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On the slenderness and FRP confinement of eccentrically-loaded circular RC columns

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ABSTRACT

This article examines the effects of column slenderness and internal confinement on the behavior of eccentrically-loaded circular RC columns strengthened with fiber reinforced polymer (FRP) sheets. Test parameters included column height, level of transverse reinforcing steel, absence/presence of FRP jackets, fiber orientation and stiffness of the jacket. Tests proved that FRP wraps can be effectively used to enhance the strength, toughness, ductility and deformation capacities of eccentrically loaded-columns and that their efficiency decreases with increased slenderness. Tests showed that variations in internal confinement have a lower impact on column behavior compared to the external FRP confinement. Negligible improvements in load-carrying capacities of columns confined with one hoop FRP sheet were encountered upon adding a longitudinal sheet. Conventional section analysis using material properties based on the stress–strain model adopted by the American Concrete Institute for FRP-confined concrete under combined axial compression and bending resulted in over estimation of axial column strengths.

1. Introduction

The use of fiber reinforced polymers (FRP) has recently emerged as a favorable alternative for the more traditional repair and rehabilitation systems of reinforced concrete (RC) structures that typically involve the use of concrete or steel jackets. In repair of reinforced concrete columns, FRP fabrics are mainly used to provide passive hoop confinement for the dilating concrete core under axial loading which results in an increase of axial load-carrying capacity and ductility of the FRP-confined columns. In fact, a large number of theoretical models [e.g. 1–16] have been developed over the past years to estimate the strength enhancement of the confined concrete. Moreover, design guidelines concerned with the design of FRP-confined RC columns have been published worldwide [17–21].

Among the existing FRP confinement models, one can only find a few models [e.g. 10,15,16] that address the strength enhancement provided simultaneously by the internal steel confinement and the external FRP confinement.

Furthermore, the majority of existing studies on FRP confinement have considered axially loaded concrete cylinders or even short unreinforced concrete columns. Eccentric axial compressive loading, which could take place as a result of accidental loading eccentricities even in the absence of design end moments, produces a non-uniform confining stress to the concrete core caused by the strain gradient over the column cross section which in turn reduces the axial load-carrying capacity of the column. Researchers [22–42] have examined the effect of loading eccentricity on the effectiveness of FRP confinement in enhancing the strength of RC columns under the combined action of axial compression and bending moments. Their studies have confirmed that FRP wrapping can also provide strength and ductility enhancements for such members. Yet, strength enhancement was found to be of significance only for members in which compression failure is the controlling mode [43].

On the other hand, a few studies [44–50] have indicated that an originally short RC column may have to be considered slender as a result of the confinement provided by FRP jacketing. Few researchers have examined the effect of FRP confinement on the behavior of originally slender columns. In fact, one can confirm that most of the existing FRP confinement models have been developed for short rather than slender columns. The model proposed by Jiang and Teng [51] for slender FRP-confined circular RC columns offers an almost “unique” exception.

A quick review of the existing research results and design guidelines highlights the lack of necessary information on many behavioral aspects of eccentrically-loaded FRP-confined RC columns. To the best knowledge of the authors, the effect of internal transverse confinement (provided by steel ties) on the behavior of eccentrically-loaded columns confined with FRP wraps has not yet been investigated. Hence, this

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research was intended to bridge some of these information gaps by testing medium scale circular RC short columns of varying slenderness ratios, internal steel confinement, and carbon FRP (CFRP) wrapping schemes under eccentric loading. The tests were devised to provide a better understanding of the complex behavior of FRP-confined columns under axial-flexural loading.

The experimental program reported herein aims basically at examining the effect of three parameters on the behavior of unconfined and FRP-confined short columns under eccentric axial compression, namely: (a) column slenderness; (b) internal transverse reinforcement; and (c) using different FRP wrapping schemes in terms of fiber orientation (longitudinal versus circumferential) and stiffness (in terms of wrap thickness) of the FRP jacket.

2. Test program

2.1. Test specimens

Thirty-two medium scale circular RC short columns, with a diameter *D* of 192 mm, were tested under compression loading with an eccentricity of 50 mm (equivalent to 0.26*D*) which exceeds the minimum eccentricity of 0.1*D* implicitly considered by the ACI 318-14 [52] design stipulations for stocky tied columns and that of 15 mm + 0.03*D* for slender columns. Following ACI 318-14 [52] provisions, columns were reinforced with six longitudinal steel deformed rebars of 10-mm diameter providing a reinforcement ratio of 0.017.

The test parameters included column slenderness, spacing of internal transverse reinforcement, absence/presence of external FRP reinforcement and orientation and stiffness of the FRP wrapping sheets. To examine the effect of column slenderness, test specimens were divided into two height groups of sixteen columns each: Group C1 with a height of 1175 mm and a slenderness ratio (*kl/r*) of 19.6; and group C2 with a height of 800 mm and a *kl/r* ratio of 13.3. To assess the effect of confinement to the concrete core provided by the internal transverse reinforcing steel, both column groups (C1 and C2) were subdivided into two main subgroups Ci-S1 and Ci-S2, eight specimens each, where *i* indicates the main group number and takes the values of 1 and 2. The S1 and S2 terms are used to differentiate columns in the two subgroups based on the spacing of steel ties: Columns in subgroups Ci-S1 and Ci-S2 were reinforced with 6-mm diameter steel ties, with a 60 mm overlap, at a uniform center-to-center spacing of 125 mm and 187.5 mm, respectively. The 125 mm tie spacing was chosen to satisfy design code requirements [52] whereas the 187.5 mm spacing exceeded maximum spacing specified by the code. Fig. 1 presents cross-sectional details of the test specimens.

Furthermore, to examine the effect of absence/presence and configuration of the external FRP reinforcement, specimens in each of the four subgroups (Ci-Sj), where both *i* and j take the value of 1 or 2, were grouped into four identical pairs as follows: Columns Ci-Sj were reserved as control un-strengthened columns, i.e. without FRP wrapping, whereas the remaining six columns were strengthened using CFRP sheets. Three different strengthening systems were considered: (a) Columns Ci-Sj-1C were fully wrapped with one hoop CFRP ply with fibers oriented parallel to the column's circumference; (b) Columns Ci-Sj-1V1C were fully wrapped using two plies of the fabric sheets with

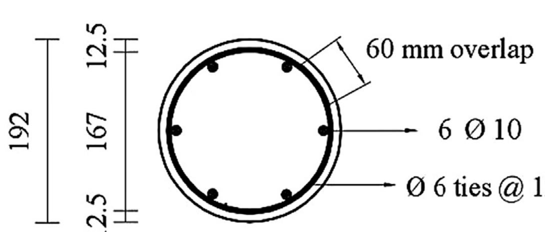

Fig. 1. Cross-sectional details of test columns (dimensions and bar diameters are in mm).

Table 1
Summary of test specimens and parameters.

Specimen designation	No. of specimens	Spacing of steel ties (mm)	CFRP strengthening scheme	
			Number of FRP plies	
			Fiber orientation longitudinal	Fiber orientation circumferential
C1-S1	2	125	None	
C1-S1-1C	2		0	1
C1-S1-1V1C	2		1	1
C1-S1-1V2C	2		1	2
C1-S2	2	187.5	None	
C1-S2-1C	2		0	1
C1-S2-1V1C	2		1	1
C1-S2-1V2C	2		1	2
C2-S1	2	125	None	
C2-S1-1C	2		0	1
C2-S1-1V1C	2		1	1
C2-S1-1V2C	2		1	2
C2-S2	2	187.5	None	
C2-S2-1C	2		0	1
C2-S2-1V1C	2		1	1
C2-S2-1V2C	2		1	2

C1, C2: Columns with heights of 1175 and 800 mm, respectively.
S1, S2: Ties spaced at 125 and 187.5 mm on centers, respectively.
1C: One circumferential FRP layer.
1V1C: One vertical/longitudinal FRP layer and one circumferential layer.
1V2C: One vertical/longitudinal FRP layer and two circumferential layers.

fibers oriented parallel to the longitudinal column axis in the first ply and parallel to its circumference in the second; and c) Columns Ci-Sj-1V2C were wrapped using three plies of the fabric sheets with fibers oriented parallel to the longitudinal column axis in the first ply and parallel to the hoop direction in the two outer plies.

Specimen details are summarized in Table 1. Designations used in the table indicate column height (C1 and C2 with heights of 1175 and 800 mm, respectively), spacing of steel ties (S1 and S2 with ties spaced at 125 and 187.5 mm, respectively), number of longitudinal/vertical CFRP plies (1V), number of hoop CFRP plies (1C and 2C), and a designation A or B where two identical specimens are used.

2.2. Material properties

The concrete mix included ordinary Portland cement (Type I), siliceous limestone aggregates with a maximum size of 9.5 mm in addition to a mixture of fine aggregates and silica sand (73% fine aggregate and 27% silica sand by volume). The mix was designed using a water-to-cement ratio of 0.54 according to ACI 211.1-91 [53] design procedures to achieve an average 28-day compressive strength of 30 MPa and a 75-mm slump. To improve workability, a commercially available super plasticizer (Flocrete SP33) conforming to ASTM-C494 [54] was used at 1% by cement weight. Thirteen concrete batches were used to cast the columns with an average 28-day compressive strength of 33 MPa. In addition, 39 concrete cylinders (150 × 300 mm) were cast (3 per concrete batch), wet-cured and tested with their companion column specimens 3 months after casting resulting in an average compressive concrete strength of about 41 MPa.

Average yield strength (f_y) of the longitudinal reinforcing steel was 451 MPa with about 18% elongation at failure whereas the average yield stress of the transverse steel was about 528 MPa with 15% elongation.

FRP products from BASF were used for the external column reinforcement. Unidirectional high strength carbon FRP sheets (MBRACE FIBER CF 230/4900.300 g/5.100 m) were used in conjunction with MBrace Saturant (epoxy resin). Based on manufacturer's data, the 500 mm wide carbon FRP sheets with a nominal thickness of 0.166 mm