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Precast Concrete Columns Strengthened With CFRP and GFRP Laminates Under Eccentric Load

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Abstract—**This paper presents the experimental results of precast concrete columns strengthened and repaired with externally bonded carbon fiber reinforced polymer (CFRP) and grass fiber reinforced polymer (GFRP) laminates. The aims of the study were to investigate the structural behaviors of a precast concrete column with a notch and the efficiency of CFRP and GFRP laminates in strengthening and repairing the columns subjected to eccentric load. A total of 15 precast concrete columns with notches were tested up to failure. Load was applied on a column notch causing eccentric load on a column. The specimens were equally divided into five groups based on the types of fiber reinforced polymers and damage conditions of columns (undamaged or partially damaged): columns with non-strengthening/repairing; columns with CFRP strengthening; columns with GFRP strengthening; columns with CFRP repair; columns with GFRP repair. The results were compared and discussed in terms of load carrying capacity, lateral deflection, and mode of failure. It was concluded that the application of CFRP and GFRP laminates in strengthening and repairing precast concrete columns improved the load carrying capacities up to 27.6%.**

Keywords—precast column, eccentric load, CFRP laminate, GFRP laminate

I. INTRODUCTION

Concrete columns are considered to be one of the most essential structural members in residential homes due to their failure causing collapse of a whole structure. Several experimental and numerical studies, therefore, have focused on the issue of strengthening and repairing of concrete columns [1-4]. Among other applications, the use of fiber reinforced polymer (FRP) to retrofit and repair concrete columns has widespread due to the advantages of high strength and stiffness to weight ratio, high corrosion resistance, and application flexibility [4-7]. Commercial FRP materials typically used for structural strengthening and rehabilitation are carbon fiber reinforced polymer (CFRP) and glass reinforced polymer (GFRP). In comparison of both types of FRPs, GFRP is less expensive; however, CFRP exhibits greater tensile strength and stiffness. In general, CFRP laminates would be three times thinner than GFRP laminates in order to achieve the same tensile stiffness [8]. Besides cast-in-place concrete column, precast concrete column is used in order to save construction time and to control the quality of the construction more efficiently. Since precast columns are fabricated from manufacturing plants before transporting to the site, it is convenient to form them into the particular shape suitable for some structures such as concrete-wooden homes as shown in Fig. 1. Such columns have notches at the top end in order to place wooden beams which are generally bolted to the side of columns. The beam-column connection is illustrated in Fig.1. Based on the notch and connection, a column is subjected to eccentric concentrated load transferred from beams.

The previous studies [4-7] have evaluated several types of columns retrofitted with various FRP and configurations. However, research on the precast column with a notch and a specific connection to beams is limited. The purpose of the current paper is to investigate the ultimate load and mode of failure of the columns to deliver a guideline for development of precast concrete columns. In addition, the effectiveness of CFRP and GFRP laminates in strengthening and repairing the precast columns were examined to provide safety to home occupants.

II. EXPERIMENTAL PROGRAM

A. Test setup

In the experimental program, 15 full-scale destructive tests were conducted on precast concrete columns repaired and strengthened with both CFRP and GFRP laminates. The load was applied using a hydraulic jack on a rectangular solid steel block placed on the column notch. The block was bolted to the lateral side of the top part of the column representing a wooden beam and beam-column connection in a realistic construction practice. Pinned end restraints were applied at the bottom end and at the notch location of the column. Lateral deflections at mid height of the column where maximum deflections occurred were measured in both directions using dial gauges. While the hydraulic pressure was increased gradually during testing, crack initiation and crack propagation were continuously observed. The test setup and connection between a steel block and column are depicted in Fig. 2.

Fig. 1. Concrete-wooden home (left) and beam-column connection (right).

B. Test specimens

All precast columns had a cross-sectional dimension of 12.7 cm x 12.7 cm and a height of 2 m. The columns had concrete compressive strength of 240 ksc and were reinforced with four internal round bars of 9-mm diameter (RB9) corresponding to a longitudinal reinforcement of 1.57 %. The stirrups were 6-mm round bars (RB6) with a spacing of 100 mm. Fixed and lateral roller support were applied to the bottom and the top end of the column, respectively. The specimens were equally divided into five groups consisting of non-strengthening/repairing columns set as control specimens, CFRP strengthened columns, GFRP strengthened columns, CFRP repaired columns, and GFRP repaired columns. Each group comprises three columns to check repeatability of the results. The test program is described in Table I. A group of three control specimens were tested up to the ultimate. A total of six specimens were loaded to partial damage or pre-crack (approximately 75% of the ultimate load of the control specimens) to determine the FRP repair applications. Accordingly, three of six pre-cracked columns were wrapped using three layers of CFRP laminates with a width of 40 cm which covered all the expected cracks, based on the crack patterns of the controls at ultimate load,. as the repaired specimens C-REP. Likewise, the other three pre-cracked specimens were strengthened with the identical amount and configuration of GFRP laminates as the repaired specimens G-REP. The strengthening tests for specimens C-STR and G-STR were implemented on undamaged precast concrete columns strengthened with the identical FRP and epoxy system applied in the repaired tests.

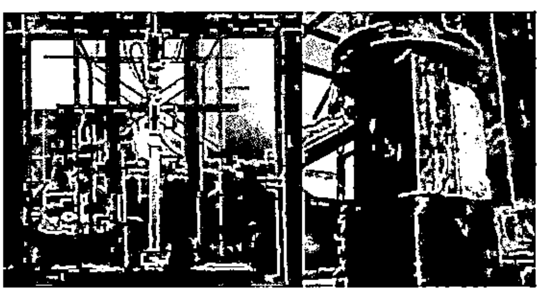

Fig. 2. Test setup and a simplified beam-column connection.

Both CFRP and GFRP laminates were carefully bonded to the specimens according to the recommendations from ACI 440.2R-17 code [9] and the prescribed installation procedures from the manufacturer. After the substrate surfaces were cleaned, epoxy was well mixed from two components and applied onto a precast column as illustrated in Fig. 3. When the primer was cured, a prepared FRP sheet was thoroughly saturated with epoxy resin. A precast column was wrapped by the saturated fabric in which the fiber direction was perpendicular to the column axis as shown Fig. 4. Properties of CFRP and GFRP fabrics obtained from well-known manufacturers are summarized in Table II. Also, properties of epoxy are presented in Table III. After the epoxy resin set, all strengthened and repaired specimens were tested until failure occurred

Fig. 3. Mixing of epoxy resin (left) and coating column of substrate (right).

Wrapping columns with saturated CFRP (left) and GFRP (right).

TABLE I. TEST PROGRAM

Specimen	No. of specimen	Description
CONT	3	Non-strengthening/repairing precast columns
C-STR	3	Strengthened precast columns using 3 layers of CFRP laminates
G-STR	3	Strengthened precast columns using 3 layers of GFRP laminates
C-REP	3	Repaired precast columns using 3 layers of CFRP laminates
G-REP	3	Repaired precast columns using 3 layers of GFRP laminates

TABLE II. PROPERTIES OF CFRP AND GFRP CURED LAMINATES

Properties	CFRP	GFRP
Tensile strength, N/mm2	724	450
Tensile modulus, kN/mm2	56.5	18.1
Elongation, %	1.29	2.25
Nominal thickness, mm	1.0	1.0

TABLE III. PROPERTIES OF EPOXY RESIN

Properties	Nominal value
Compressive strength, N/mm2	65
Tensile strength, N/mm2	50
Tensile adhesion strength, N/mm2	greater than 2.1
Elongation at break, %	2.5

III. TEST RESULTS AND DISCUSSIONS

The general behaviors of controls, FRP-strengthened, and repaired columns were similar. The test results were discussed in terms of ultimate load, lateral deflection corresponding to the ultimate load, as well as crack development and mode of failure.

A. Ultimate Load and Lateral Deflection

The averaged ultimate loads and lateral deflections were determined from the test results of three specimens in each group. For the tests of CONT, an average applied load of 101 kN caused failure of the columns with an average maximum lateral deflection of 0.27 mm at mid height of the columns. For pre-cracked specimens C-REP and G-REP used in repair application, the experiment was paused at an average applied load of 75 kN equivalent to approximately 75% of the average ultimate load of the control specimens CONT. The average failure load of C-STR was 129 kN with an average mid-height deflection of 0.60 mm. The average ultimate load of G-STR was 127 kN with an average mid-height deflection of 0.52 mm. The average ultimate capacities of repaired specimens with CFRP and GFRP, namely C-REP and G-REP, respectively 121 kN with a mid-height deflection of 1.87 mm and 117 kN with a mid-height deflection of 1.67 mm. Based on the experimental results, CFRP and GFRP laminates can enhance ultimate load carrying capacities of both undamaged and pre-cracked columns. However, the use of both FRP types showed no improvement on a lateral deflection of the columns, particularly repaired columns C-REP and G-REP. The average load carrying capacities, average maximum lateral deflections at mid height and percentage increases in load carrying capacities of the specimens are summarized in Table IV.

It is clear that the highest load carrying capacity among all specimens was achieved by strengthening the column with CFRP laminates, namely C-STR. However, the increases in ultimate load carrying capacities using CFRP and GFRP laminates are slightly different for both cases of strengthening and repairing applications (approximately 1.6% and 3.4%, respectively). Since CFRP fabric is considerably more expensive than GFRP fabric, the use of GFRP sheet is more beneficial if a strength increase-to-cost ratio are considered.

TABLE IV. SUMMARY OF EXPERIMENTAL RESULTS

Specimen	Average ultimate load carrying capacity (kN)	Average max. lateral deflection (mm)	Percentage increase in load carrying capacity
CONT	101	0.27	-
C-STR	129	0.60	27.64
G-STR	127	0.52	26.36
C-REP	121	1.87	19.74
G-REP	117	1.67	15.79

B. Crack Development and Mode of Failure

According to the experimental observation of non-FRP strengthening columns, the initial cracks were visually detected at corners of the column notch where the stress concentration occurred. As the applied load gradually increased, the cracks propagated downward at an approximate 45 degree angle from the corners to the edges of the column and crack width continued to grow. Simultaneously, hairline cracks took place at the bolt hole and propagated downward due to an axial compression. The crack pattern of pre-cracked specimens at the applied load of approximately 75% of the average ultimate load was demonstrated in Fig. 5 (right). The specimen finally failed at the ultimate load due to a sudden shear failure representing a brittle behavior as shown in Fig. 5 (left).

For both groups of strengthened specimens C-STR and G-STR, the ultimate failure mode also was shear failure. However, specimens could carry load although shear cracks propagated throughout the failure plane due to the confinement of CFRP/GFRP laminates. The failure part of the column on which the steel block was placed was slightly slipped out, and thus the compressive load was transferred to a bolt connection instead. Consequently, the tip of the column which connected to the steel block was severely damaged as illustrated in Fig. 6.

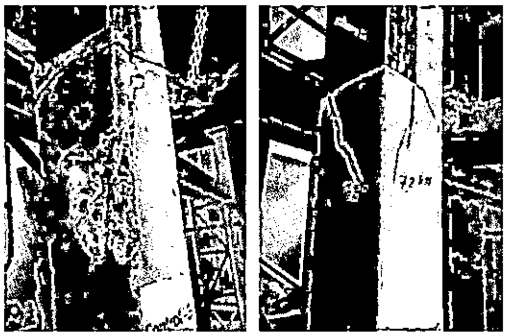

Fig. 4. Failure of control specimen (left) and pre-cracked column for FRP repair application (right).

Fig. 5. Failure of strengthened columns using CFRP laminates (left) and GFRP laminates (right).

Fig. 6. Failure of repaired columns using CFRP laminates (left) and GFRP laminates (right).

The failure characteristic of both sets of repaired specimens C-REP and G-REP is the same as that of strengthened specimens as shown in Fig. 7.

In the previous studies, the RC columns wrapped with CFRP and GFRP can improve the axial load carrying capacity up to 91.75% and 70.80%, respectively [10,11]. The CFRP and GFRP strengthened columns in this study are found to have lesser increment in strength due to the difference in failure mode which is shear failure instead of axial compressive failure.

Since FRP laminates were applied only at the top parts of the specimens where cracks appeared, the stiffness of the columns slightly increased locally and thus an improvement in the lateral deflection resistance of the columns was negligible.

IV. Conclusions

Based on the experimental study, the following conclusions can be drawn:

- Load carrying capacity of the precast concrete column is 101 kN.
- All specimens failed by shear at the notch in the vicinity of the steel block and showed the brittle failure behavior due to high stress concentration and the lack of internal steel reinforcement.
- Application of CFRP and GFRP strengthening can improve load carrying capacity of the precast concrete column up to 27.6%.
- Application of CFRP and GFRP repair can increase load carrying capacity of the precast concrete column up to 19.7%.
- The CFRP/GFRP amount and configuration applied in this study exhibited ineffectiveness on the improvement of the lateral deflection resistance of the columns.

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