Finite Element Modeling of FRP-Confined Concrete using Extended Damage-Plasticity Approach

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Abstract: A study on finite element (FE) modelingof fiber-reinforced polymer (FRP)-confined normal-strength and high-strength concrete (NSC and HSC) based on an extended concrete damage-plasticity approach is presented. The study focuses on the extension ofLubliner's model by accurately incorporating the effects of confinement level, concrete strength, and nonlinear dilation behavior of FRP-confined concrete. Failure surface and flow rule were established using an up-to-date database. In order to validate the extended damage-plasticity model, the predictions of the FE modeling are compared with the experimental results. These comparisons indicate that the extended approach accurately predicts the compressive behavior of FRP-confined NSC and HSC.

Keywords: Damage-Plasticity; Finite Element Model; FRP-Confined Concrete; Stress-Strain Relations.

I. INTRODUCTION

Fiber-reinforced polymer (FRP) composites have recently been widely used for confinement of concrete [1]-[8]. It is now well understood that the compressive strength and ductility of concrete are enhanced by its lateral confinement. In order to evaluate the mechanical properties of FRP-confined concrete, a large number of studies have been conducted and over 100 stress-strain models have been developed [9].

Finite element (FE) method has been extensively used as a powerful tool to accurately model the behavior of confined concrete. However, a relatively few number of research studies have been reported to date on FE modeling of FRP-confined concrete (e.g. [10]-[12]). Furthermore, most of the existing models are based on actively confined concrete and adopt an approach that has recently been experimentally shown to be inaccurate, especially for HSC [13]. Therefore, there is a need for an accurate FE model that is applicable to both FRP-confined NSC and HSC.

In this study, a constitutive model for FRP-confined concrete based on an accurate non-associative flow rule and hardening/softening rule is proposed for NSC and HSC with circular sections. The model uses a failure surface and flow rule that are carefully established based on an up-to-date test database. The modeling is implemented in a finite element program ABAQUS [14] for the prediction of mechanical behavior.

II. EXPERIMENTAL DATABASE

An extensive review of the literature was performed to assemble the database of FRP-confined NSC and HSC. Specimens containing internal steel reinforcement or partial FRP confinement were not included in the database and only monotonically loaded circular specimens with unidirectional fibers orientated in the hoop direction and an aspect ratio (*H/D*) of less than three were considered in the database. As a result, the database contained 1156 datasets collected from 108 experimental studies [13],[15]-[18].

III. Extended Damage-Plasticity Model

Different theories have been proposed for constitutive modeling of concrete. The main characteristic of plasticity models is a plasticity yield surface that includes pressure sensitivity, path sensitivity, non-associative flow rule, and strain hardening, without addressing the degradation of the material stiffness due to micro-cracking [10]. Furthermore, concrete-damage theory only considers degradation of the material stiffness without addressing the irreversible deformations and inelastic volumetric expansion in compression [19]. On the other hand, concrete damage-plasticity model considers both benefits of plasticity and damage models. Therefore, the concrete damage-plasticity model that was proposed by Lubliner et al. [20] and later modified by Lee and Fenves [21] is adopted and extended in the present study.

The original model proposed by Lubliner et al. [20] considers linear trendline for the compression and tensile meridians. However, it is evident from the experimental results that compression and tensile meridians are curve-shape [22], [23]. Equation(1) is proposed in this study for parameter α, which is used in the failure criterion [20], to define the curve-shape compression and tensile meridians:

$$\alpha = \frac{k_1 - 1}{2 + k_1}\left(\frac{\gamma}{3} + 1\right) - \frac{\gamma}{3} \quad (1)$$

whereγ is dimensionless constant and k_1 is the enhancement ratio of axial compressive stress (f^*_{cc}) of concrete under uniform lateral pressure (f^*_l), which is calculated by $\left(f^*_{cc} - f'_{co}\right)/f^*_l$.In order to define a relationship between f^*_{cc} and f^*_l, (2) proposed by Lim and Ozbakkaloglu [24] is used.

$$f^*_{cc} = f'_{co} + 5.2{f'_{co}}^{0.91}\left(\frac{f^*_l}{f'_{co}}\right)^{a} \quad where \quad a = {f'_{co}}^{-0.06} \quad (2)$$

A confining pressure gradient (i.e. $\Delta f_l = f^*_l - f_l$, in which f_l is a variable confining pressure for FRP-confinement) proposed by Lim and Ozbakkaloglu [13], which is defined as $0.13{f'_{co}}^{0.24}{K_l}^{0.95}\varepsilon_l$, is used to apply the axial stress difference between FRP-confined and actively confined concrete.

In order to relate the dilation behavior from test results to the flow rule of the extended model, plastic dilation angle (ψ) is related to the plastic strains as following [12]:

$$tan\psi = -\frac{3\left(d\varepsilon_{c,p} + 2d\varepsilon_{l,p}\right)}{2\left(d\varepsilon_{c,p} - d\varepsilon_{l,p}\right)} \quad (3)$$

where$\varepsilon_{c,p}$ and $\varepsilon_{l,p}$ are plastic axial and lateral strains, respectively. Equation(4) is used for establishing the relationship between the axial strain and lateral strain of concrete.

$$\varepsilon_c = \frac{\varepsilon_l}{\nu_i\left(1 + \left(\frac{\varepsilon_l}{\nu_i \varepsilon_{co}}\right)^n\right)^{\frac{1}{n}}} + 0.04{\varepsilon_l}^{0.7}\left(1 + 21\left(\frac{f_l}{f'_{co}}\right)^{0.8}\right) \quad (4)$$

where ν_i, ε_{co}, and n are the initial Poisson's ratio of concrete, the axial strain corresponding to f'_{co}, and the curve shape parameter, respectively. $f_l$in (4) is variable by gradually increasing the lateral strain (ε_l) until the hoop rupture strain of FRP jacket ($\varepsilon_{h,rup}$). The lateral pressure corresponds to $\varepsilon_{h,rup}$ is defined as $f_{lu,a}$. $\varepsilon_{h,rup}$ can also be predicted using (5) proposed by Lim and Ozbakkaloglu [16].

$$\varepsilon_{h,rup} = \left(0.9 - 2.3f'_{co} \times 10^{-3} - 0.75E_f \times 10^{-6}\right)\varepsilon_f \quad (5)$$

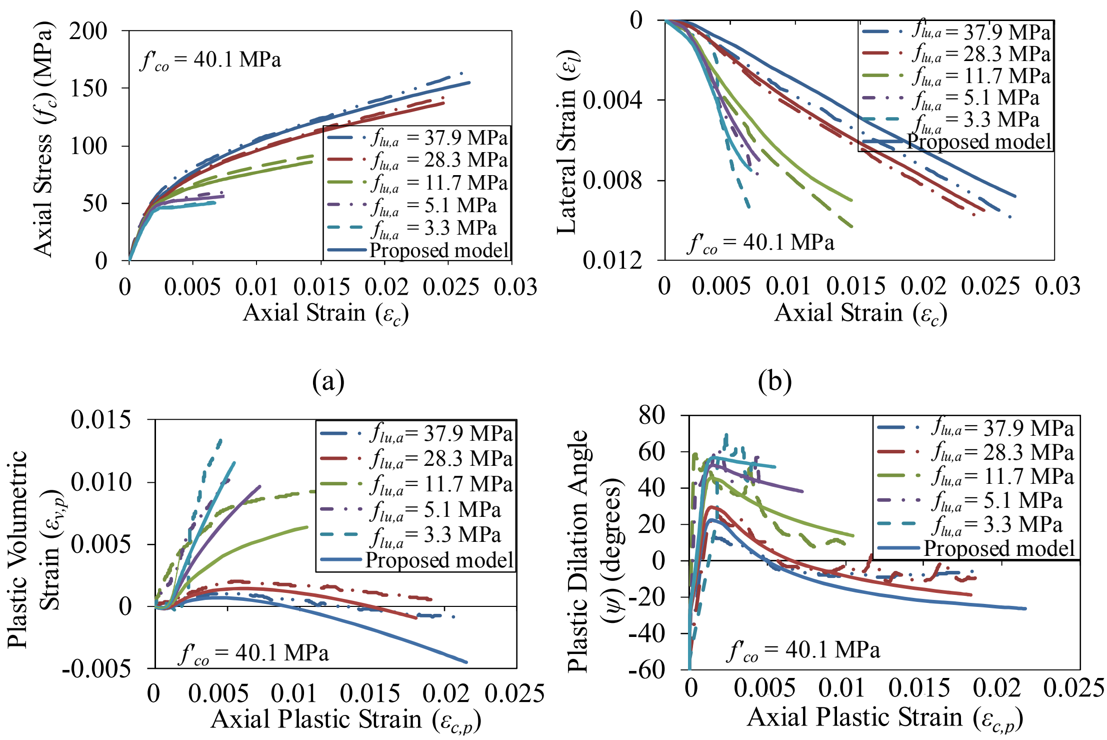
Therefore, the effects of the confinement level, concrete strength, and nonlinear dilation behavior on the flow rule were considered through (4) and (5) adopted in this study.

IV. Modeling Predictions and Comparison with Experimental Results

The predictions obtained from FE analysis based on the extended constitutive model are compared with the experimental results of FRP-confined NSC and HSC. Two groups of specimens (i.e. U40 and U80) have been used to validate the extended model. Figs. 1 and 2 show the axial stress-strain, lateral-axial strain, plastic volumetric strain-axial plastic strain, and plastic dilation angle-axial plastic strain relationships of the specimens with the characteristics summarized in Table 1.

Table.1 Summary of test results used in Figs. 1 and 2

Group ID	Study	Dimensions of cylinder (mm)	Lateral confinement	$f_{lu,a}$ (MPa)	f'_{co} (MPa)
U40	Berthet et al. [25]	ø160 × 320	1, 2, 4, 9, 12 layers of Carbon-FRP	3.3, 5.1, 11.7, 28.3, 37.9	40.1
U80	Ozbakkaloglu and Vincent [26]	ø100 × 200	1, 3, 4 layers of Aramid-FRP	10.4, 24.1, 30.1	37.0, 85.9, 110.1



(c) (d)

Fig. 1. Variation of: (a) axial stress-axial strain;(b) lateralstrain-axial strain; (c) plastic volumetric strain-axial plastic strain; and (d) plastic dilation angle-axial plastic strain relationships with level of confinement and concrete strength (Group U40)

Figs. 1(a) and 2(a), 1(b) and 2(b), and 1(c) and 2(c) respectively show that the proposed model closely predicts the axial stress-strain, lateral strain-axial strain, and plastic volumetric strain-axial plastic strain behaviors of both NSC and HSC specimens. Figs. 1(d) and 2(d) show the plastic dilation angle-axial plastic strain relationships for FRP-confined concrete under different levels of confinement. It is evident from the figures that the plastic dilation angle becomes positive after inelastic densification. This behavior corresponds to the contraction to expansion in Figs. 1(c) and 2(c). The accurate estimation of the plastic dilation angle leads to the accurate prediction of the dilation behavior of confined concrete as seen in Figs. 1(c) and 2(c). The accuracy of the model was achieved by the use of accurate hardening/softening flow rules, which were established based on the level of confining pressure, and incorporation of the effect of the f'_{co} into the modeling of the failure surface.

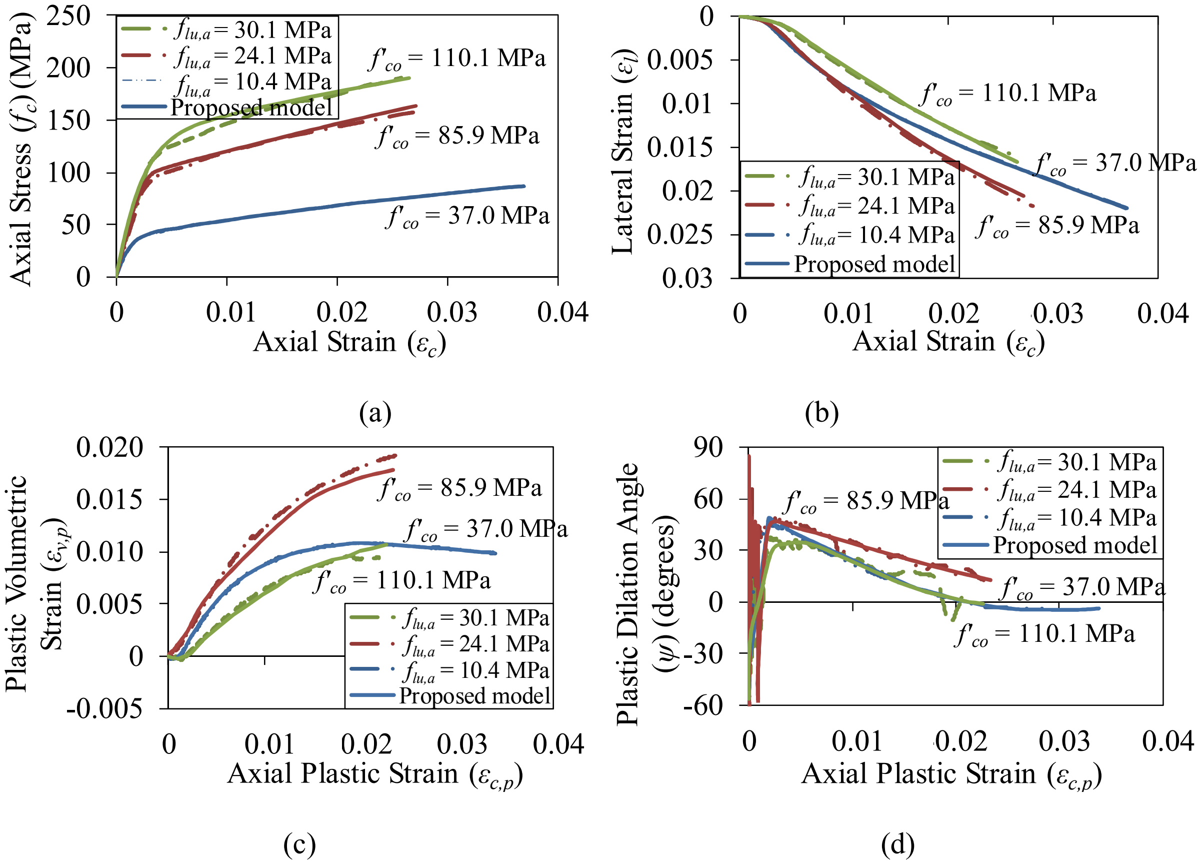


Fig. 2. Variation of: (a) axial stress-axial strain;(b) lateral strain-axial strain; (c) plastic volumetric strain-axial plastic strain; and (d) plastic dilation angle-axial plastic strain relationships with level of confinement and concrete strength (Group 80)

V. CONCLUSIONS

This paper has presented the results of a study on FE modeling of FRP-confined concrete in circular sections based on an extended constitutive model. An existing concrete damage-plasticity model was extendedby makingimprovements tothe failure surface and flow rules throughthe incorporation of the influences of confinement level, concrete strength, and nonlinear dilation behavior. Comparisons with the experimental results show that the predictions of the extended model are in good agreement with the test results of FRP-confined NSC and HSC.

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