EFFICIENCY OF CFRP SHEETS IN UPGRADING AND/OR STRENGTHENING SQUARE REINFORCED CONCRETE COLUMNS

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ABSTRACT

Strengthening and/or upgrading reinforced concrete columns through utilization of composite sheets is now receiving wide acceptance worldwide. The technique is simple to use and has many advantages over other available methods. However, limited data is available about its efficiency in confining non-cylindrical shape columns. In this paper, the influence of using different schemes of wrapping of carbon fibre reinforced polymer (CFRP) sheets on the behaviour of reinforced concrete columns with and without utilizing mechanical anchoring system is reported. The columns were 300 × 300 mm in cross section and 2005 mm in height and were subjected to incremental monotonic loading until complete failure.

Test results indicated that the horizontally aligned CFRP sheets had more contribution to enhancing the ductility of the columns than the strength whereas the vertically aligned sheets had more contribution to increasing the column's ultimate capacity. The results also showed that both ductility and strength of the wrapped columns can be significantly increased by utilizing mechanical anchoring system that reduces the distance between the unsupported nodal points for the sheets.

INTRODUCTION

It is well known that concrete expands laterally before failure. If the lateral expansion is prevented, a substantial concrete strength and deformation enhancements may be gained. Therefore, when a column is wrapped with FRP sheets, its axial load capacity is expected to be enhanced due to two factors; firstly: the confinement effect of the externally bonded transverse fibres, and secondly: the direct contribution of longitudinally aligned fibres.

Saadatmanesh et al [1994] investigated the effectiveness and the benefit of using FRP in wrapping columns. The investigators, used glass fibre reinforced polymer mats to wrap circular columns that had insufficient splice lengths between the foundation and the column. A cement grout was pressure injected under the mat to prestress the mat to the column. As a result of the confinement provided by the mat, failure strain of the concrete increased, in comparison to the unconfined concrete, by a factor of more than 6. It was also noticed that the technique they used increased the axial carrying capacity of the column.

Nanni et al. [1993] reported experimental test results on the effect of wrapping on three cylindrical groups of concrete specimens under compression (Groups A, B, and C). All specimens were 150 mm in diameter. The heights of Groups A, B and C were 1500, 3000, and 1525 mm, respectively. The latter specimens had different longitudinal/transverse steel reinforcement characteristics and were subjected to cyclic flexure with and without axial compression. The lateral FRP reinforcement consisted of a continuous flattened tube made of braided Aramid fibre in one case, and in the other, of a continuous glass strand placed by a filament winding machine. The effects of different areas and spiral spitches for the tape, and thickness of the FRP

shell for filament winding were investigated. Significant enhancements in strength and ductility were reported.

Soudki and Green [1996] presented the results of an experimental study on the performance in cold weather conditions of circular concrete columns strengthened with CFRP wraps. Forty-two circular plain and reinforced concrete columns (152 x 305 mm) were tested. The test variables include the percentage of reinforcement (0, 1, and 2.3%), the number of CFRP layers (0, 1, or 2 layers) and environmental exposure condition. The specimens were conditioned in four different environments; room temperature (about + 20 °C), low temperature (-18 °C), freeze/thaw cycles (-18 °C to +20 °C) and under water. After completion of the cold climate exposure, the columns were tested for axial strength, and load versus axial strain plots were obtained. The efficiency of the composite material was demonstrated from the results obtained from the confinement of tested cylinders. The strength of all strengthened elements was increased showing the effect of using this composite material in structural elements.

Mirmiran et al. [1996] discussed in their study how FRP tube significantly enhances the strength, ductility and durability of concrete columns. The longitudinal fibre used serve as the flexural reinforcement, while hoop fibres provide confinement and shear strength. Analytical and experimental studies indicated higher compression and flexural strength as well as excellent pseudo-ductile characteristics. A new confinement model was proposed to quantify the gain in strength of column confined with FRP material. The test results indicated that a fibreglass tube with 3 mm thickness can almost triple the strength of a standard concrete cylinder.

Tan [2001] tested eight 1.2 m long, with a cross section of 115 mm by 420 mm under concentric axial compression members. Each column had a longitudinal steel ratio of 2.2%, nominal transverse reinforcement and an average concrete compressive strength of concrete of 25 MPa. Of the eight columns, two served as reference (unstrengthened) specimens, three were reinforced with GFRP sheets and the other three with CFRP sheets. Fibre configurations and anchorage system, with the fibre running longitudinally or transversely were the main variables in the study. The researcher reported that while the reference columns failed by sudden spalling of the concrete cover followed by crushing of the core concrete, the columns strengthened with FRP sheets experienced delamination of the sheets just before the concrete began to crush. He also indicated that the externally bonded FRP sheets with and without using FRP bolts confined the concrete effectively and increased both the strength and ductility of the columns. However, it was not possible to report the exact figures of those gains as, in most cases, the variation in concrete compressive strength was high.

It is clear that wrapping circular columns with FRP helps in mitigating the deficiency associated with inadequate transverse reinforcement and lap-splice length and greatly increases not only their ductility capacity, but also their shear resistance. However, for non-circular columns the data is relatively scarce. Some preliminary reported results have indicated that efficiency in improving the engineering characteristics of non-circular columns due to FRP wrapping is highly affected by column's shape and the degree of confinement which is, in turn, influenced by the FRP type (CFRP, AFRP or GFRP) and the applied axial load.

EXPERIMENTAL PROGRAM

Details of the Column Specimens and Reinforcing Materials

Three reinforced concrete columns were cast, strengthened and/or repaired with FRP sheets and tested. To ensure that the test specimens (columns) will fail at the instrumented area (middle third), the two ends of all

specimens were enlarged (tapered shape) and received extra confinement with the help of welded-steel boxes made from 10 mm steel plate. The test specimens had a cross section of 300×300 mm and an overall height of 2005 mm with a middle test region of 1219 mm long. The columns were cast vertically using wood forms supported with steel rods. The longitudinal reinforcement were 8ϕ16 mm deformed steel bars with a yield strength of 530 MPa and a modulus of elasticity of 200×10^3 MPa. The tie reinforcement was of plain steel with 8 mm diameter and a yield strength of 260 MPa. The CFRP had a tensile strength of 3550 MPa, a modulus of elasticity of 235000 MPa and a thickness of 0.165 mm.

Concrete Details and Casting Procedure

The concrete used to cast the specimens was obtained from a local ready mix plant with a specified 28-day compressive strength, f_c', of 48.5 MPa. In preparing the specimen, the reinforcement cage was first tied then the end plates (10mm trapezoidal-like steel plates) were attached to the cage. Special attention was paid to ensure the alignment and verticality of the end plates. Then, the reinforcement cage was instrumented with strain gages to measure the vertical and horizontal strains in the reinforcing steel. Having completed the instrumentation, the cage was then placed in wooden moulds and made ready for vertical casting. Casting was done in layers and duly vibrated by Poken type vibrator. In addition to the specimen casting, a total of nine 150×300 cylinder specimens were cast to determine the engineering characteristics of the concrete. The specimens were then covered with wet burlap and polypropylene sheets. Starting from the second day of casting, the specimens were subjected to intermittent spraying of water twice a day for 14 days and then left to dry under laboratory conditions until the specified wrapping and testing days.

Repairing and Strengthening Schemes

As indicated earlier, three columns were cast and tested. They were categorized as Col1, Col2 and Col3. However, each column was tested more than one time to use different schemes of strengthening and repairing. Details of the different schemes considered in this study along with the column designation for each scheme are presented in Table 1.

Table 1: Schemes for the strengthening and repair of the second series of column test specimens.

Specimen Designation	Details of strengthening and repair
Col 1	Control (reference) specimen without wrapping
Col 2-3CF	All untapered part of the column (1219 mm) received three layers of horizontally aligned CFRP sheets to provide confinement.
Col 3-2CF	The 1219 mm long of the column received one layer of vertically aligned CFRP sheets first, then horizontally aligned layer of the same CFRP.
Col 1-3CR	It is Col 1 after testing and repairing. The repairing process consisted of removing all loose concrete and replacing it with new layer of concrete with the same quality as the old concrete. The column was then wrapped with 3 horizontally aligned CFRP layers as that used with Col1.
Col 1-EMR-SA	It is also Col 1 after testing and repairing for the second time. The repaired process this time consisted of removing all loose materials; restore the column

	again using epoxy mortar. In addition, holes were drawn through the column to insert ϕ14 mm bolts on top of the sheets. One vertically and two horizontally aligned CFRP were used to strengthen the column after repairing. Immediately after sheeting, sheets were anchored with 8 bolts and plates system (4 bolts in each two opposite sides).

Test Procedure

Before the start of the testing, with the help of the strain gages attached to the vertical steel bars, every effort was considered to ensure the verticality of the column. Then, the load was applied at a rate of 5kN/sec and the strains and LVDT's readings were recorded using a data acquisition system. For the pre-maximum load part of loading, the data were recorded for every 50 kN increment. However, after passing the maximum load, the data were recorded at about every 20kN drop in the applied load. The loading continued until the applied load dropped to about 60% of the maximum-recorded value (whenever possible). A photoprint of the column during testing is presented in Fig. 1.

TEST RESULTS AND DISCUSSION

The load-strain and load-displacement curves shown in Figs. 2 and 3, respectively, are for three identical columns except for the content of the CFRP sheets. The results clearly show that prior to the peak load (where the slope of the curves is steep) all curves are almost identical. This means that up to the peak load level, the applied stresses are carried mainly by the concrete and the longitudinal steel bars and the CFRP sheets had only, if any, marginal contribution in carrying the stresses. The kink point on the curves represents the point where the concrete reached its maximum strength and the longitudinal steel yielded. Shortly after reaching the ultimate load, the curve represents the unwrapped specimens dropped down as there was, as was designed for, not enough confinement provided by the ties. On the other hand, the load carrying capacity of the strengthened specimens increased slowly even after yielding the longitudinal bars, and a ductile failure mode was encountered for those specimens. Furthermore, the control specimen failed due to buckling of the longitudinal reinforcement but the strengthened specimens failed due to the crushing of concrete and localized rupture of the CFRP sheets in the compression region. Before terminating the test for the wrapped specimens, they produced several series of acoustic emission. At the end of testing, bulging of the jacket in the transverse direction and wrinkle near the top of the jacket were observed. Also, partial fracture was observed at the wrinkled area without any appreciable reduction of the load carrying capacity. The increase in carrying capacity of the wrapped specimens was attributed only to the presence of the sheets as the concrete and the steel already reached their ultimate capacity. The increase in the ultimate capacity of both Col 2-3CF and Col 3-2CF was 6%. It is worth to observe in the figures the improvement in the ductility due to the horizontally aligned CFRP sheets is much more than the corresponding increase in the strength.

For the wrapped specimens, the tests were terminated at a point where there were some doubts about the safety of the measuring devices. As a result, no measuring values were reported about the improvements in the ductility. However, it can be easily figured out from Fig. 3 where the ductility factor, defined as the ratio of displacement at failure (or when the strength reduced to 85% of the ultimate strength [Foster et al., 1997]) to that at yielding, attained more than 4, even when the tests for the strengthened specimens were terminated before achieving the 15% reduction in the strength. A ductility factor of 4 is usually required for seismic design [Samra et al., 1990]. It can also be concluded from the results shown in Figs. 2 and 3 that transverse (horizontally aligned) CFRP sheets had more contribution in enhancing the ductility than the strength. On the

contrary, the longitudinal aligned sheets, when confined by transverse sheets, had more contribution in enhancing the strength than the ductility.

Due to the cross sectional shape and the reinforcement configuration, the sheet can develop high restraining forces at the corners, where it is supported laterally by transverse legs, and low restraining action between the corners. The restraining force at the corners depends on the force that can be developed in the transverse legs, which is related to the area and strength of sheet and the hoop steel. The restraining action of the sheet and the hoop, between the corners is related to their flexural rigidities, which depend on the size and unsupported length of the sheet and the hoop steel. This restraining action is proportional to the elastic rigidities of the FRP and the hoop steel (until yielding of the hoop reinforcement). However, the combined flexural rigidity of the sheet and the hoop between the laterally supported nodal points and the resulting restraining action is very small as compared to the restraining action of the corners and the other nodal points. Therefore, as the concrete expands laterally under axial compression, there will be higher reactive pressures building up at the nodal points than at locations away from the nodes. This explains why the improvement in the strength and ductility of the rectangular column due to FRP wrapping increases as the cross sectional dimensions of the column decrease. The above discussion also explains why column Col 2-2CF, although contained only two layers of CFRP sheets, provided similar or better performance than column Col 2- 3CF which contained 3 layers of the same CFRP sheets. The only difference between the two columns is that one of the two layers of the sheets used to wrap Col 3-2CF was aligned vertically and thus contributed in carrying the axial stress as an extra longitudinal reinforcement. However, in Col 2-3CF all 3 CFRP layers were aligned horizontally and therefore did not provide appreciable contribution in enhancing the axial capacity of the column. The results presented in Fig. 4 also reveal that the failure of the Col 2 -3CF occurred while the lateral strain in the CFRP sheets at the middle of the mid-height of the column was not more than 1000 microstrain. This clearly supports the above discussion that the fibres of the sheets were stressed only at the corners. On the other hand, the lateral strain at the time of failure of column Col 3-2CF was about 6000 microstrain, a value expected to increase had more than one layer of the sheet was used to the confine the vertically aligned sheet.

The results presented in Fig 5 and 6 show that the repaired technique followed for Col 1-3CR, repaired by concrete patching followed by wrapping with CFRP, as explained in Table 1, did not retain the original rigidity of the column. Therefore, the initial load-deflection and load-strain relationships for Col1 appeared steeper than that of Col 1-3CR. However, this may be ascribed to the fact that some of the longitudinal reinforcing bars had some buckling from the previous loading which were not repaired during the repairing process. The effect of pre-buckled bars appeared further when the applied load was closer to the ultimate capacity of the column. As the applied load reached about 60 to 70% of the ultimate capacity of the column, the strains in the longitudinal bars of the Col 1-3CR reached about 0.002, the same strain recorded at the ultimate capacity of Col 1. Therefore, the concrete cover was totally crushed and the already buckled reinforcing bars did not carry any more loads, which led to total failure of the specimen.

On the other hand, when the column was repaired for the second time, using epoxy mortar, rather than normal concrete, and anchoring bolts (Specimen Col 1-EMR-SA, according to Table 1), the response of the column to the applied load was significantly improved. That was the case even though the column had buckled reinforcing bars. Col 1-EMR –S-A also showed more ductile behaviour than the original column. This may be attributed to the combined effect of the anchored bolts and the CFRP sheets. The presence of the bolts in the middle of the column provided extra confinement to the column and, at the same time, reduced the distance between the unsupported nodal points for the sheets.

Fig. 1: Instrumentation of column specimen.

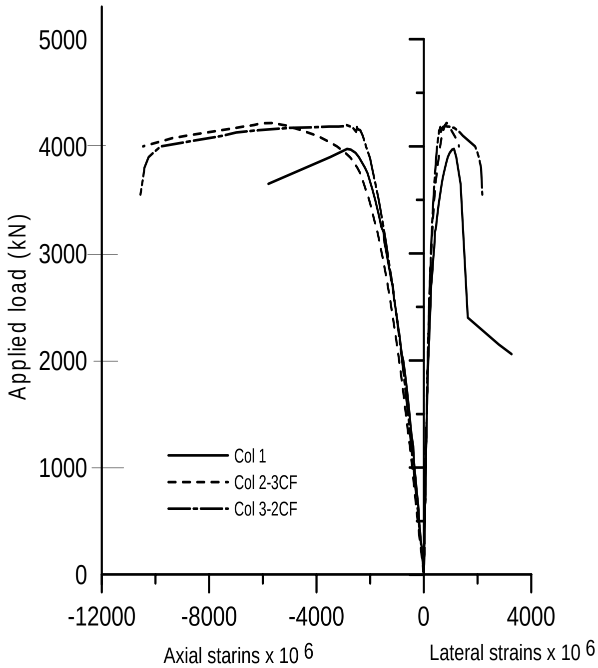

Fig. 2: Applied load versus strains in steel bars at mid-height for the three columns.

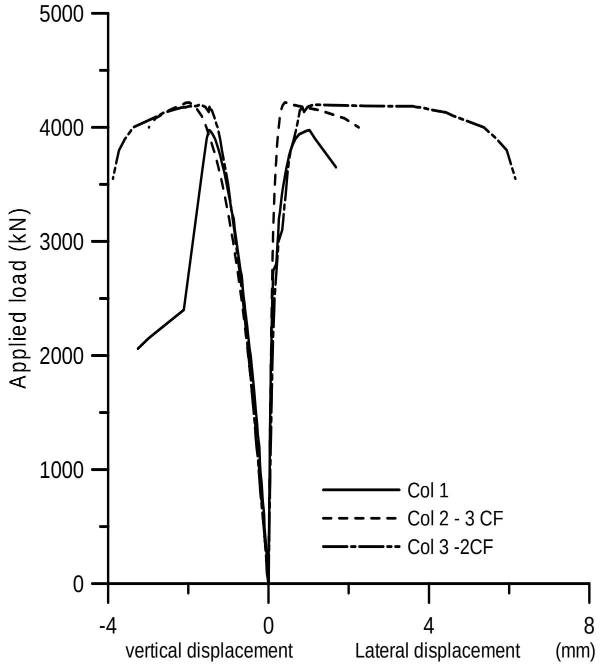

Fig. 3: Applied load versus displacement at the mid-height of the three strengthened columns.

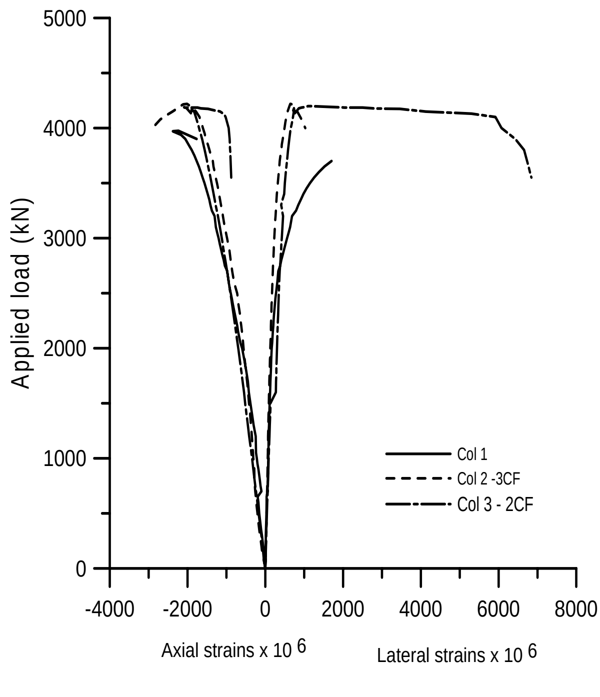

Fig. 4: Applied load versus strains on the surface of the three strengthened columns.

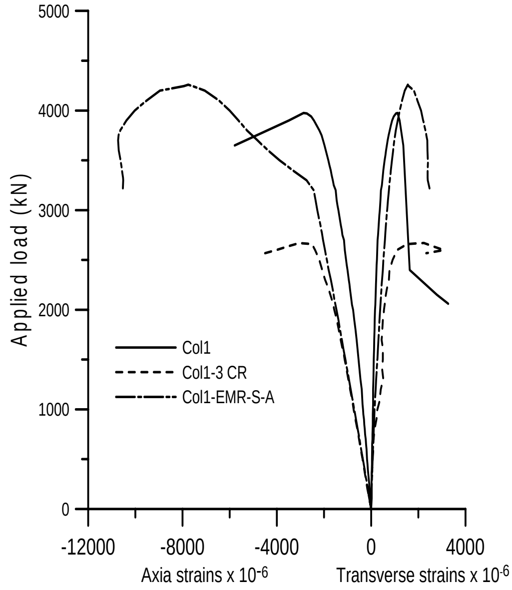

Fig. 5: Applied load versus axial strains in reinforcing bars at mid-height of the repaired specimens (Col 1).

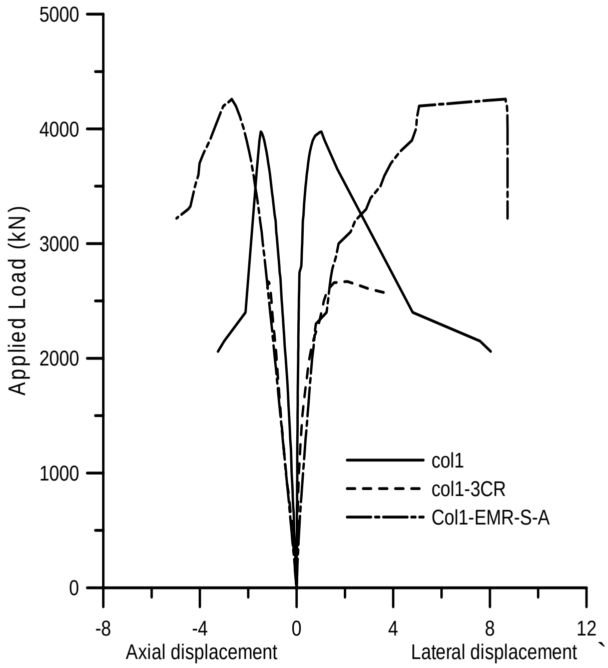

Fig. 6: Applied load versus vertical and lateral displacements at mid height of the repaired specimens (Col 1).

CONCLUSIONS

Based on the results of the study, the following conclusions may be drawn:

1. The size effect should be considered when proposing a strength model for confined concrete. A considerable reduction in confined concrete strength for large size or full size specimen is observed. This phenomenon should be investigated further by performing a large number of tests on large or full scale specimens.

2. FRP sheets do not provide uniform confining pressure on square or rectangular cross sections. Confining pressure at the corners of the columns is much higher than the confining pressure on the sides. Therefore, efficiency factor about confinement provided to square columns by FRP sheets is much lower than that provided for circular columns. The efficiency factor may be reduced further for columns without rounded corners.

3. In rectangular columns, mechanical anchoring of the FRP sheets highly improves the gain in the strength and ductility of the wrapped columns.

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