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Unified model for evaluating ultimate strain of FRP confined concrete based on energy method

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HIGHLIGHTS

- Derivation of ultimate strain of FRP confined concrete columns with an energy method.
- Unified ultimate strain model that is applicable to circular, square and rectangular columns.
- Model applicable to both concentric and eccentric loading.
- Improved accuracy compared with existing models.

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ABSTRACT

An energy balance approach is adopted to develop the model for calculating the ultimate strain of fiber-reinforced polymer (FRP) confined concrete columns in this work. The proposed model can be used to predict the ultimate strain of columns under both concentric and eccentric loading. In the meantime, it makes use of a unified form so that it can be applied to different shapes of columns. A database that includes a large number of updated test results is used to evaluate the model parameters and coefficients. Compared with other existing models reported in extant literature, the proposed model exhibits a better performance.

1. Introduction

External confinement of concrete columns using fiber reinforced polymer (FRP) has become a popular technology for structural rehabilitation in recent years. To facilitate the application of the technology, extensive studies on modeling of the structural response of FRP retrofitted concrete structures have been undertaken [1–32], especially on the stress–strain characteristics of FRP-confined concrete columns. The factors considered in existing models include type of confining materials [1–7], shape of column cross-section [8–16], strength of concrete [3,17–20], pre-damage [21,22] and type of loading [23–25]. The latest models are capable of predicting the stress–strain behavior of different shapes of columns under a unified framework [19,26–28], allowing for different confining materials [27–29] and considering load eccentricity [30].

While significant advances have been made in this area, there are problems yet to be resolved. Determination of the ultimate or failure strain ε_{cu} of FRP confined concrete columns is one of them. It has been concluded that none of the available models reported in extant literature can evaluate the ultimate strain with a sufficient accuracy [29,33]. Furthermore, majority of the existing models are only applicable to columns under concentric axial loading [3,10,23,26,28,34–38]. Few models were developed for columns under eccentric compression loading [39,40]. To the best of knowledge of the authors, no existing model is applicable to both concentric and eccentric loadings and for general shape of column cross-sections. Therefore, further research works are needed on modeling of ε_{cu} of FRP confined concrete columns.

Existing models of ultimate strain have generally been developed by direct regression of test results. Mander et al. [41] proposed a novel and more rational approach based on the principle of energy balance in the late 1980s. With this approach, the

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increase in the energy absorption capacity of a confined concrete column is equal to the energy absorption capacity of the confining material up to rupture. This energy based approach has since been widely used by the research community to develop ultimate strain models of concrete columns confined by transverse reinforcement or external jacket [42–46]. Saadatmanesh et al. [42], Campione and Miraglia [43] and Purba and Mufti [44] directly used the energy method to calculate the ultimate strain of confined concrete. Matthys et al. [45] observed that this method yields unrealistic results compared to experimental ones. They believed that the energy balance method neglected the lateral strain energy stored in the concrete. Pham and Hadi [46] concluded that the original method of Mander et al. [41] is inappropriate for FRP-confined concrete and suggested a linear relationship between the energy stored in FRP jacket and the additional longitudinal work capacity of confined concrete.

In this paper, the energy balance method is applied to derive a more general model for the ultimate strain of FRP confined concrete columns. The originality of this work includes: (1) the relationship of balance between the energy stored in the transverse reinforcement and additional longitudinal strain energy is adjusted to better suit test results; (2) a unified framework is adopted so that the developed model is applicable to square, rectangular and circular columns; and (3) the unified model can be applied to both concentrically and eccentrically loaded columns. An updated and carefully selected experimental database for FRP-confined concrete columns, including 278 axially loaded columns and 40 eccentrically loaded columns is used for model regression. The proposed model has a better performance compared with existing ones.

2. Energy balance in confined concrete columns

The typical stress–strain relationship of FRP confined concrete columns is illustrated in Fig. 1. The typical model is applicable to general shape of column including circular, square and rectangular ones. The first part up to the turning point is generally modeled by a curve such as a polynomial and the second part after the turning point is often represented by a straight line. This typical model is adopted in the following derivations. For any concrete column, the area under a stress–strain curve is equal to the energy absorbed by unit volume of concrete, i.e.

$$U_{co} = v_{column}\int_0^{\varepsilon_{cuo}} f_c(\varepsilon)d\varepsilon \tag{1}$$

$$U_{cc} = v_{column}\int_0^{\varepsilon_{cu}} f_{cc}(\varepsilon)d\varepsilon \tag{2}$$

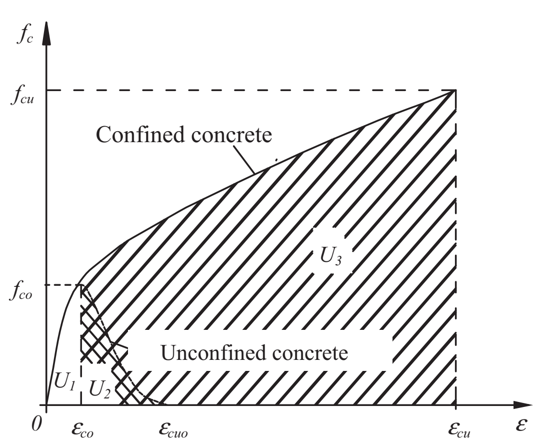

Fig. 1. Energy absorption of FRP-confined concrete.

where $f_c(\varepsilon)$ and $f_{cc}(\varepsilon)$ are the stress–strain relationships of concrete for unconfined and confined concrete column, respectively; v_{column} is the volume of concrete column; and ε_{cuo} and ε_{cu} are the ultimate strain of concrete for unconfined and confined column, respectively. U_{co} and U_{cc} represent the work done by the external load for unconfined and confined column, respectively.

FRP confinement increases the energy absorption capacity of a column. The increased energy absorption due to confinement is

$$U_{cf} = v_{column}\left[\int_0^{\infty}(f_{cc}(\varepsilon) - f_c(\varepsilon))d\varepsilon\right] \tag{3}$$

From Eqs. (1)–(3), the following relationship is obtained

$$U_{cf} = U_{cc} - U_{co} \tag{4}$$

If the full stress–strain curve of confined concrete is divided into two parts at the peak strain of unconfined concrete ε_{co}, the left side of ε_{co} (unshaded) can be approximated by the stress–strain curve of unconfined concrete. U_{co} and U_{cc} can be divided into the following parts, as shown in Fig. 1:

$$U_1 = v_{column}\int_0^{\varepsilon_{co}} f_c(\varepsilon)d\varepsilon \tag{5}$$

$$U_2 = v_{column}\int_{\varepsilon_{co}}^{\varepsilon_{cuo}} f_c(\varepsilon)d\varepsilon \tag{6}$$

$$U_3 = v_{column}\int_{\varepsilon_{co}}^{\varepsilon_{cu}} f_{cc}(\varepsilon)d\varepsilon \tag{7}$$

U_2 is the post-peak strain energy from peak strength to the final crushing of unconfined concrete. The ultimate strain of unconfined concrete ε_{cuo} is often defined as [3]

$$\varepsilon_{cuo} = 1.75\varepsilon_{co} \tag{8}$$

The post-peak strain curve and energy absorption of unconfined concrete are often represented by a flat plateau [3,47,48]. Therefore, Eq. (6) is equal to:

$$U_2 = f_{co}(\varepsilon_{cuo} - \varepsilon_{co})v_{column} \tag{9}$$

where f_{co} is the unconfined concrete strength.

Based on the division of the sub-area in Fig. 1, the following relationship is obtained

$$U_{cf} = U_{cc} - U_{co} = (U_1 + U_3) - (U_1 + U_2) = U_3 - U_2 \tag{10}$$

For confined concrete, the stress–strain curve after the turning point can be approximated by a straight line [3,26,37,38]. Therefore, Eq. (10) can be written as

$$U_{cf} = 0.5(f_{co} + f_{cu})(\varepsilon_{cu} - \varepsilon_{co})v_{column} - U_2 \tag{11}$$

where f_{cu} is the confined concrete strength. Substituting Eqs. (8) and (9) into Eq. (11) gives

$$U_{cf} = [0.5(f_{co} + f_{cu})(\varepsilon_{cu} - \varepsilon_{co}) - 0.75 f_{co}\varepsilon_{co}]v_{column} \tag{12}$$

The energy absorbed by FRP jacket U_{frp} can be calculated by the integration of its stress–strain curve (Fig. 2):

$$U_{frp} = v_{column}k_{frp}\int_0^{\varepsilon_{f,rup}} f_{frp}(\varepsilon)d\varepsilon \tag{13}$$

where $\varepsilon_{f,rup}$ is the strain at rupture of FRP jacket; $f_{frp}(\varepsilon)$ gives the stress–strain relationship of the FRP material; and k_{frp} is FRP volume ratio defined as

$$k_{frp} = \frac{v_{frp}}{v_{column}} \tag{14}$$

where v_{frp} is the volume of FRP jacket. The value of k_{frp} depends on the shape of the column and can be calculated by