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Particularities of FRP structural rehabilitation of concrete columns in frames

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Summary

Columns, in general, and reinforced concrete (RC) columns, in particular, are barely used as individual elements. In most of the structures, columns are but a part of the designing problem. The complex state of combined internal efforts makes the design of structural columns a very laborious task for the engineers.

When rehabilitation interventions are required, the problem becomes even more difficult. Lately, the use of Fibre Reinforced Polymer (FRP) composite materials in retrofitting the columns have shown to significantly improve the performance of RC columns as parts of frames.

The most usual problems related to the topic are the insufficient lap lengths in reinforcement splices, spalling of concrete resulting in premature loss of anchorage of the reinforcement bars and possible sudden/brittle failure mechanisms, insufficient transversal reinforcement leading to poor resistance in shear.

The present paper tries to point out the main aspects related to columns behaviors in shear, to make a comparative discussion of existing models for columns in shear and testing procedures. The principal methods of enhancing the shear strength of structural columns using FRP composite materials are also to be presented.

KEYWORDS: structural reinforced concrete columns; rehabilitation; shear resistance; fibre-reinforced polymers

1. INTRODUCTION

As they play the main role in undertaking lateral loads and are the principal resisting elements of RC structures, the RC columns are the most likely to fail in case of large loads acting transversely to their longitudinal axis. Such loads act upon the columns when earthquakes occur. Therefore, when speaking about columns as parts of frames, the main problems are related to preventing from premature failure of columns in case of earthquakes [1]. Further on, we may state that a good approach in seismic retrofit of structures should be focused on the retrofitting of columns.

The need for retrofit procedures may arise from various causes; yet, the most important may be considered the fact that relatively old structures do not meet anymore the present design philosophies.

The experience of last severe earthquakes, resulting in disastrous damages to a large number of buildings (e.g. Whittier Narrows 1987, Loma Prieta 1989, Northridge 1994, and Kobe 1995) made clear the necessity of a different designing philosophy concerning the seismic design of buildings. Changes concerning this aspect have been performed in most of the countries that have to deal with this problem.

2. TYPICAL RC COLUMNS FAILURE MODES UNDER SEISMIC LOADS

RC columns have to undertake a combination of lateral cycling loads and existing axial loads when earthquakes occur. Lack of sufficient shear, flexural strength, or ductility may lead to failure (rather brittle in most of the cases) of columns. There were established three typical modes of failure in case of RC columns when subjected to seismic loads: (1) shear failure; (2) failure of confinement in flexural plastic hinge regions; (3) lap splice failure of the longitudinal steel reinforcement.

2.1 Shear failure

Probably the most dangerous failure mode, the shear failure starts with diagonal concrete cracking, followed by a rapid failure or opening of transverse reinforcement. The successive buckling of longitudinal steel reinforcement results in a sudden, explosive failure of the column. (Figure 1, a))

Insufficient transverse reinforcement, improper detailing or bad anchorages of existing transverse steel reinforcement are common causes leading to shear failure. Problems concerning the improper detailing include steel hoops insufficiently lap spliced, insufficient anchorage lengths of hoops in the concrete core.

Columns that are identified as having such problems must be strengthened in shear when retrofitting is discussed, thus avoiding the most catastrophic failure mode.

2.2 Plastic hinge failure

Also very common during earthquakes, the flexural plastic hinge failure mode occurs at the column ends. Spalling of concrete cover, failure of transverse steel reinforcement and buckling of the longitudinal reinforcement are typical for this failure mode. (Figure 1, b); c))

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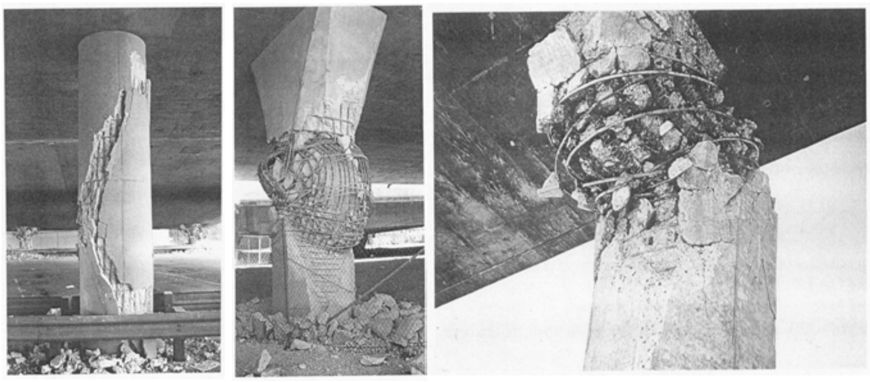
Since generally large flexural deformations occur, this failure mode is less brittle than the previous one and thus considered as much desirable.

2.3 Lap splice failure

This problem mostly happen in cases where the longitudinal reinforcement has been lap spliced in potential plastic hinge regions, with maximum moment values are likely to occur. Under the lateral forces induced by earthquakes, the splices may fail resulting in loss of capacity for undertaking large deformations.

The retrofitting procedure should end in a clamping device for the longitudinal steel reinforcement in order to prevent the loss of structural integrity of the column. This way, it will be able to sustain larger deformations, the failure being a more ductile one.



a) b) c)

Figure 1. Failure modes due to lateral (seismic forces) in case of columns: a) progressive shear failure; b) buckling of longitudinal steel reinforcement; c) flexural plastic hinge failure [2]

3. USE OF FRP COMPOSITE MATERIALS FOR COLUMN RETROFITTING

The traditional methods for column seismic retrofitting consisted in RC or steel jacketing. Apart from the disadvantages related to the increase of the column own weight and the economical inconvenient these methods introduced a new problem. Together with the relative enhancement of mechanical properties, these jacketing procedures significantly increased the stiffness of the column. The increase in stiffness induced supplementary seismic forces in the column.

Katsumata (in 1987, 1988) was the first to suggest the use of FRP composites for the retrofit of columns with problems related to seismic resistance.

Later on, two approaches were defined for the column retrofitting using FRP composite materials: (1) retrofit methods focused on the increase of ductility, and (2) retrofit methods focused on the strength enhancement. [1]

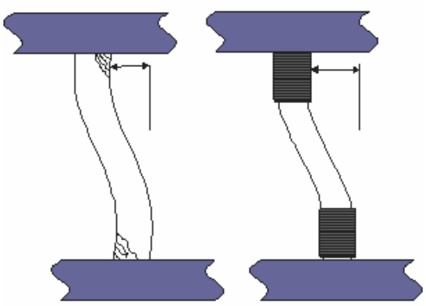


Figure 2. Ductility increase of RC column using FRP composite materials

The first method relies on bonding FRP plates in order to increase the flexural strength of the member; the second method consists in wrapping FRP materials having the fibres oriented in the hoop direction of the column. The result is desired to be a column that has an improved capacity for energy absorption.

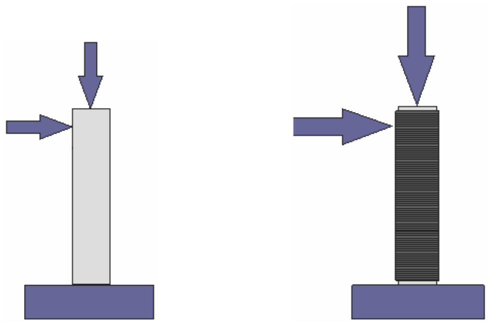


Figure 3. Strength enhancement of RC column using FRP composite materials

3.1 FRP jackets with fibres oriented in the hoop direction

The well known procedures of wet laying-up of fibre sheets or winding of fibre strands may be used using resins are also suitable when the shear capacity and ductility are to be enhanced.

The fibres will generally oriented in the hoop direction of the column, either the wrapping is performed on site or there are applied the previously prefabricated jackets. (Figure 4) Under lateral forces, the tensile stresses developed in the FRP fibres directly contribute to the shear resistance of the retrofitted column.

A much greater ductility is obtained by the confinement resulted from flexure, increasing the strength and the concrete ultimate strain.

Figure 4. Shear strength enhancement of RC column using FRP composite materials: a) discrete rings with hoop oriented fibres; b) wet-laid up continuous jacket; c) prefabricated jacket

In case of shear strengthening, it is recommended that the entire column height should be covered by the FRP jacket. If other results are desired, the wrapping should be performed only in the region with the plastic hinge occurrence hazard or the lap splice clamping lengths. The jacket should be prevented from any direct axial loading.

When the shape modification of the column section is considered, the wrapping must be realized only in the region of the plastic hinges; any direct loading of the supplementary concrete or FRP jacket must be also avoided. (Figure 5)

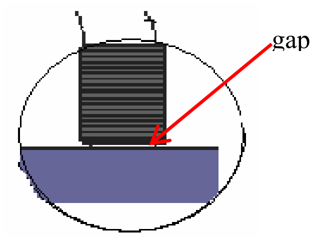


Figure 5. Imposed gap for preventing direct loading of the FRP jacket

3.2 FRP plates longitudinally bonded on the column

When the column is subjected to important axial loads, the lateral confining FRP jacket induces also an important flexural strength enhancement. Yet if not enough, this flexural capacity may be increased by additional longitudinally disposed FRP fibres (sheets or plates bonded on the longitudinal direction of the column).

The combined effect of both longitudinal and lateral oriented fibres may be specifically positive in case of slender columns presenting low flexural capacities (Figure 6). When applied, this system directs the flexural failure of the column towards the plastic hinge regions.

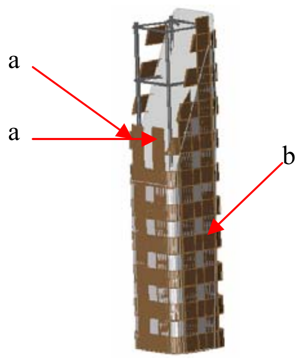


Figure 6. Combined shear and flexural strength enhancement of RC column using FRP composite materials: a longitudinally bonded FRP plates; b) discrete rings in hoop direction

4. COMMON TESTING METHODS FOR EVALUATING THE FRP COMPOSITES EFFECTS ON LATERALLY LOADED COLUMNS

The basic testing procedure used in order to evaluate the effect of FRP composites retrofitting of columns is laterally loading the columns in cycles while they are subjected or not to simultaneous axial loads. (Figure 7)

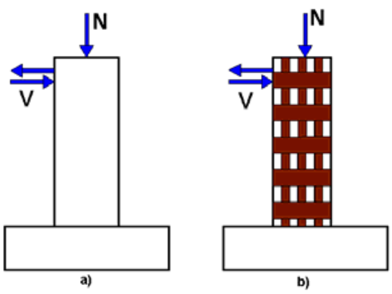


Figure 7. Typical test procedure for seismic retrofitted columns: a) control test specimen; b) retrofitted element

The first such a test was performed as mentioned by Katsumata *et al.* (1987, 1988) when introducing the idea of FRP composites retrofitting of columns. Both circular and rectangular columns retrofitted or not, were subjected to combined axial and cyclic lateral loads. [1]

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Among the parameters that are considered in tests there are:

- the shear span (level of lateral cycling load V related to the bottom end of the column);
- the cross-sectional dimensions of the section;
- the axial force ratio;
- the characteristic strength of the concrete;
- the CFRP reinforcement ratio (and the related strength ratio).

Strain gauges applied both on the concrete surface and the FRP composite material should provide data concerning the variation of stress and strain state in the two materials as the element is loaded. The loading start with the axial loading of the column (up to a level that will remain constant afterwards) then, lateral force is induced (most commonly as a lateral controlled displacement). Cycles of positive and negative lateral forces (change in direction of loading) and loading/unloading cycles are used. [3]

The targeted result data include the increase in shear and/or flexural strength, the increase of ductility, the failure mode, and load displacement relationships.

5. DESIGN ASPECTS IN CASE OF SEISMIC RETROFITTING OF RC COLUMNS

A rather common analysis that is used in case of shear capacity of RC columns retrofitted with FRP composites implies three factors (equation (1)) [4]:

$$V_r = V_c + V_s + V_{frp} \tag{1}$$

where,

V_r -total factored shear resistance;

V_c - factored shear resistance attributed to concrete;

V_s - factored shear resistance attributed to the transverse steel;

V_{frp} - factored shear resistance attributed to the FRP.

The required thickness of the FRP wrap may be computed considering the last term in equation (1) as a function of FRP wrapping parameters (equation (2)).

$$N_b \cdot t_{frp} = f(\Phi_{frp}; E_{frp}; d(D); \theta) \tag{2}$$

where:

$N_b \cdot t_{frp}$ -total thickness of FRP wrap;

Φ_{frp} - resistance factor for FRP;

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E_{frp} - FRP modulus of elasticity;

$d(D)$ - side length (diameter) of the cross-section;

θ - angle of principal compression strut to the column axis or the shear crack inclination.

6. CONCLUSIONS

Columns are very fragile members when laterally loaded. As main parts of frames, retrofitting procedures for frames should focus on them.

FRP composite materials are very suitable for increasing shear/flexural strength capacity and ductility (energy absorption capacity). Shear failure mode is the most dangerous one for columns as it is brittle, explosive. Should an earthquake occur, shear failure gives virtually no time for eventual escaping actions for people.

Modern retrofitting methods imply the use of CFRP sheets disposed in the transversal (hoop) direction and longitudinally bonded FRP sheets/ plates.

Tests methods try to simulate the combined action of cycling lateral load with the (permanent) axial load.

References

1. Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L. (2002). FRP strengthened RC Structures, Wiley, Chichester, U.K.
2. Sieble F., Priestley M.J., Hegemier G. A., Innamorato D. (1997). Seismic Retrofit of RC Columns with Continous Carbon Fiber Jackets. Journal of Composites for Construction May: pp 52-56
3. Lieping Ye, Qingrui Yue, Shuhong Zhao, Quanwang Li. (2002). Shear Strength of Reinforced Concrete Columns Strengthened with Carbon-Fiber-Reinforced Plastic Sheet. J Struct Eng, December: pp 1527-1530
4. ISIS Canada, Strengthening Reinforced Concrete Structures with Externally-Bonded Fiber Reinforced Polymers-Design Manual No.4 (2001): pp 5.11-5.13