Combined flexure-compression loading for RC columns externally strengthened with longitudinal and transverse CFRP retrofitting

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Summary

This paper presents results of an experimental investigation into the performance of reinforced concrete columns externally strengthened with carbon fiber-reinforced polymer material. Four types of reinforcement techniques were tested involving plates, unidirectional and bidirectional composite fabrics. To obtain representative experimental results, ten representative-scale square columns were cast, reinforced with commercially available techniques and tested under complex loading. The intent of column's reinforcement design was to cover a wide spectrum of techniques to provide a set of experimental data for validating future suitable retrofitting design methods. Then reinforcement rates, quantities and cost of material are thus not directly comparable between all techniques. Results indicate that the strength capacity and ductility of columns improved significantly thanks to CFRP application but the improvement in ductility strongly depends on the reinforcement techniques.

Keywords: carbon fibers, concrete, ductility, representative-scale, eccentric loading, columns, CFRP retrofitting, confinement.

1. Introduction

Wrapping a column with a high strength fiber composite jacket is a widely studied and used method for repair/ strengthening columns. Usually, the jacketing is achieved by saturated fiber wrap in special epoxy formulation which allows them to be easily wrapped around columns. This simple technique provides a passive confinement that has been proven to enhance the mechanical properties of concrete members especially when loaded axially [1].

However, in building structures or bridges, no column bears perfect concentric loading. Therefore, due to existing strain gradient in the carbon fiber-reinforced polymer (CFRP) wrap, a non-uniform confining pressure is applied and the stress-strain relationship for the concrete at varied locations in the column cross section is not the same. Finally, it was experimentally demonstrated that the flexural deformation of the column reduces the retrofit efficiency of the FRP jacket [2].

Moreover, the strengthening of flexural members by externally bonded FRP plates or fabrics to their tension face is a commonly accepted and widespread technique [3]. A typical application of this technique deals with the rehabilitation of damaged reinforced concrete beams. As an extension of this technique, flexural strengthening carried out by prefabricated laminates is commonly proposed by engineering department of FRP planners and applicators to moderate effect of eccentric loads which may lead to a buckling moment in columns.

A previous experimental investigation of Chaallal and Shahawy [4] demonstrate that the strength capacity of beam-columns improved significantly as a result of the coupled action of the longitudinal and the transverse weaves of the bidirectional composite fabric. As an extension of this previous study, the purpose of the presented experimental work is to investigate the variations of the combined reinforcing effect of (longitudinal) flexural reinforcement and (lateral) confinement when different types of commercially available techniques are used. With this aim in view, tested specimens were retrofitted using different combinations of plates, unidirectional and bidirectional composite fabrics.

2. Experimental study

2.1. Test program

Ten square columns were tested under combined axial-flexural loading up to failure. The experimental program comprised five groups of two identical specimens; a first group of two control columns (CC-a and CC-b) and four groups of similar columns but externally strengthened with 4 kinds of CFRP combining longitudinal and transverse reinforcement. The specimens were labeled as ESX-a and ESX-b for the two columns externally strengthened using the technique labeled X. In a same group, the external reinforcement was the same for each specimen. Repeating twice experiments was an experimental choice to increase the confidence level in quantitative obtained results.

2.2. Loading frame

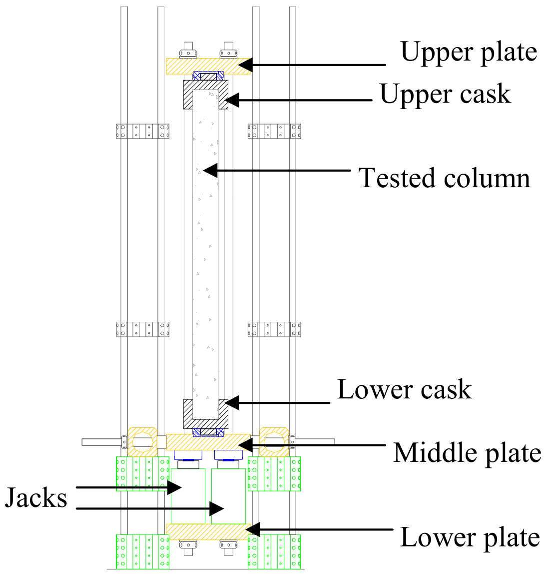

Fig. 1 Test set-up for combined flexure-compression

In order to test representative full-scale columns, it was necessary to create a loading frame capable of bringing stout specimens to failure. Assumptions (based on previous experience [5]) were made on the expected concrete strength when reinforced with two layers of CFRP materials. Then, the design of the testing frame was based on a global vertical load capacity of 4.4 MN applied by four annular hydraulic jacks (filled in parallel within the same servo-controlled closed loop) inserted in a closed frame made of struts and ties and fixed to the strong floor of LCPC structures laboratory (*Fig. 1*).

Basically, a vertical load is applied by hydraulic jacks (filled in parallel within the same servo-controlled closed loop) on the lower and middle plates. While the middle plate is fixed on the structure laboratory, a vertical displacement of the lower plate is resulting from the jacks thrust. Lower and upper plates are linked by ties. Then consecutively to the displacement of the lower plate, a displacement of the upper plate is generated, also directed downwards.

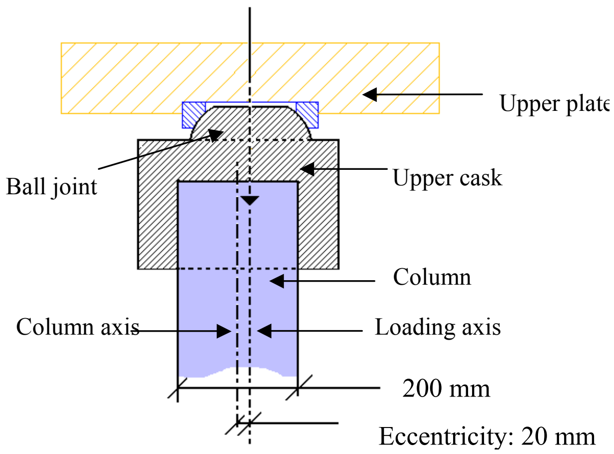

Fig. 2 principle of load application device (cask)

Steel diffusion elements (called casks) were designed to receive the load applied by plates and to transmit that loading eccentrically to the column, thus generating the combined flexure-compression load. The bearing zone of casks on plates is realized with partially spherical shapes of the cask thus forming a ball joint (*Fig. 2*). This kind of bearing ensures a free rotation of the column. Symmetrical bearing conditions are provided by the lower cask and upper cask.

Particular care was taken of the experimental boundary conditions (design of cask, lubrication of the ball joint, connection between the column and the cask ensured by a high strength grout) and the effectiveness of the expected mechanical scheme was checked during the tests.

2.3. Specimens

2.3.1. Column's details

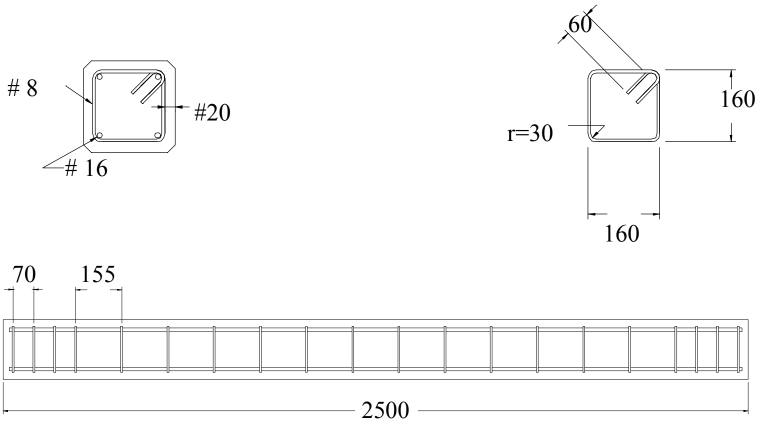

Fig. 3 Column's internal reinforcement details (dimensions in mm)

Tested columns had a 200 x 200 mm^2 square cross section and an overall length of 2,500 mm. For all the specimens, a unique batch of self-compacting concrete was delivered by a local supplier, with an average compressive strength (at the age of column tests) of 55 MPa, thereby simulating concrete that can be encountered in common structural applications. The specimens were cast in moulds with smoothed corners in order to avoid the premature fracture of the CFRP fabric due to kinking and to enhance the confining effect of the wrap.

The details of internal reinforcement are presented in *Fig. 3*.

2.3.2. CFRP strengthening configurations

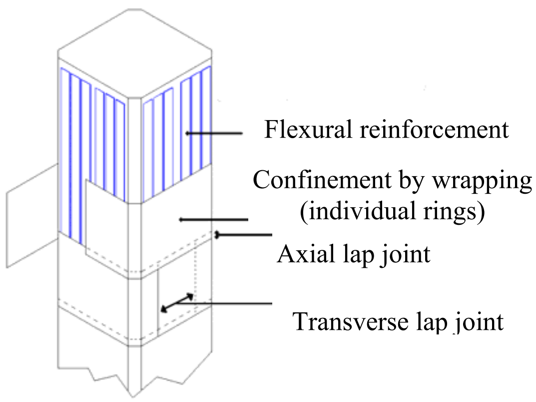

Fig. 4 Principle of Column's reinforcement

Except for the two reference specimens, two layers of CFRP were bonded on columns. A flexural reinforcement was first achieved by a unidirectional composite (plate or sheet) bonded in the axial direction. Then each column was externally confined by transverse composite straps wrapped in a continuous spiral or in discontinuous rings (see *Table* 1 for details). Such method, widely recognized, permit to exert a lateral pressure that increases strength and ductility of concrete in the axial direction [6].

Structural analysis and resultant design was carried out by authors while the strengthening of columns was accomplished by technical professional teams using their own procedures and products to assure the representativeness of experimental results.

It must be emphasized that the intent of column's reinforcement design was to cover a wide range of reinforcement rates and techniques. Based on this design consideration, it is easy to understand that no mechanical equivalence was targeted for the studied reinforcement techniques. The type 4 dry stretched sheets were saturated in special epoxy formulation before being laid to the columns. For others reinforcement using dry sheet, CFRP was fabricated by the "wet lay-up" technique; that is, the dry sheets were placed on the surface of the column and then impregnated with epoxy resins. Prior to such laying of the sheets, adhesive was applied to column sides. The type 1 dry sheet was hand-laid with a winding angle (between transverse direction of column and fill direction of the fabric) of 20 degrees. In all cases, a unique epoxy formulation was used for saturant and adhesive.

Table 1 CFRP strengthening configuration of columns

Specimen series	Flexural reinforcement	CFRP wrapping material	Wrapping configuration
CC	None	None	None
ES1	Six type x plates on each side	One layer of type 1 woven sheet	Continuous spiral
ES2	One layer of type 2 stretched sheet	One layer type 2 stretched sheet	Discontinuous rings
ES3	Two type y plates on each side	One layer type 3 stretched sheet	Discontinuous rings
ES4	One layer of type 4 stretched sheet	One layer type 4 stretched sheet	Discontinuous rings

The CFRP system manufacturer's reported material properties are shown in *Table 2*. The type 1 woven sheet is a bidirectional fabric (70% of fibers are in wrap direction).

Table 2 Manufacturer's reported CFRP system properties.

Carbon fiber product	Thickness (mm)	Tensile modulus	Tensile strength (MPa)
Type 1 woven sheet	- of one layer of CFRP: 0.43	of fibers: 240-221 of CFRP: 105	of fibers 4,900-4,510 of the CFRP layer: 1,400
Type 2 stretched sheet	of the dry sheet: 0.117 of one layer of CFRP: 0.334	of fibers: 240 of CFRP: 84	- of the CFRP >1,050
Type 3 stretched sheet	of the dry sheet: 0.13 -	of fibers: 230 -	of fibers > 3,500 -
Type 4 stretched sheet	of the dry sheet: 1 of one layer of CFRP: 1	of fibers: 235 of CFRP: 62-70	of fibers 3,450 of the CFRP: 620-700
Type x plate	of a plate: 1.2	of plate: 180	of plate: 3,000
Type y plate	of a plate: 1.2	of plate > 165	of plate > 2,800

2.4. Structural monitoring

All specimens were instrumented using surface strain gauges both on the longitudinal and transverse direction on each face of the specimens. Strain gauges were glued on concrete surface for control columns and on CFRP outer layer for other specimens. The strains on the internal steel reinforcement were also monitored. The deflections have been recorded at 7 locations as well as the axial displacement (2 sensors). The applied load was recorded with four load cells. On the whole, 56 measurement channels help describing the structural behavior of the columns. This extensive measurement program will be useful for calibration of future FE modeling and definition of serviceability and ultimate limit states for design recommendations. Only main results are presented in this paper.

2.5. Test procedure

The load was increased monotonically up to 70 % of the expected failure load, with a constant 1 kN/s loading rate. Then the jack displacement was used as the servo-control parameter (~ 0.08 mm/s) which helps recording post-peak behavior, provided the failure is ductile enough. Due to an operator error, loading was the only control parameter during the test of specimen ES3-a.

3. Test results

3.1. Bearing capacity and failure

It is not possible to present all the experimental results in this paper and therefore only a summary of the combined flexure-compression results is given in *Table 3*. The table focuses on the rates of strength enhancement (basically calculated here as the ratio of the maximum load of reference segments to the maximum load of the considered type of reinforcement) and deformability enhancement (defined as the ration of the maximum deflection until loss of stability). Moreover, a comparison of load-deflection curves between externally reinforced columns and the reference specimens is presented in *Fig. 5* for each series of test.

This confirms visibly the main external CFRP reinforcement efficiency in enhancing strength and ductility of reinforced concrete members subjected to eccentric loading.

Both externally reinforced columns and reference specimens failed by crushing of the concrete and buckling of longitudinal bars on the side with larger compression near the column midheight.

For CFRP reinforced specimens, one could see the hoop fracture of fibers during the last loading stage. The CFRP jacket failure was always initiated at a corner of the column and only appears at the tensile face during post-peak behavior when flexure of the column was increased. The failure mode of presented CFRP reinforced columns is much less brittle than those described by Li and Hadi [7] for high-strength concrete columns

Table 3 Results for Axial Load

Specimen label	Load (kN)		Rate of strength enhancement (Max./Av. CC)	Transverse deflection (mm)		Rate of deformability enhancement (Max./Av. CC)
	Max.	Average		Max.	Average	
CC-a	1267	1254	1,00	8,22	8,78	1,00
CC-b	1240			9,33		
ES1-a	1598	1711	1,36	44,95	48,48	5,52
ES1-b	1823			52,00		
ES2-a	1740	1653	1,32	15,92	27,67	3,15
ES2-b	1565			39,42		
ES3-a	1740	1689	1,35	-	13,08	1,49
ES3-b	1637			13,08		
ES4-a	1506	1628	1,30	56,28	56,71	6,46
ES4-b	1749			57,13		

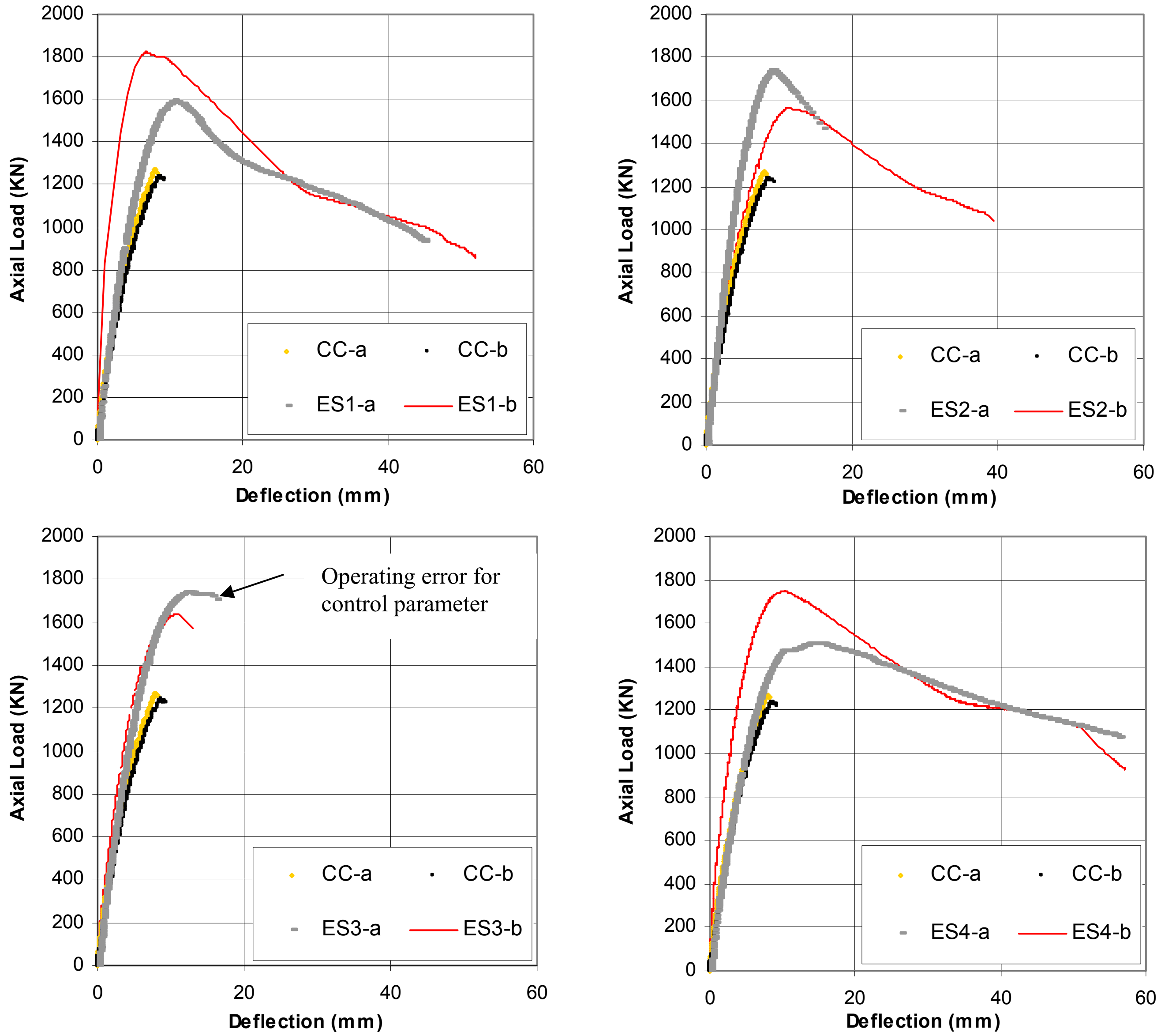

Fig. 5 Load-Deflection curves for each reinforcement technique

3.2. Overall behavior and discussion

From 0 to about 700 kN all CFRP reinforced columns and reference specimens exhibit comparable behavior, except specimens ES1-b and ES4-b exhibiting a considerable higher initial stiffness. This result is due, firstly to limited transverse elastic expansion of concrete (Poisson's effect) that can not take benefit of an effective confinement and secondly to the enhancement of bending stiffness provided by longitudinal CFRP strengthening material that is not significant considering the elastic stiffness of undamaged columns.

However, when loading increase, the confinement action continuously intensifies with the lateral expansion of the column due to onset of concrete nonlinear crushing in compression. Then confinement and flexural reinforcement become efficient and the maximum load enhancement reached by externally reinforced columns varied from 30 to 36% if we consider average values of each series.

This strength capacity enhancement of columns is a result of the combined action of the longitudinal and transverse reinforcement. As ever underlying, the transverse reinforcement enhances the compressive capacity of concrete through confinement action whereas the longitudinal reinforcement reduces the curvature of the column and consecutive secondary moment, hence limiting the risk of concrete cracking on the tensile face. Moreover, it is evident that the lateral pressure exerted by the straps also provides additional support against buckling of longitudinal bars.

Depending on the reinforcement technique (type of material and gluing process), significant increase in deformability can be achieved. The maximum gain was characterized by a ratio of 6.46.

4. Conclusion

Experimental results of RC columns externally strengthened with longitudinal and transverse CFRP retrofitting established that such external CFRP reinforcement is effective in enhancing strength and ductility of reinforced concrete members subjected to combined flexure-compression loading. Presented data can be used as templates for future validation of CFRP reinforcement design methods.

5. Acknowledgements

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6. References

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