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Simplified design-oriented axial stress-strain model for FRP-confined normal- and high-strength concrete

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ABSTRACT

This study presents a simple yet powerful design-oriented model that makes use of commonly available input data to predict the axial stress–strain behavior of fiber reinforced polymer (FRP)-confined concrete in circular sections. The approach of identifying the most influential parameters on the axial compressive behavior of FRP-confined concrete and developing new expressions based on these parameters by balancing accuracy and simplicity of use was adopted. A comprehensive experimental test database of FRP-confined normal-strength and high-strength concrete (NSC and HSC) was compiled and used in the model development. Although the proposed expressions to predict the axial stress and strain at the ultimate and transition point of the stress-strain curve were simple, the results show that they performed as good as or better than the best performing existing models. Based on these expressions a model to predict the complete axial stress-strain curve of FRP-confined concrete was developed and verified against the available experimental data. The proposed model is applicable to both FRP-confined NSC and HSC with compressive strengths up to 120 MPa, and is the first accurate design-oriented model to provide the complete stress-strain curve of FRP-confined HSC.

1. Introduction

For the design of fiber reinforced polymer (FRP)-confined concrete members, a model to accurately predict the axial stress-strain behavior of FRP-confined concrete is essential. Previously developed models included design-oriented models given in closed-forms and analysis-oriented models that predict stress-strain behavior through an incremental process [1]. Design-oriented models are based on the direct interpretation and regression analysis of experimental results, with examples of this type of model [e.g., 2–8] presented and assessed in Section 5 of this study. Analysis-oriented models consider the interaction between the concrete and the FRP jacket, in an explicit manner. These models [e.g., 9–12] can be extended to predict the behavior of concrete confined with other materials.

Although they are shown to be versatile and capable of predicting the entire stress-strain curves, the analysis-oriented models use a time-intensive iterative approach and their accuracy depend greatly on their prediction of the lateral strain-to-axial strain relationship. In the majority of these models this relationship is based on the modification of an implicit expression originally proposed for actively confined concrete, which is unable to accurately capture the dilation behavior of FRP-confined concrete [13,14]. Furthermore, as was shown recently [9,15], the use of the path independency assumption for the application of the confining pressure can result in modeling inaccuracies. A notable example of these inaccuracies is the predictions of the stress-strain curves of FRP-confined high-strength concrete (HSC) based on the approach adopted by conventional analysis-oriented models. To overcome this shortcoming a new approach was proposed in Lim and Ozbakkaloglu [9] that resulted in accurate models for FRP-confined normal and high-strength concrete. However, because of the iterative nature of the model, its application requires a significant computational effort.

Conversely, design-oriented models use explicit and often simple expression forms that make them attractive for use in design applications. Recognizing these advantages, in this study a design-oriented model was adopted for further development to provide a complete axial stress-strain curve of FRP-confined concrete in circular sections. In such models the prediction of key stress and strain values is essential because these points define the stress-strain curve. One of these key points is the transition point, where there is a change in trend of the stress-strain curve after the termination of the initial ascending branch. The other key point on the stress-strain curve is the point corresponding to the ultimate condition, which represent the axial stress and strain of

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Nomenclature

AAE	average absolute error
D	diameter of the column (mm)
E_c	elastic modulus of unconfined concrete (MPa)
E_2	slope of the second branch of the stress-strain curve (MPa)
E_f	elastic modulus of fibers used in FRP jackets (MPa)
EL	error lines
f'_{co}	unconfined concrete strength (MPa)
f'_{c1}	axial stress at the transition point (MPa)
f'_{cc}	compressive strength (MPa)
f_{cc}	axial stress (MPa)
f_f	tensile strength of FRP (MPa)
f_l	lateral confining pressure (MPa)
f_{lu}	ultimate lateral confining pressure (MPa)
H	height of specimens (mm)
K_l	lateral stiffness of the FRP jacket (MPa)
k_1	compressive strength enhancement coefficient
k_2	ultimate axial strain enhancement coefficient
k_3	strength enhancement coefficient for the prediction of f'_{c1}
k_4	strain enhancement coefficient for the prediction of ε_{c1}
M	mean
n	a term introduced to define concrete brittleness
RMSE	root mean square error
SD	standard deviation
t_f	total fiber thickness of FRP jackets (mm)
ε_c	axial strain
ε_{c1}	axial strain at the transition point
ε_{fu}	ultimate tensile strain of fibers
$\varepsilon_{h,rup}$	hoop rupture strain
ε_{cu}	ultimate axial strain

confined concrete at the time of failure.

As discussed in Ozbakkaloglu et al. [1], many models for prediction of the ultimate condition (f'_{cc}, ε_{cu}) have been proposed in the last three decades. However, only a few models have been developed to predict the transition point (f'_{c1}, ε_{c1}) of the stress-strain curve [16–19], as discussed in detail in Sections 4.2 and 5.2, whose accurate determination is important to obtain an accurate curve. The expressions proposed for the transition point were developed based on limited experimental data, and hence in the presence of a larger database it should be possible to improve their accuracy.

The use of high-strength concrete (HSC) in column construction has received a great deal of attention because of the benefits offered by higher strength concretes over normal-strength concrete (NSC) in these applications [3]. Until 2014, the availability of models applicable to FRP-confined HSC was extremely limited [2,20–23] both in number and in accuracy. Since then, new and accurate design-oriented models have been proposed for FRP-confined HSC [3,24]. Although these models are capable of accurately predicting the ultimate condition of FRP-confined HSC they do not provide to predict the complete axial stress-strain curve. Therefore, there is need for a design-oriented model that can accurately predict the complete axial stress-strain curve of FRP-confined HSC.

It is now well-known that the hoop strain measured on the FRP jacket at the time of FRP rupture ($\varepsilon_{h,rup}$) is often lower than the ultimate tensile strain of the fibers (ε_{fu}) or FRP material (ε_{FRP}) used in the jacket as discussed in detail in many previous studies (e.g. [7,16,25–30]). As discussed in Ozbakkaloglu and Lim [31], models that make use of the hoop rupture strain ($\varepsilon_{h,rup}$) predict the ultimate axial strain (ε_{cu}) and stress (f'_{cc}) of FRP-confined concrete significantly more accurately than those that make use of the ultimate tensile strain of fibers (ε_{fu}). Although using the hoop rupture strain ($\varepsilon_{h,rup}$) provides increased accuracy for models, it comes at the cost of increased complexity, because these data are often not readily available to design engineers. As a result, the development of a stress-strain model that does not require hoop rupture strain ($\varepsilon_{h,rup}$) as input data, and that performs with comparable accuracy to most accurate existing models based on $\varepsilon_{h,rup}$, will be of vital importance for practical design applications.

This paper presents a model to accurately predict the complete axial stress-strain curve of FRP-confined concrete using simple expressions. To achieve this goal, the format of the expressions to predict the ultimate point and transition point was borrowed from existing research but new coefficients were created. These coefficients (k_1, k_2, k_3 and k_4) were developed by closely investigating the influential parameters and monitoring the accuracy of the proposed expressions to maintain comparable accuracy with expressions of the best performing existing models, without the need for parameters that are not always readily available (e.g. $\varepsilon_{h,rup}$).

For the prediction of the ultimate point (f'_{cc}, ε_{cu}), this study proposes two new expressions for coefficients which were a result of investigating influential parameters as mentioned above. A similar procedure was performed for stress at transition point (f'_{c1}) where an

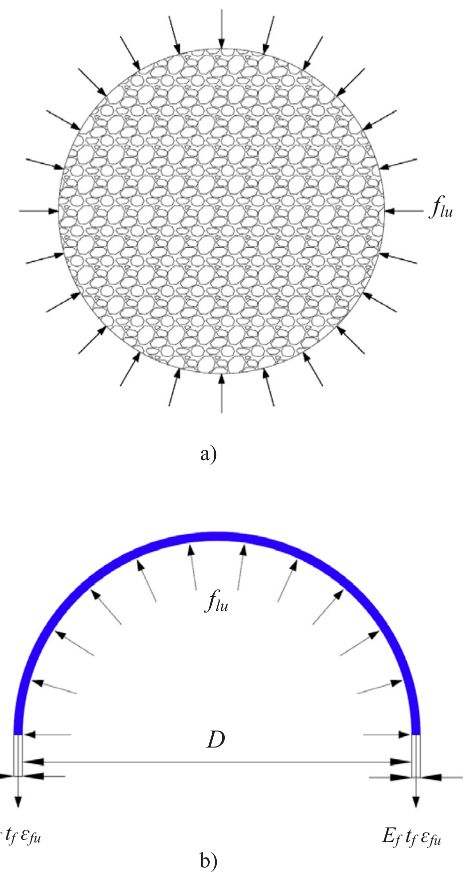

Fig. 1. Confining action of FRP jacket to concrete: (a) concrete, (b) FRP jacket. E_f, t_f, ε_{fu} and f_{lu} are the elastic modulus, total nominal thickness, ultimate tensile strain of fibers and ultimate lateral confining pressure, respectively.