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Finite element modeling of steel-polypropylene hybrid fiber reinforced concrete using modified concrete damaged plasticity

Yin Chi [a], Min Yu [a,*], Le Huang [a,b,*], Lihua Xu [a]

[a] School of Civil Engineering, Wuhan University, 430072, China
[b] Wuhan Municipal Construction Group Co. Ltd., 430024, China

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ABSTRACT

This paper presents a modified concrete damaged plasticity model (CDPM) based on ABAQUS, in order to accurately simulate the mechanical responses of steel-polypropylene hybrid fiber reinforced concrete (HFRC). The modifications mainly include the determination of fiber effect-dependent parameters in terms of damage evolution, yield criterion, hardening/softening law and plastic potential. The influences of respective parameter on the numerical results are discussed in detail. Subsequently, the CDPM with refined parameters is validated by independent experimental results having various fiber reinforcement indexes in both material scale and structural scale, where the mechanical behavior of FRC material under multiaxial loadings and the seismic performance of HFRC column subjected to cyclic loadings are respectively simulated. The close agreements between numerical predictions and test results solidly substantiate the applicability of the modified model, which serves as a solid foundation for accurate simulation of FRC behavior using ABAQUS.

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1. Introduction

The plain concrete is well acknowledged to demonstrate a brittle nature, which has been regarded as one of the most important reasons for the potential structural failure and the substantial construction waste [1]. In the context of developing a sustainable society, considerable attempts in concrete modification have been made over the past few decades [2,3], among which the fiber reinforced concrete (FRC), in particularly with hybrid fiber technology, has gained increasing recognition for the superior performance in tension, energy dissipation, and the resistance to cracking [4,5]. A wide review of literature demonstrated that, the substitution of HFRC for plain concrete in critical regions of a structure, such as the beam-column joint, beam bottom, and column base, etc (Fig. 1), can effectively enhance the overall structural responses [6,7], and for this reason, HFRC has also been more and more applied in the repairment of damaged infrastructures in the last decades [8–10]. However, owing to the practical demands, the majority of current interests were mainly concentrated on the experimental study and subsequent engineering application, only a few attentions were devoted to the development of an applicable constitutive relation as well as the numerical modeling.

Of the limited theoretical investigations, the pioneering work conducted by Cox [11] in the early times is worth noting, in which the redistribution of load in matrix caused by fiber breaking was systematically discussed. Shortly afterwards, the model was further developed by Daniels [12] and Harlow et al. [13] respectively based on different assumptions. Moreover, considering the actual failure modes, the cohesive crack model [14–16] and J-integral approach [17] combined with multi-parameter fracture criterion were proposed to simulate the FRC structure. However, it should be noticed that, although those models can offer detailed information of matrix cracking and fiber bridging separately, their implementations in the analysis of sophisticated structures are hard to achieve, which greatly restrains the use of these models as a consequence [18]. More recently, great efforts have been done in plasticity-based constitutive modeling. For example, the work conducted by Chi et al. [19] treated the HFRC as a homogeneous continuous material, the degradation of mechanical performance induced by concrete cracking and fiber debonding was governed by some key internal variables. The developed models are observed to provide a close estimation of the multiaxial stress-strain behavior of HFRC. However, to implement these models, a user-material subroutine suitable for finite element software is usually required to be developed, which will bring about some complicated issues,

* Corresponding authors at: School of Civil Engineering, Wuhan University, 430072, China (M. Yu).

E-mail addresses: ceyumin@whu.edu.cn (M. Yu), huangle@whu.edu.cn (L. Huang).

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Nomenclature

ε^{el}, ε^{pl} elastic and plastic strains
d_c, d_t uniaxial compressive and tensile damage variables
σ_{ij} function of stress state
D^{el}_{ijkl} initial elasticity matrix
ε_{ij},ε^{pl}_{ij} total and plastic strain tensor, respectively
$\bar{q}$ Mises equivalent effective stress
$\bar{p}$ hydrostatic stress
$\bar{\sigma}_{\max}$ maximum principal effective stress
σ_{c0}, σ_{t0} uniaxial compressive and tensile stresses
σ_{b0} equibiaxial compressive yield stress
K_c ratio of second stress invariant on the tensile meridian to that on the compressive one
ψ dilation angle
e eccentricity that defines the rate at which the function approaches the asymptote
$\varepsilon^{in}_{c,norm}$, $\varepsilon^{ck}_{t,norm}$ normalized compressive and tensile inelastic strains
ε^{in}_{cu}, ε^{ck}_{tu} corresponding ultimate strains
m_c, m_t parameters that control damage evolution speed
λ_{sf}, λ_{pf} characteristic parameters of steel fiber and polypropylene fiber, respectively
V_{sf}, V_{pf} volume fractions of steel fiber and polypropylene fiber, respectively
(l_{sf}/d_{sf}), (l_{pf}/d_{pf}) aspect ratio (length/diameter) of steel fiber and polypropylene fiber, respectively
G potential flow function
ϕ plastic flow angle
σ_1, σ_2, σ_3, ε^p_1, ε^p_2, ε^p_3 principle stresses and corresponding plastic strains

such as the incompatibility problem, convergence of calculation, etc. [20,21].

With the rapid promotion of ABAQUS worldwide, the concrete damaged plasticity model (CDPM) has raised extensive concerns, which is a continuum plasticity-based damage model [22–24]. By adopting the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity, the model can provide a general capability for modeling the nonlinear deformation and irreversible damage of plain concrete with high accuracy in all structural types and loading paths [10,25]. Inspired by it, many beneficial efforts have been made to refine the parameters, and the achievements enable researchers to study the mechanical behavior of FRC conveniently by making a few adjustments to the original CDPM. Nevertheless, it has been widely accepted that the predictions yielded by this approach are usually validated conditionally, because without a systematical modifications, those adjustments are generally made only special for the situation where the FRC is subjected to a certain loading path, which however is not applicable for other complex loading conditions [26,27].

To this end, this paper presents a modified concrete damaged plasticity model (CDPM) based on ABAQUS, facilitating an accurate simulation of HFRC material and structural behavior. The four main components of CDPM, involving the damage evolution, yield criterion, hardening/softening law and plastic potential function, are quantitatively refined to be fiber effect-dependent. The proposed approach can realistically capture the main features of FRC in terms of strength and deformation with varying fiber parameters.

The paper is organized as follows. In Section 2, a brief theoretical background on the CDPM is presented, and the proposed modifications to the CDPM are elaborated in Section 3. Subsequently, in Section 4, the numerical results from modified model are validated by independent experimental studies in the different scales. At last, the conclusions are summarized in Section 5.

2. Overview of CDPM

The CDPM mainly includes four major components, namely, the damage evolution, yield criterion, hardening/softening law and flow rule.

2.1. Damage

Traditionally, in order to reflect the concrete nonlinearity and irreversible deformation, the total strain ε can be decomposed into two parts according to the classic elasto-plasticity theory,

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} \tag{1}$$

where ε^{el} and ε^{pl} are the elastic and plastic strains, respectively. However, numerous test results has evidenced that the concrete nonlinearity can be attributed to damage or plasticity individually, or stem from a combination of both, while the degradation of unloading stiffness is mainly associated with the damage evolution. Hence, during the numerical simulation, it is desirable to isolate the effect of damage from that of plasticity reasonably.

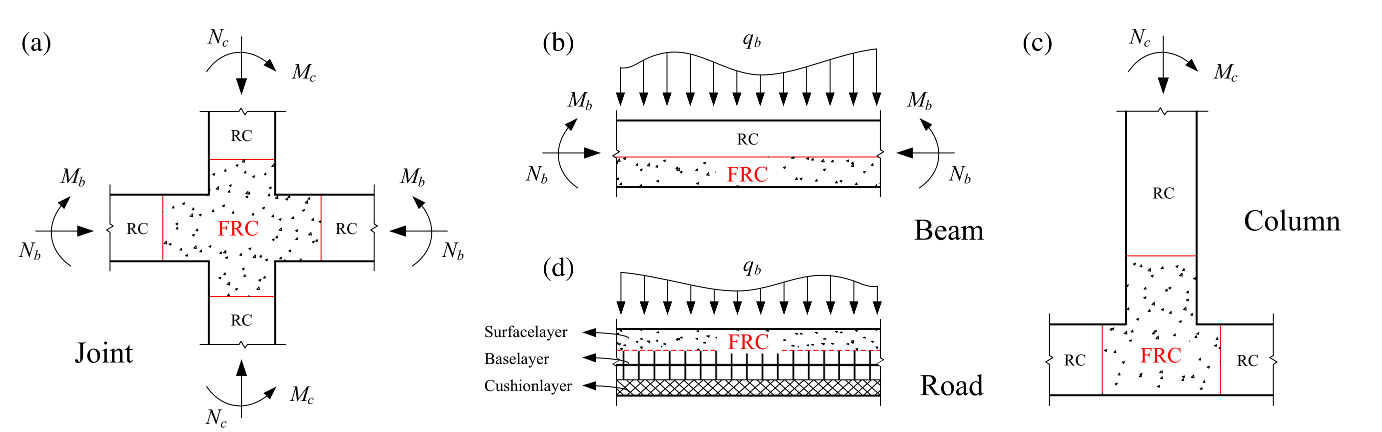

Fig. 1. Typical applications of FRC. (a) beam-column joint, (b) bottom of beam, (c) base of column, and (d) surface layer of road.

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