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Experimental investigation of slender circular RC columns strengthened with FRP composites

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HIGHLIGHTS

- Response of CFRP wrapped circular RC columns under eccentric compression is studied.
- Columns of 150 mm diameter having three heights: 600, 900 and 1200 mm, were tested.
- Columns were strengthened using three schemes of hoop and longitudinal CFRP wraps.
- Hoop wraps provide lateral support to longitudinal fibers and increase column strength.
- An expression for the slenderness limit of FRP-strengthened RC columns is proposed.

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ABSTRACT

The relevant design code provisions for Fiber Reinforced Polymer (FRP) strengthened RC columns are restricted to the short RC columns strengthened with FRP jackets. These design provisions are thus strictly not applicable to those long RC columns where second-order/slenderness effect is substantial. In the present study, the effectiveness of hoop and longitudinal Carbon FRP (CFRP) wraps in reducing the lateral deflections and improving the strength of slender circular RC columns has been studied experimentally. A total of 12 small-scale circular RC columns of 150 mm diameter were cast in three groups, each group containing 4 columns of the same height. The columns of the first group belonged to short columns of 600 mm height, whereas the columns of second and third groups of 900 and 1200 mm heights respectively represented slender columns. Columns of each group had one control and 3 strengthened columns. The strengthened columns were prepared using three different strengthening schemes. In the first strengthening scheme, the columns were wrapped using a single layer of hoop CFRP sheet, whereas other strengthening schemes employed 2 and 4 longitudinal CFRP sheets in addition to one layer of hoop CFRP wrap. The columns were tested under monotonic compression with initial eccentricity of 25 mm. In general, CFRP-strengthening improves the strength and ductility of slender RC columns substantially. The test results indicate that the CFRP hoop wraps provide confinement to concrete and lateral support to the longitudinal fibers and thus increase the strength of the RC columns. In slender columns, the effect of longitudinal FRP fibers in carrying the load in post-yielding stage is more significant than hoop FRP fibers. The existing ACI expression of slenderness limit for RC columns was extended to propose a simple analytical equation for the slenderness limit of FRP-strengthened RC columns. The proposed expression for slenderness limit is valid for both RC and FRP-confined columns and matches well with the experimentally observed slenderness limit.

1. Introduction

All over the world, strengthening and repair of reinforced concrete (RC) components using Fiber Reinforced Polymers (FRP) are gaining a wide popularity and acceptance due to its well-established and promising performance [1–5]. The FRP-jacketing of short RC circular columns is more effective in improving its ductility and strength due to the effective lateral confinement. Although, FRP-strengthening technique is very effective for short columns, still the designers are facing difficulties in using this material for the strengthening of slender/long RC columns. Two of the main reasons are the limited researches and unavailability of complete guidelines and design provisions for

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FRP-strengthening of slender RC columns. The design provisions of majority of the design Codes such as ACI-440.2R [6,7], CNR-DT200 [8]; fib Bulletin No. 14 [9], ISIS Canada [10]; Concrete Society [11]; GB-50608 [12] etc. are limited to the FRP-strengthening of short columns in which slenderness or second-order effect is negligible.

The early study in the field of FRP-confined slender column was performed by Mirmiran et al. [13]. They studied concrete-filled fiber-reinforced polymer tubes (CFFT) and observed a substantial reduction in the column load-carrying capacity with an increase in the slenderness ratio. The CFFT columns were more sensitive to slenderness effects because the used GFRP (Glass FRP) materials have a lower stiffness and higher strength than steel. Pan et al. [14] confirmed that the effectiveness of FRP-strengthening decreases with an increase in the slenderness ratio. They concluded that the effect of the slenderness ratio on the load-carrying capacity of FRP-strengthened RC columns is more noteworthy than that of unconfined RC columns because confinement increases the strength instead of bending stiffness. Tao and Han [15] also confirmed that increasing load eccentricity and slenderness ratio decreases the effect of CFRP confinement on the improvement of column load-carrying capacity. Gajdosova and Bilcik [16] studied the two strengthening methods, transverse CFRP sheet wrapping and longitudinal Near Surface Mounted (NSM) CFRP strips bonding into the grooves in concrete cover. They found that the effect of transverse CFRP jacketing on the increase in strength is greater for short RC columns subjected to predominant compressive loading, and longitudinal NSM CFRP strips are more effective in enhancing the flexural load-carrying capacity of slender RC columns subjected to eccentric loading. Tao et al. [17], Fitzwilliam and Bisby [18], and Bisby and Ranger [19] studied the long FRP-strengthened RC columns experimentally. All the studied columns were hinged at the ends and were tested under equal eccentricity conditions. The longest column was 20.4 times its diameter, whereas maximum eccentricity was equal to the diameter of the column. They demonstrated that the longitudinal CFRP not only decreases the lateral deflection, but also increases the strength of the long RC columns. Jiang and Teng [20,21] proposed analytical models for slender FRP-confined columns and validated the results with the test results taken from the literature. Tamuzs et al. [22] studied the stability of plain concrete slender FRP-confined columns under concentric compression. They showed that a tangential wrapping increases the load-carrying capacity only for columns with slenderness ratio less than 40.

The available researches on FRP-confined slender RC columns have revealed the two facts: (i) FRP jacketing may convert a short RC column into a slender column, that is, a reinforced concrete column which was classified as a short column may have to be considered as slender column after FRP confinement; and (ii) effective utilization of enhanced concrete strength due to FRP-confinement decreases as the column becomes more slender. The prime reason behind above observations is the almost bilinear axial stress–strain response of FRP-confined columns (Fig. 1) in which transition occurs at the level of the concrete unconfined strength. Although the two branches are almost linear, the slope of the second branch is substantially smaller than the first branch. It is due to this reason the elastic modulus of the column decreases above failure load value of unconfined column [23]. The flexural rigidity of the FRP-confined column thus decreases. Consequently, the increase in strength due to FRP-confinement cannot be utilized unless the slenderness ratio of the confined column is smaller than a limiting value. In other words, if slenderness ratio of FRP-confined column is more than the limit value, the column will fail due to buckling much earlier than reaching to its ultimate strength. Consequently, FRP-confinement cannot be exploited fully for increasing axial load capacity of the column through FRP-confinement. In the recent past a few Codes (e.g. ISIS Canada, [10]) and a few investigators [20,21,23] have proposed simple expressions for estimating the slenderness limit of FRP-confined columns. Their proposed limits however, differ substantially from each other. Thus there is a need for such a simple and rational expression for slenderness limit which is valid for both RC and FRP-confined columns and validated with experimentally observed slenderness limit.

The objective of the present research is to (i) experimentally study the effectiveness of hoop and longitudinal CFRP wraps in reducing the lateral deflections and improving the strength of circular RC columns, and (ii) propose a simple and rational expression for slenderness limit which is valid for both RC and FRP-confined columns and validated with experimentally observed slenderness limit.

2. Experimental program

To study the response of CFRP-wrapped columns, 12 small scale circular RC columns were cast in three groups, each group having 4 columns of the same height. Columns of the three groups were of 600, 900 and 1200 mm heights respectively. Columns of each group had one unstrengthened (control) column and 3 strengthened columns. The control columns were steel-reinforced with 4–8 mm diameter longitudinal rebars (percentage of steel, $\rho_g = 1.1\%$) and 6 mm diameter ties at a uniform spacing of 100 mm c/c, as shown in Fig. 2. While the columns are small

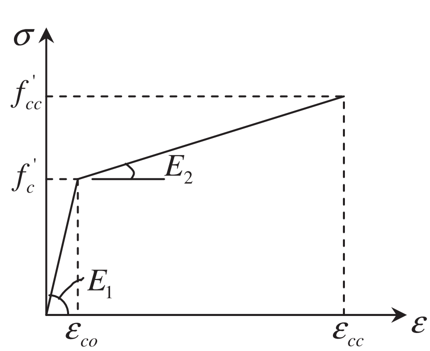

Fig. 1. Idealized axial stress–strain diagram for FRP-confined columns.

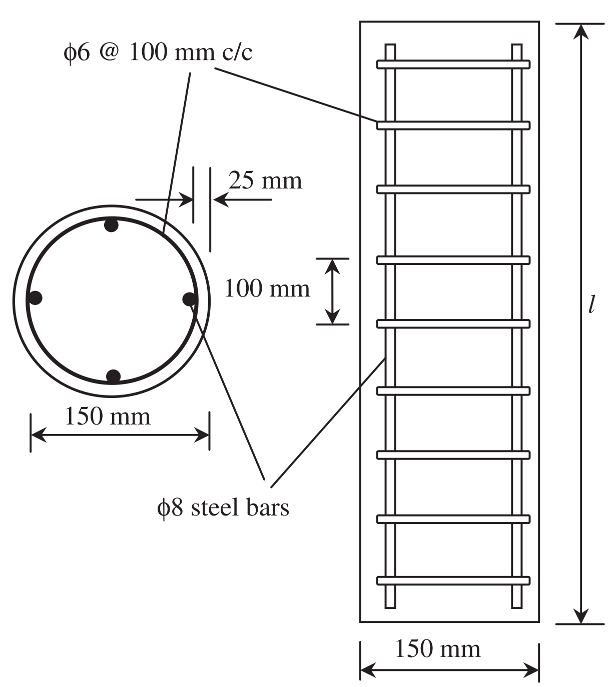

Fig. 2. Reinforcement of columns (l = 600, 900 and 1200 mm).