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Behavior of RC columns strengthened with different CFRP systems under eccentric loading

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ABSTRACT

The present study investigates the performance of eccentrically loaded columns externally strengthened with different carbon fiber-reinforced polymer (CFRP) systems. The 10 specimens were representative-scale square columns made of normal-strength concrete with substandard (internal) reinforcement details that were designed to represent old building structural columns. Eight columns were upgraded by four types of commercially available systems of external reinforcement, using plates, unidirectional or bi-directional composite fabrics. It was considered necessary to get information on a wide spectrum of carbon fiber-reinforcement systems in order to provide a satisfactory set of experimental data for validating future suitable retrofitting design methods. Experimental results presented in this paper show that a significant improvement of the strength capacity, deformation capacity and ductility of columns can result of the CFRP application, but the observed gains strongly depend on the reinforcement systems.

1. Introduction

Strengthening and rehabilitation of reinforced concrete (RC) structures by externally-bonded carbon fiber-reinforced polymer (CFRP) systems is now a commonly accepted and widespread technique. Typical applications deal with the strengthening of flexural members or the confinement of concrete under axial load. However, while practical execution and the majority of design problems are well documented [1–3], strengthening design of columns under flexure–compression loading is subject of ongoing research and development [4–10].

Although such loading configuration is considered by the Japan Building Disaster Prevention Association [11] and CNR-DT 200 [12], proposed design rules are not fully satisfactory since they do not clearly establish the portion of the flexural strengthening and the portion of the confinement in the behavior the strengthened element.

Several investigations considering such loading have shown that external CFRP reinforcement is effective in improving a column's capacity both in terms of strength and ductility [13,14] and of seismic resistance [15–17]. Nevertheless, it was experimentally demonstrated that the flexural deformation of the column reduces the retrofit efficiency of the fiber-reinforced polymer (FRP) jacket [18,19].

Moreover, studies conducted so far on external strengthening of concrete columns have mainly concentrated on retrofit systems designed for confinement only without specific flexural strengthening [20–23]. For such strengthening configuration, the jacketing is achieved by saturating fiber wrap in special epoxy formulation that allows them to be easily wrapped around columns. This simple technique provides a passive confinement that has been proven to increase the compressive strength of concrete.

However, the strengthening of flexural members by externally bonded FRP plates (prefabricated laminates) or fabrics to their tension face is a widespread technique (see for example Taerwe and Matthys [24]) that can be applied to columns when their load-carrying capacity must be maintained despite significant deformations [25]. Such flexural strengthening is commonly proposed by design department in charge of the drawing of the FRP retrofitting project to moderate effect of eccentric loads that may lead to a buckling moment in columns.

As a combination of these two techniques, specifiers now propose to associate a flexural strengthening coupled with a confinement by wrapping. Such retrofitting is particularly adapted to structural concrete columns that are rarely perfectly axially compressed.

A prior experimental investigation of Chaallal and Shahawy [13] demonstrated 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 bi-directional composite fabric.

To study this concept of coupled reinforcement, Quiertant et al. [26] have tested different types of commercially available systems combining (longitudinal) flexural reinforcement and (lateral) confinement. Various arrangements of plates, unidirectional and

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bi-directional composite fabrics were investigated. Tested columns were designed to be representatives of bridge structural applications, and were eccentrically loaded up to failure. The main conclusion of this preliminary study was that the strength capacity and ductility of columns loaded eccentrically improved significantly thanks to CFRP application but a large difference in ductility was observed between reinforcement systems.

As a continuity of this previous work, the experimental study described in this paper investigates the reinforcement effectiveness of the same combination of retrofitting systems (longitudinal and lateral reinforcement) applied to columns with inferior quality of concrete and insufficient ratio of transverse reinforcement which might be found in old constructions or structures affected by corrosion. In the present study, the considered loading is still the eccentric loading.

As there is a lack of consensus as to which model is the most suitable for design of columns [27–29], the main target of this paper is to present a database established from the most important experimental result of this research program. This database, extended from results proposed in Quiertant et al. [26], aims at being used as templates for future validation of CFRP strengthening design methods.

2. Experimental procedure

The experimental program consisted of testing 10 square columns under combined axial–flexural loading up to failure. The 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 four kinds of CFRP systems combining longitudinal and transverse reinforcement. The specimens were labeled as ES*x*-a and ES*x*-b for the two columns externally strengthened using the system labeled *x*. In a same group, the external reinforcement was the same for each specimen. Repeating the experiments twice was an experimental choice to increase the confidence level in the results.

3. Specimens

3.1. Details of columns

The columns tested had a 200 × 200 mm^2 square cross section and an overall height of 2500 mm. For all the specimens, a unique batch of self-compacting concrete was delivered by a local supplier. The specimens were cast in moulds with chamfered corners in order to avoid the premature fracture of the CFRP fabric due to kinking, and to enhance the confining effect of the wrap.

All columns were reinforced longitudinally with four deformed rebars with 12 mm nominal diameter. The transverse reinforcement consisted of deformed rebars with 6 mm nominal diameter. For longitudinal and transverse reinforcement, steel with 500 MPa nominal tensile strength was used. The dimensions of columns and details of internal reinforcement are shown in Fig. 1. A low amount of internal reinforcement was planned to be representative of ancient building applications for which retrofitting should be necessary.

3.2. External strengthening

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 around the column. Such method, widely recognized, permits to exert a lateral pressure that increases strength and ductility of concrete in the axial direction [20]. The sheet was bonded as a continuous spiral on columns ES1-a and ES1-b (first strengthening method). The type 1 dry sheet was hand-laid with a winding angle (between transverse direction of column and fill direction of the fabric) of approximately 20° and with an axial lap joint measuring approximately 20 mm. Analysis of the effect of winding angle is not developed here, but a study of the influence of wrap angle configuration is proposed in Parvin and Jamwal [30].

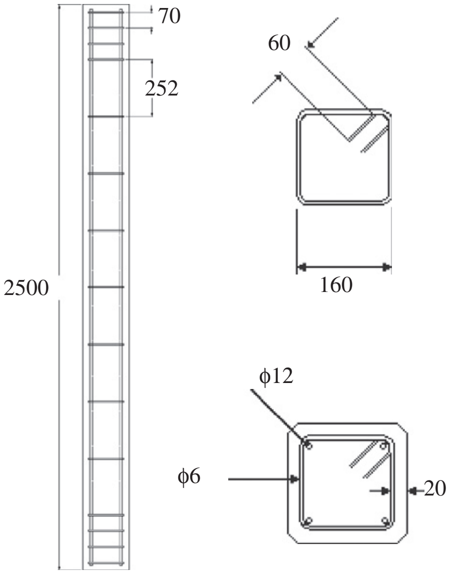

Fig. 1. Reinforcement details of tested columns (dimensions in mm).

All remaining columns were wrapped with discontinuous straps with transverse lap joints measuring approximately 100 mm (Fig. 2) but without (or with no significant) axial lap joints. The value of 100 mm for the transverse lap joint is consistent with previous study concerning the transfer length of CFRP-to-concrete bonded joints (see for example [31]).

Similarly to prior studies (see for example [19]), the ends of all externally strengthened columns were reinforced with one more transverse layer of FRP strap to prevent premature failure outside the test region.

Structural analysis and resultant design was carried out by the authors while the strengthening of columns was accomplished by four different technical professional teams using their own procedures and products to ensure the representativeness of experimental results. It must be emphasized that the intent of the column's strengthening design was to cover a wide range of strengthening

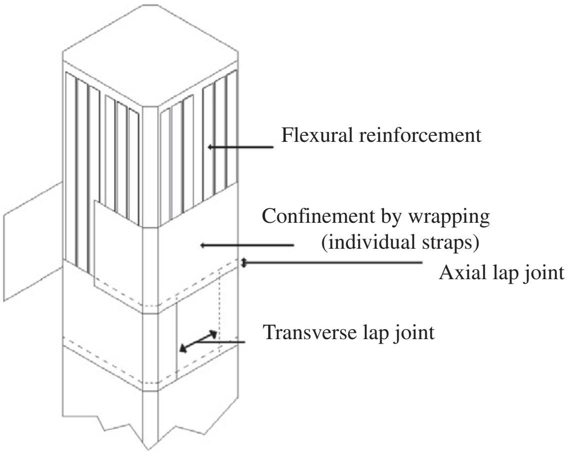

Fig. 2. Principle of column's external reinforcement (wrapping by discontinuous rings).