TESTS ON CONCRETE SQUARE COLUMNS CONFINED BY COMPOSITE WRAPS

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Abstract

Fiber reinforced plastic (FRP) jacketing has emerged as a very effective way to retrofit concrete columns in recent years. The existing experimental work on FRP confined concrete column is mainly concentrated on concrete columns under concentric axial loading. This research involves the study of FRP confined square concrete columns under axial compressive loading with small eccentricities. The effects of the FRP jacket thickness and various eccentricities on concrete columns confined by the FRP jacket were investigated experimentally. The experimental results of square concrete columns under eccentric loading with and without FRP jacket were compared. It has been found that the strain gradient reduces the retrofit efficiency of the FRP jacket on concrete column, and the retrofit efficiency is proportional to the stiffness of the FRP jacket. Results indicate that, even in the case of small eccentricity, a lower enhancement factor should be used in designing FRP confined concrete columns.

Introduction

Recently, earthquake damage to reinforced concrete columns of many bridges and buildings built before 1970's exposed the inadequate strength and deformation capacities of these columns, and the urgent requirement to retrofit the same. Since the emergence of fiber reinforced polymer (FRP) as a potential repair material during the last decade, on-going research has been conducted on fiber composite retrofitting of various structural components [1]. Many researchers have demonstrated the effectiveness of retrofitting the reinforced concrete columns by FRP jackets and noted their durability with respect to drastic temperature variations, and humidity [2-7].

The research carried on so far on FRP confined concrete columns is mainly concentrated on investigating circular columns subjected to concentric loading. However, in actual construction, there is no column that is subject to perfect concentric loading. Therefore, nonuniform confining stress due to strain gradient must be measured. Because of this nonuniformity, the concrete stress-strain relationship at various locations in the column cross-section is not the same. Consequently, the strain gradient can induce complex retrofit effects.

This research investigates the effect of strain gradient and FRP thickness on square concrete columns reinforced with FRP wraps. The chosen eccentricity values are small enough not to produce any longitudinal tension in the wrap. Nine square concrete columns were tested under concentric load and two different levels of eccentricity. Experimental results were validated by nonlinear finite element analysis elsewhere [8].

Experimental Study

In order to study the behavior of FRP confined concrete square columns under eccentric loading, a series of experiments were conducted in the Laboratory for Composite Materials in Structures of the Civil Engineering Department at the University of Toledo. These experiments consisted of

- Concrete compression test was performed to evaluate the strength of the concrete employed.
- FRP coupon test was conducted to estimate the tensile strength, the modulus of elasticity and Poisson's ratios of the FRP jacket.
- Small-scale concrete columns test was utilized to generate experimental data for load-displacement, stress-strain relationships for FRP jacketed concrete columns with various jacket thicknesses and eccentric as well as concentric axial loads. Additionally, control specimens without FRP jackets were built for comparison purposes.

Concrete Compression Test

The target compressive strength of the concrete was 3,000 psi. The concrete specimens were fabricated using type I Portland cement, local sand and lime stone gravel. The strength of the concrete used in the compression test was found to be about 3100 psi.

FRP Coupon Test

The FRP was unidirectional carbon fiber designated as MBrace™ CF 130 from the Master Builder Company. The tensile test was performed on the FRP coupons in order to determine the uniaxial tensile strength, Young's modulus and Poisson's ratio of the carbon FRP jacket used in this experiment. The relevant test method is described in ASTM D3039 [9]. The collected data were as follows: modulus of elasticity along the fiber direction E_{11}=2.74×10^7 psi and modulus of elasticity perpendicular to the fiber direction E_{22}=6.2×10^5 psi, Poisson's ratio ν_{12}=0.22, and ultimate strain ε = 0.016 in the fiber direction.

Small-Scale Concrete Column Fabrication and Test Setup

The concrete columns were 4.25 in by 4.25 in and 12 in tall. The corner radius of the cross-section was 0.325 in. The rounded-off corners were required to reduce the stress concentration and to avoid the kink damage to the FRP jacket from the concrete column. Than the FRP wraps were placed on the surface of the concrete using wet lay-up technique; that is, the fiber materials were placed on the surface of the columns and then impregnated with epoxy resins to form the FRP laminate. Table 1 illustrates the test matrix of all nine columns.

Table 1. Configuration of Column Specimens

Specimen	Eccentricity (in)	Number of CFRP Layers
C00	0.00	NA
C01	0.30	NA
C02	0.60	NA
C10	0.00	1
C11	0.30	1
C12	0.60	1
C20	0.00	2
C21	0.30	2
C22	0.60	2

A Tinius Olson compression machine with a load capacity of 400 kip was used to apply the axial compressive load to the top of concrete columns. For the eccentrically loaded columns, a steel end plate and a V block were employed to provide the pin-support and the required level of eccentricity (Figure 1). The load was increased until the column failed. The ends of the column were reinforced with an additional layer of FRP strap to prevent premature failure outside the test region. The axial deflection of the columns was measured by four linear variable differential transducers (LVDT). The concrete columns confined by the FRP fabric were instrumented with electrical strain gages at the mid-height of the column.

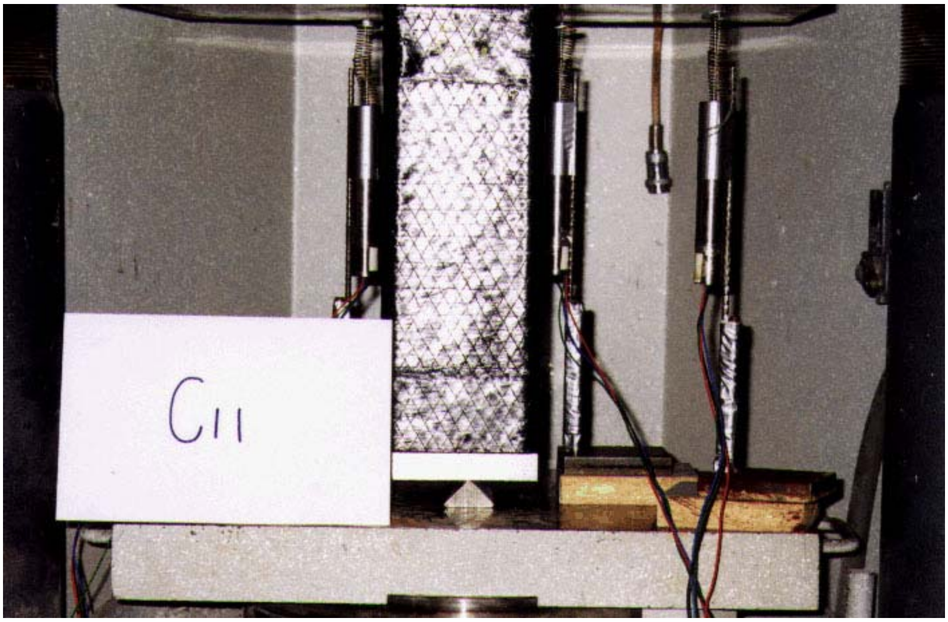


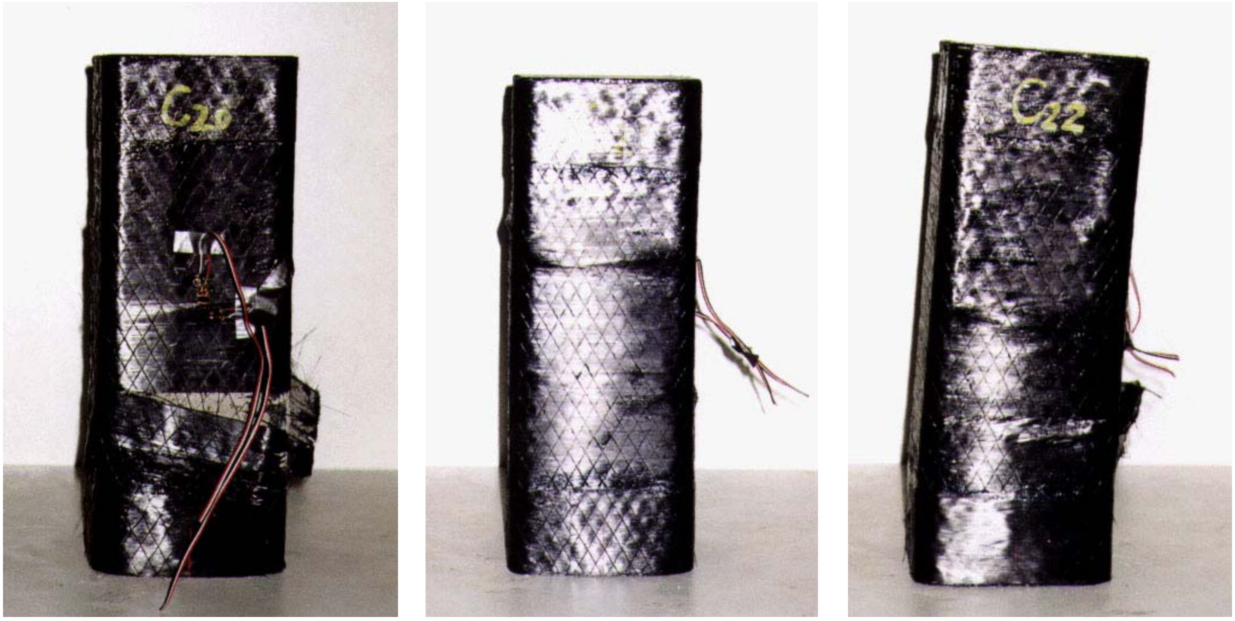
Figure 1. Test Setup for Columns with Eccentric Loadings

Experimental Results

The initial stage of testing included control column specimens. The axial load was added monotonically until the columns failed. Cones formed at both ends of the column under concentric loading (C00). The columns under eccentric loading (C01, C02) failed by the crushing of the concrete on the side with larger compression near the column mid-height. They both split on the compressive side longitudinally.

The second testing set utilized specimens with one layer of FRP (C10, C11, and C12). The specimen C10 was tested under concentric loading. While testing this specimen, the load increased to about 91 kips and then the capacity of the column dropped. An early cracking noise was due to the cracking of the concrete material inside the FRP jacket. The circumferential fracture of fibers was visually noticeable. The FRP jacket was separated from concrete surface that came apart and resulted in total failure of the column. When testing specimen C11 with eccentricity of 0.3 in, cracking of the concrete inside the jacket was heard when the load approached the ultimate load of the unconfined column. At the last stage of loading, when ultimate load capacity was reached, the FRP jacket on the compressive side began to delaminate quickly. The capacity of the column dropped immediately when the FRP jacket broke. Specimen C12 was tested with a load eccentricity of 0.6 in. The behavior of this column was similar to C11. When the load reached 66 kips, the capacity of the column dropped, and only a small area of FRP jacket was separated. The FRP jacket failed at the columns' corner in all the specimens. Larger area of FRP jacket failed with the decrease of eccentricity. This is contributed to the fact that there was more concrete area under high lateral confining pressure.

The third testing set employed specimens with two layers of FRP (C20, C21, and C22). The behaviors of these columns were similar to their counterparts with one layer of FRP composite fabric, but with larger damage area of FRP wrap (Figure 2). Furthermore, local axial buckling of the jacket was observed in the columns with two layers of FRP composites.



(a) C20 **(b) C21** **(c) C22**

Figure 2. Specimens with Two Layers of FRP after Failure

Table 2 illustrates P_u, the ultimate axial load, and Δ, the corresponding axial deflection for all columns. It is observed that the FRP jacket can greatly enhance the strength and ductility capacities of the concrete columns.

Table 2. Test Results for Column Specimens

Specimen	P_u (kip)	Δ (in)
C00	58.9	0.020
C01	49.1	0.021
C02	44.7	0.022
C10	90.6	0.159
C11	70.9	0.115
C12	66.1	0.114
C20	118.0	0.244
C21	87.9	0.178
C22	80.9	0.156

The axial load-deflection curves for the specimens with 0, 1 and 2 layers of FRP fabric under various eccentricities (0, 0.3 and 0.6 inch) are given in Figures 3, 4 and 5, respectively. The results show the strain gradient had caused a decrease in strength and deformation capacity of the concrete columns. The retrofit efficiencies for the axial compressive loading with various load eccentricities are presented in Table 3. It is observed that the small eccentricity reduces the retrofit efficiency of the FRP jacket. This is because lesser area of concrete columns is effectively confined.

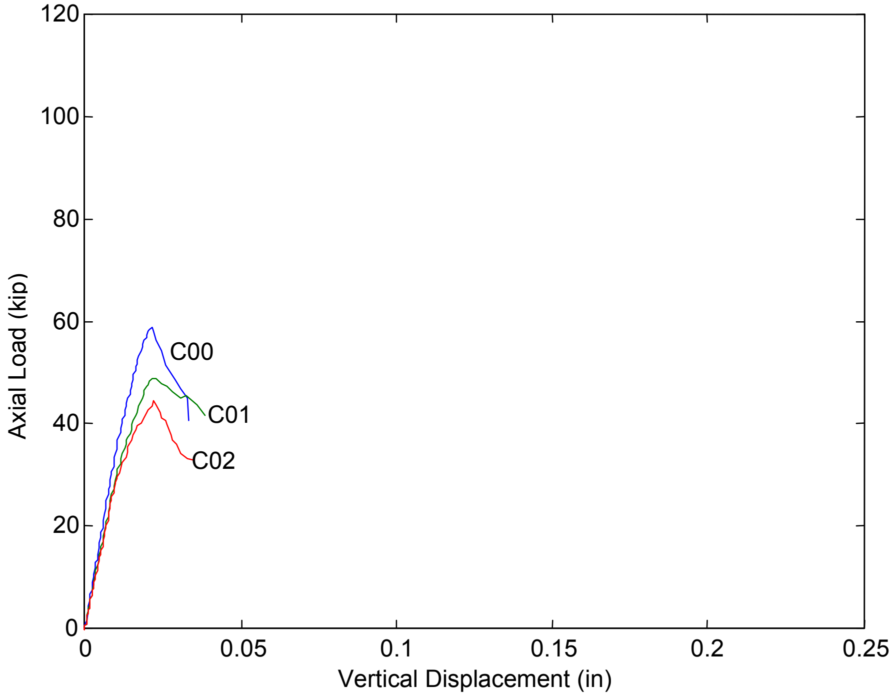


Figure 3. Load-Deflection Curves for Specimens without FPR Jacket

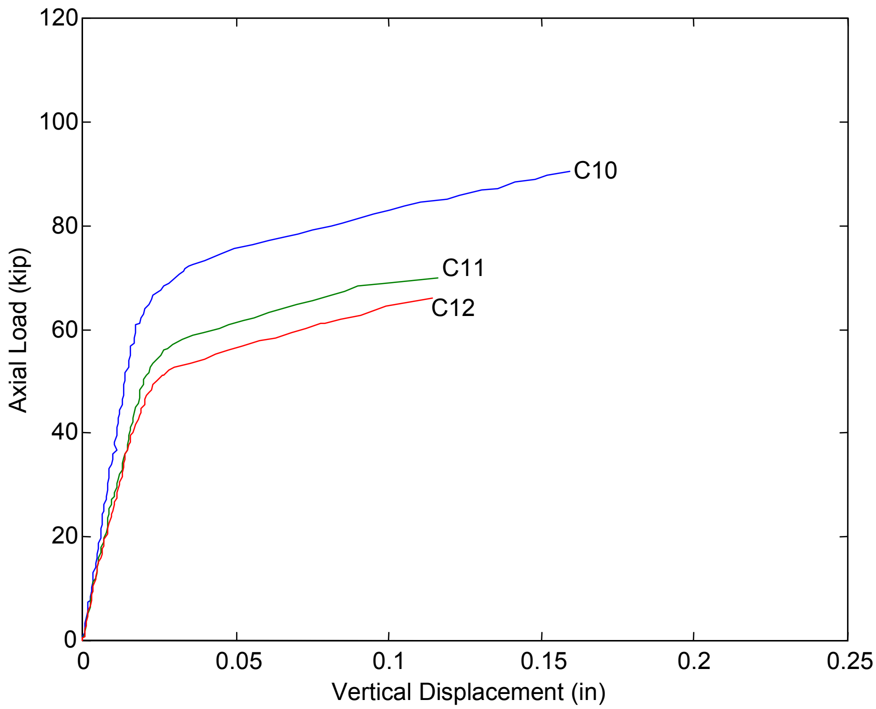


Figure 4. Load-Deflection Curves for Specimens with One Layer of FRP Jacket

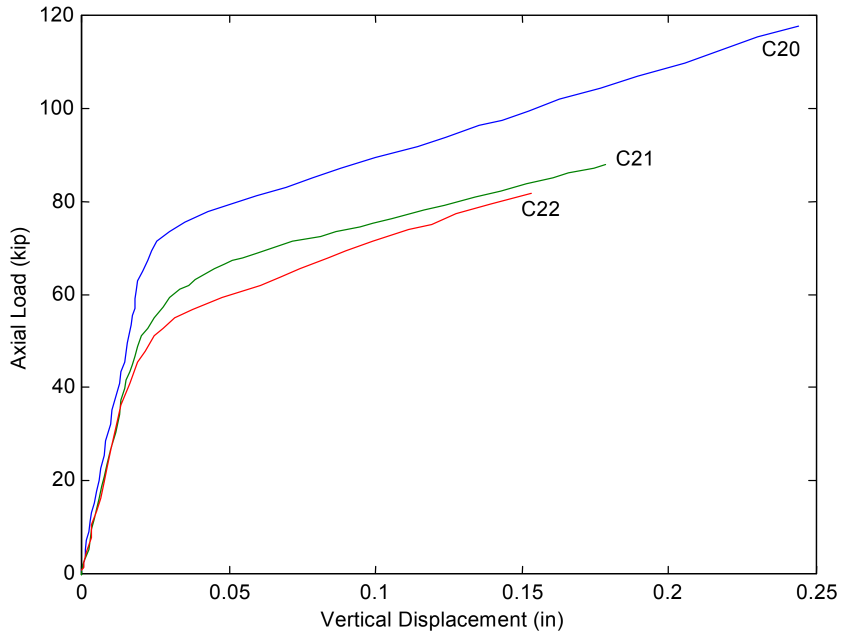


Figure 5. Load-Deflection Curves for Specimens with Two Layers of FRP Jacket

Table 3. Strength and Deformation Enhancement for FRP Jacketed Columns

Specimen	Axial Load (%)	Axial Deflection (%)
C10	53.8	695
C11	44.4	448
C12	47.8	418
C20	100	1120
C21	79	748
C22	80.9	609

For the concrete columns confined by two layers of FRP composite fabric, the axial compressive strain and lateral horizontal strain at the mid-height were measured and they both showed a bilinear response (Figure 6). The ultimate horizontal strains in the FRP jacket in the middle of the column side were less than the ultimate strain (0.016) measured by the coupon test; the failure of the FRP wrap was not at the middle of the column side but rather at the corners. This was consistent with the observation of the broken corner of the square concrete columns.

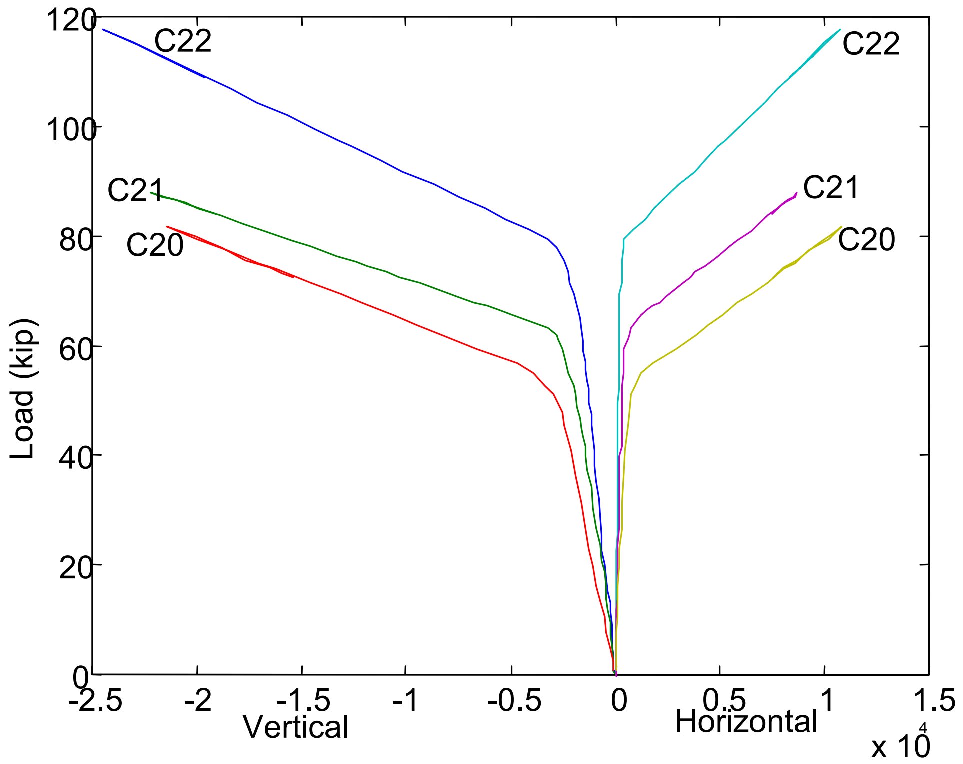


Figure 6. Vertical and Horizontal Strains at Mid-height for Specimens with Two Layers of FRP Jacket

Conclusions

Based on the results of this research work, it can be concluded that the FRP jacket can greatly enhance the ductility and strength of eccentrically loaded concrete columns. The efficiency of FRP retrofitting is proportional to the stiffness of the jacket and decreases with the strain gradient. Therefore, even in the case of small eccentricity, a lower enhancement factor should be used in designing FRP confined concrete columns.

Acknowledgments

The authors wish to thank Master Builders, Inc., Cleveland, OH for their donation of MBrace Composites and their guidance for the use of materials. The expert help by Mr. Robert Dunmyer, the Civil Engineering Department Laboratory Machinist 2, in building the forms and test fixture is appreciated.

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