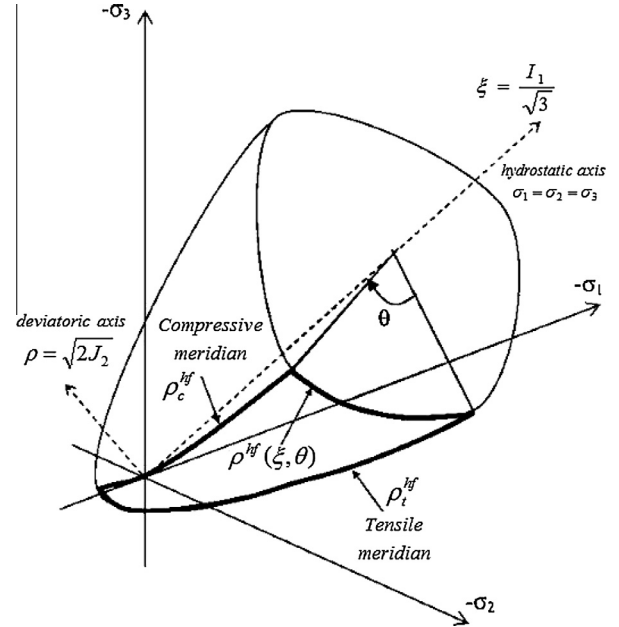


Fig. 1. Schematic diagram of failure envelop in Haigh–Westergaard coordinates.

hydrostatic pressure  $\xi$  and deviatoric stress  $\rho$ , where  $\xi = I_1/\sqrt{3}$  and  $\rho = \sqrt{2J_2}(I_1 = \text{tr}(\sigma_i)/3)$  is the first invariant of stress tensor, and  $J_2 = \frac{1}{2}s_{ij}s_{ij}$  is the second invariant of deviatoric stress tensor. The notation  $\sigma_i (i = 1, 2, 3)$  represents the principal normal stress in the  $i$ th direction. The material constant  $a_0, a_1, a_2, b_0, b_1, b_2$  are determined from a large variety of experimental data points [23], which relate to the uniaxial strength, uniaxial tensile strength, equal biaxial compressive strength and the triaxial strength with high confinement. Since the W–W model has shown its robustness in prediction of failure strengths of various concrete materials, and the failure envelope also satisfies the requirements of smoothness, convexity with separate descriptions of the compressive and tensile meridian, these features allow flexible modification of a specific section to account for the presence of hybrid fibers.

Consequently, it is noted from Eqs. (2)–(4) that, two modification coefficients ( $k_c, k_t$ ) are introduced into the meridional functions that are able to account for the increase in stress state at failure along both meridians, which will also result in a change

in the entire failure envelop that can reflect the fiber effect subject to other loading scenarios. In this study, These two coefficients were calibrated based on true triaxial compression tests as described in following section.

### 2.2. Experimental program

Cubic specimens were prepared for the true triaxial compression testing using 18 HFRC mixes (Table 1), containing 0%, 0.5%, 1.0% and 1.5% volume fraction of corrugated steel fibers with aspect ratio of 30 and 60, and 0%, 0.05%, 0.1% and 0.15% volume fraction of monofilament polypropylene fibers with aspect ratio of 167 and 396. For comparison, plain concrete as well as single fiber rein-

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