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Stress–strain model for circular concrete columns confined by FRP and conventional lateral steel

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ABSTRACT

Behavior of reinforced concrete columns confined by Fiber Reinforced Polymer (FRP) or conventional lateral steel (tie/spiral) reinforcement has been studied extensively by many researchers. Although FRP wrapping is used when lateral steel is not sufficient to confine the concrete core, the ability of lateral steel to provide confinement in most of the cases is not negligible. A constitutive stress–strain model is proposed for concrete confined by FRP and conventional lateral steel reinforcement when they act simultaneously. The accuracy of the proposed model in predicting the monotonic stress–strain relationship of concrete confined by both FRP and conventional reinforcement is assessed compared to various experimental data from specimens tested under concentric monotonic load, and several representative models. Additionally, the moment–curvature response of a section, using the proposed model in a fiber-based analysis, is compared and benchmarked against several independent experimental results.

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1. Introduction

Application of FRP to enhance the ductility, flexural strength, and shear capacity of existing deficient concrete structures has increased during the last two decades. Accordingly, various aspects of FRP-confined concrete members, specifically monotonic and cyclic behavior of concrete members confined and reinforced by FRP, have been studied in a number of research programs. As a result, various monotonic models have been proposed for concrete confined by only FRP. Ozbakkaloglu et al. [1] reported 88 monotonic models for FRP-confined concrete circular sections until year 2011. They categorized these models into two design-oriented and analysis-oriented groups based on the Lam and Teng's suggested categorization [2]. Using selected statistical indicators, models' performance were assessed compared to reliable experimental data. According to their investigation, models by Lam and Teng [2] and Tamuzs et al. [3] most accurately predict the ultimate strength and strain of FRP-confined concrete [1].

FRP wrapping is typically used to confine the existing concrete members containing conventional lateral steel reinforcement (tie/spiral). The confining effect of lateral steel reinforcement in analytical studies has been considered differently in different models. A majority of related models considers confinement due to FRP and ignore the effect of conventional lateral steel reinforcement. Shao et al. [4] used the model proposed by Samaan et al. [5], which was proposed for concrete confined only by FRP, in a fiber-based analysis of concrete specimens confined by FRP and tie. Although the amount of lateral steel reinforcement was not negligible in their test specimens, they ignored its confining effect and achieved a reasonably good agreement between experimental data and analytical results.

The model by Kawashima et al. [6] was the first model to consider the confining effects of both FRP and conventional lateral steel reinforcement. After that Harajli et al. [7] proposed a novel model for circular and rectangular concrete columns confined by both FRP and conventional lateral steel. Eid and Paultre [8] proposed a relatively complicated model requiring numerous parameters with good accuracy compared to experimental data. Based on test results from 24 specimens, Lee et al. [9] proposed a new empirical model to predict monotonic behavior of concrete confined by FRP and steel spiral in circular sections. Chastre and Silva [10] proposed a model for circular sections using Ricard and Abbott [11] stress–strain relationship. Pellegrino and Modena's model [12] was proposed for circular and rectangular sections confined by FRP with or without lateral steel reinforcement. Recently, Hu and Seracino [13] proposed a constitutive model using Popovics [14]

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Nomenclature

A_{st}	transverse steel cross section area
D	diameter of concrete section
d_c	diameter of core concrete between tie or spiral bar for circular section
E_c	modulus elasticity of concrete
E_{frp}	modulus of elasticity of FRP
E_1	initial slope in stress–strain model in Ref. [5]
E_2	second slope in stress–strain model in Ref. [5]
f_0	intercept or reference stress in axial direction in Ref. [5]
f_c	axial compressive stress in concrete
f'_{c0}	maximum axial compressive strength of unconfined concrete
f_{cs}	compressive stress of confined concrete at yielding of steel spiral
f'_{cu}	ultimate compressive stress in concrete
f_{lf}	normal lateral pressure caused by FRP reinforcement
f_{ls}	normal lateral pressure caused by transverse steel reinforcement applied to the concrete core
f_t	stress corresponding to ε_t
f_{yf}	ultimate strength of FRP
f_{ys}	steel yield strength
k	Thorenfeldt parameter
n	curve-shape parameter in axial direction
s	transverse steel spacing
t_f	total thickness of FRP wraps
ε_c	axial compressive strain in concrete
ε_{c0}	axial strain in unconfined concrete corresponding to f'_{c0}
ε_{cft}	strain at the FRP jacket at the point that FRP jacket is activated completely
ε_{cs}	compressive strain of confined concrete at yielding of steel spiral
ε_{cu}	ultimate compressive strain in concrete
ε_{frp}	rupture strain of FRP
ε_{jt}	strain at the FRP jacket in Ref. [17]
ε_t	strain of the point which FRP jacket is activated completely in Ref. [17]
ε_{ys}	steel yield strain

equation and modified Mander et al. [15] equations to predict the peak stress and its corresponding strain for concrete confined by FRP and lateral steel reinforcement. However, their model does not predict the ultimate stress and its corresponding strain, two important parameters of monotonic models.

A majority of the models were based on experimental data from tests performed by originators only. The performance of these models in prediction of the experiments conducted by others degrades considerably, which will be discussed later. A comparison of the models proposed for conventional confined concrete shows this fact [16]. Exploring performance of the existing models in prediction of the behavior of several specimens tested by different researchers shows a reasonable need for improvement of the existing algorithms. The model proposed in this paper is a step in this direction.

In addition to the proposed model, performance of four representative models in the literature is assessed in this study. Two of the four models [5,17] have been proposed for concrete confined by FRP only, but used as a model in their analytical studies for concrete confined by FRP and lateral steel. The other two models [6,9] were originally proposed for concrete confined by FRP and lateral steel and are chosen because of their easy-to-use equations and accuracy in predicting the experimental monotonic behavior of specimens confined by both FRP and lateral steel.

The new model proposed in this paper has been developed for concrete confined by both FRP and conventional lateral steel. The performance of the proposed model along with the four representative models from literature is compared to the experimental data from four independent databases. These specimens were reinforced laterally by FRP wraps and steel tie/spiral and tested under monotonic concentric loading by Demers and Neale [18], Eid et al. [8] and Lee et al. [9].

In order to show the accuracy of the proposed model compared to the four aforesaid models, a blind verification was performed using nonlinear moment–curvature analysis and the experimental moment–curvature response of two specimens not used to calibrate the proposed model. These two specimens are from experimental works performed by Kawashima [19]. They were reinforced by Carbon-FRP (CFRP) and steel tie laterally and were tested under constant axial load and cyclic lateral force.

2. Monotonic model for concrete confined by FRP and lateral steel (tie/spiral)

Most concrete members retrofitted or designed using FRP wraps contain internal lateral steel reinforcement. Core concrete in these members is under the confining action of steel tie/spiral and FRP warps. However, due to the use of limited experimental data, primarily from tests conducted by the originator, proposed models for concrete confined by FRP or FRP and tie/spiral do not provide a reasonably accurate prediction of specimen behavior tested by other researchers. The use of these models to analyze the performance of columns confined by FRP and lateral steel underestimates or, in some cases, overestimates section capacity in relation to flexibility and flexural strength. Development of the proposed model for concrete confined by internal steel and external FRP lateral reinforcement is an effort to address the aforesaid issue.

2.1. Proposed stress–strain curve

Axial stress-axial strain behavior of concrete confined by FRP and lateral steel (tie/spiral) is obtained using the Thorenfeldt et al. equation [20]. This equation is a modified version of the Popovics (1973) equation. Popovics proposed his well-known equation to describe the stress–strain behavior of unconfined concrete [14]. This equation works well for normal-weight concrete. In addition, many researchers have used this equation to simulate stress–strain behavior of concrete confined by conventional steel reinforcement. Hu and Seracino [13] used Popovics' equation for monotonic behavior of concrete confined by FRP and lateral steel. The Thorenfeldt equation is as follows [20]:

$$\frac{f_c}{f'_{cu}} = \frac{n \cdot (\varepsilon_c/\varepsilon_{cu})}{n - 1 + (\varepsilon_c/\varepsilon_{cu})^{nk}} \quad (1)$$

where $n = E_c/(E_c - f'_{cu}/\varepsilon_{cu})$; E_c is the modulus of elasticity of the concrete; f_c and ε_c are axial stress and axial strain of confined concrete, respectively, ε_{cu} and f'_{cu} are the ultimate strain and ultimate stress of confined concrete, respectively, and Thorenfeldt parameter $k = 0.8$.