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Biaxially loaded RC slender columns strengthened by CFRP composite fabrics

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The present study involves experimental and analytical investigations on carbon fiber reinforced polymer (CFRP) confined reinforced concrete (RC) slender columns subjected to combined axial load and biaxial bending. A total of five RC slender column specimens wrapped in layers with CFRP jackets were experimentally tested to failure. To assess the combination of wrapping techniques, the effect of CFRP sheet orientation in longitudinal and transverse directions of the column was studied. For all representative specimens, the average loading capacity gain was achieved with CFRP layers applied on four sides. The specimen lateral deflection was reduced when CFRP sheets were oriented in the longitudinal direction. The analytical study was taken one step further by using a modified computer program accounting for the stress–strain equation for CFRP-confined concrete to verify the behavior of tested columns. There is a good agreement between the analytical prediction and the experimental results for both ascending and descending branches of the load versus deflections and the moment versus curvature curves.

1. Introduction

Reinforced concrete (RC) columns, particularly those built prior to the 1970s, often have little confinement to the concrete core or lateral support to the longitudinal reinforcing bars. Poorly confined and originally classified as RC short columns have been recognized to behave in a more brittle manner which exhibit little deformation capacity when failure occurs. Increased loads, column deterioration, or seismic retrofit may require an additional confinement to be provided to ensure adequate load and deformation capacities for RC columns. In recent years, fiber reinforced polymer (FRP) composite jackets have been used to provide an additional confinement to RC compression members. Seible et al. [1], Xiao and Ma [2], Mirmiran and Shahawy [3], Toutanji and Balaguru [4], and Teng and Lam [5] presented results on circular RC columns under axial and/or eccentric loadings. Other studies such as Parvin and Wang [6], Pantazopoulou et al. [7], Chaallal et al. [8], and Sause et al. [9] conducted research on behavior of rectangular RC columns under axial compression and/or combined with bending moment.

On FRP jacketing design of bridge piers, Monti et al. [10], proposed a design equation to determine the optimal thickness of FRP jackets. Yeh and Mo [11] developed analysis and design procedures for carbon fiber reinforced polymer (CFRP) composites to seismic retrofit of RC hollow bridge piers. Montoya et al. [12] evaluated numerically the behavior of steel and FRP-confined concrete columns using compression field modeling. Recently Gajdosova and Bilcik [13] studied slender reinforced concrete columns strengthened with FRP, and Zaki [14] investigated the behavior of FRP strengthened circular columns under biaxial bending. Based on the literature review, it has been found that most of current researches are mainly focused on the experimental study of confined concrete members and the effect of column slenderness is not taken into account. Only small number of experimental studies on circular columns recently conducted by Bisby and Ranger [15], and Teng and Jiang [16] showed that the effect of the slenderness ratio on the load carrying capacity of slender columns after FRP jacketing is more significant than that of short reinforced concrete columns. Their observations also suggest that the detailed analytical model, such as complete stress–strain relationship is limited. Also, both experimental and analytical studies of biaxially loaded RC rectangular and slender columns confined with CFRP jackets, are not yet fully presented. As a result, the existing application of CFRP jacketing cannot be applied with confidence. To further understand the structural behavior of biaxially loaded RC slender members confined with CFRP fabric jackets, the following objectives of this research have been established:

1. To develop a complete compressive stress–strain relationship of concrete cylinders confined with CFRP composite fabrics.

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2. To investigate the load-deformation behavior of biaxially loaded RC slender columns confined with CFRP fabric jackets.
3. To modify an existing finite-segment computer program proposed by Wang and Hsu [17] for biaxially loaded RC slender columns using the proposed stress–strain relationships. The computer analyses are compared with the experimental test results to validate their usefulness.

2. Research significance

Considering that the rehabilitation of the infrastructure is an important matter for the world, the present research is expected to generate both the scientific knowledge and engineering method for the application of CFRP fabrics in the infrastructure field.

The experimental tests presented herein will help understand the load-deformation behavior of CFRP confined RC slender columns under combined biaxial bending moment and axial load; it will also be used to verify the validity of the proposed analytical model. The present study will greatly increase the applicability of the strengthening methods with externally epoxy-bonded CFRP fabrics. It will also broaden the knowledge related to the RC structures as well.

3. Proposed compressive stress–strain equation

Fig. 1 shows a typical stress–strain curve under compression for CFRP-confined concrete. The curve has an approximate bilinear shape and has no obvious descendent part. This empirical equation has been developed by the experimental results for 129 specimens of 102 × 203 mm (4 × 8 in.) [18] concrete cylinder. The behavior of the concrete-fabric system can be defined by two phases as shown to present the bilinear response of CFRP-confined concrete. The four-parameter relationship of Samaan et al. [19], which was developed and used to define concrete confined by fiber tubes, has been adopted herein and calibrated as below. Punurai et al. [20] have recently compared the proposed empirical stress–strain equation for CFRP-confined concrete cylinders under axial compression with other similar tests by Samaan et al. [19]. They showed that the proposed equation is valid:

$$f_c = \frac{(E_1 - E_2)\varepsilon_c}{\left[1 + \left(\frac{(E_1 - E_2)\varepsilon_c}{f_0}\right)\right]^n} + E_2\varepsilon_c \quad (1)$$

f_c and ε_c are axial stress and axial strain of the CFRP-confined concrete. All parameters are illustrated in Fig. 1. They can be described as follows:

E_1 is the first slope in the stress–strain curve, and the ACI equations [21] for secant modulus of normal concrete can be used here.

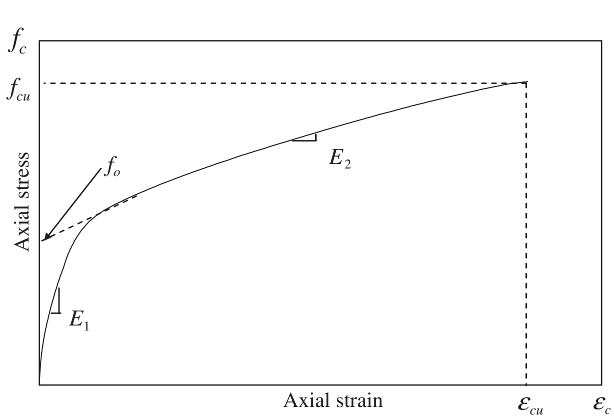

Fig. 1. Parameter of bilinear stress–strain curve of fabric-confined concrete.

$$E_1 = 57,000\sqrt{f'_c} \quad \text{(psi)} \quad (2a)$$

$$E_1 = 4730\sqrt{f'_c} \quad \text{(MPa)} \quad (2b)$$

where f'_c is the compressive strength of unconfined concrete.

E_2 is the second slope in the stress–strain curve of the present CFRP-confined concrete.

$$E_2 = 40.4 f_c'^{0.2} + 1.345\frac{E_f \cdot t_f}{D} \quad \text{(ksi)} \quad (3a)$$

$$E_2 = 189.2 f_c'^{0.2} + 1.345\frac{E_f \cdot t_f}{D} \quad \text{(MPa)} \quad (3b)$$

The parameters for E_2 are directly from the experimental results of over 40 cylinders by curve fitting where E_f is the effective modulus of elasticity of dry fabric jacket, t_f is the thickness of dry fabric jacket, and D is the diameter of the concrete core.

f_0 is the reference stress at the interception of the second slope with the stress axis. Samaan et al. [19] suggested that the intercept stress is a function of the confining pressure and the unconfined concrete strength. According to the curve fitting of the experimental results, the equation can be estimated as follows:

$$f_0 = 0.85f'_c + 1.9f_r + 1 \quad \text{(ksi)} \quad (4a)$$

$$f_0 = 0.85f'_c + 1.9f_r + 6.89 \quad \text{(MPa)} \quad (4b)$$

f_r is the confining pressure of the fabric jacket.

$$\text{where} \quad f_r = \frac{2f_f \cdot t_f}{D} \quad (5)$$

f_f is the hoop stress.

Although the proposed stress–strain equation can fully describe the stress–strain behavior of the CFRP-confined concrete, empirical equations are needed to predict the ultimate stress, f_{cu}, and ultimate strain, ε_{cu}, of the confined concrete, respectively, as shown below:

$$f_{cu} = f'_c + 3.65f_r^{0.75} \quad \text{(ksi)} \quad (6a)$$

$$f_{cu} = f'_c + 6.14f_r^{0.75} \quad \text{(MPa)} \quad (6b)$$

and

$$\varepsilon_{cu} = \frac{f_{cu} - f_0}{E_2} \quad (7)$$

It should be noted that the proposed stress–strain Eq. (1) is obtained from empirical results through curve fitting, and is specific to this study and a particular type of CFRP used at present study. For other types of CFRP, similar tests can be performed to obtain these empirical values E_2, f_0 and n.

4. Experimental program

In this research, five quarter-scale RC slender columns cast in a horizontal position were wrapped with CFRP layers (Table 1) and tested under biaxial compression loads. Based on the findings by Hsu [22] and Sabnis et al. [23], for short time loading the size effect of the load-deformation characteristics on the test specimens using the quarter-scale sizes has shown to be negligible. Three different wrapping methods were utilized during the experiments. Several experimental factors such as strength, structural ductility, post-crack behavior and the failure mechanism were studied during the tests.