Title no. 101-S51

Fiber-Reinforced Polymer Retrofitting of Rectangular Reinforced Concrete Columns with or without Corrosion

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Twenty concrete columns, with a 250 x 500 mm section and materials and detailing emulating older construction, are tested to investigate, in a systematic way, the effect of important parameters of seismic retrofit with fiber-reinforced polymer (FRP) wraps, as well as the effect of reinforcing bar corrosion on the effectiveness of the retrofitting. As far as the number of FRP layers and the fiber material is concerned, it is concluded that replacing carbon fibers by glass fibers, while maintaining the same extensional stiffness of the FRP jacket in the circumferential direction, leads to about the same performance. Nonetheless, FRP extensional stiffness seems to be the controlling factor up to a certain limit, as increasing the number of carbon fiber-reinforced polymer (CFRP) layers from two to five does not materially improve performance. Previous damage left unrepaired reduces the effectiveness of rehabilitation with FRP wraps. Confinement by the FRP is very effective in increasing concrete strain capacity to levels of 5 to 6% even in the middle of a wide side of the column. Nonetheless, rectangular columns tested in the strong direction (with a 250 mm-wide compression zone) are found to benefit more from FRP wrapping than when tested in their weak direction (with a 500 mm-wide compression zone). Although wrapping with FRP is found to significantly improve seismic performance of columns that suffer from both lack of seismic detailing and of corrosion of the reinforcement, such corrosion materially reduces the effectiveness of FRP wraps as a strengthening measure, as the corroded bars become the weak link of the column, instead of the confined compression zone.

Keywords: column; corrosion; fiber-reinforced concrete; polymers; seismic; strength; test.

INTRODUCTION

Fiber-reinforced polymers (FRPs), consisting of continuous carbon (C), glass (G), or aramid (A) fibers bonded together in a matrix of epoxy, vinylester, or polyester, are being employed extensively for rehabilitation of concrete structures. Despite their relatively high material costs, the high strength-to-weight ratio of FRPs, their immunity to corrosion, and easy handling and installation are making them the material of choice in an increasingly large number of rehabilitation projects, seismic or not.

Given that continuity and anchorage of FRPs in a joint beyond a member end is difficult to achieve, the main use of FRPs in seismic rehabilitation of reinforced concrete (RC) elements is with the fibers oriented in the circumferential/transverse direction, to enhance shear resistance and/or improve the deformation capacity of flexural plastic hinge regions at member ends, through added confinement of the concrete, anti-buckling restraint of vertical bars, and clamping of deficient lap splices.

The literature on FRP-strengthened RC elements is vast: many journal or conference papers cover a variety of aspects on seismic retrofitting. The basic concepts in the use of FRPs for strengthening of concrete structures are covered in a review article by Triantafillou.[1] Progress in various strengthening methods, questions associated with the long-term durability of FRP, as well as the development of design guidelines and codes for nonseismic applications are addressed in a review paper by Neale.[2] Comprehensive and up-to-date overviews of the subject—albeit without emphasis on seismic retrofitting—are provided in References 3 and 4. A relatively recent survey of the literature on seismic retrofitting with FRPs may be found in a review article by Triantafillou.[5]

Experimental studies of the contribution of FRP wraps in enhancing cyclic deformation capacity of RC columns has mainly focused on circular sections. In such sections, the kinematic restraint by the FRP jacket (passive confinement) is uniform in every direction transverse to the column axis and uniform around the perimeter, thus effectively controlling lateral expansion of concrete and increasing ultimate deformations. The picture is different in square and especially rectangular sections, as the effectiveness of the FRP jacket in directions orthogonal to the member axis is a function of the size and the section aspect ratio. Experimental results for the square sections are limited (for example, References 5 to 16) and are even more scarce for rectangular ones (for example, References 16 to 20), especially when considering the possibilities of loading and section aspect ratio combinations.

Old, substandard concrete structures often suffer both from deficiencies in member strength and deformation capacity and from reinforcement corrosion. Past experience has shown that reinforcement corrosion not only reduces member strength due to steel area loss, but it also adversely affects bond and anchorage, makes bars more susceptible to buckling, and reduces steel ductility. Transverse reinforcement, being of smaller diameter and closer to the concrete surface, is more vulnerable to corrosion. Thus, its contribution to confinement decreases. For these reasons, the seismic performance of RC members, especially columns, is adversely affected by reinforcement corrosion. In Europe the problem is considered to be aggravated by the widespread use of the more corrosion-prone tempcore S500 steel since the late 1980s.

ACI Structural Journal, V. 101, No. 4, July-August 2004.
MS No. 03-048 received January 30, 2003 and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published in the May-June 2005 *ACI Structural Journal* if the discussion is received by January 1, 2005.

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The efficiency of electrochemical measures against corrosion is not commensurate to their cost. As structures old enough to develop significant reinforcement corrosion normally lack sufficient earthquake resistance, the need for measures against the ongoing corrosion often paves the way for seismic rehabilitation as well. When retrofitting is realized through external confinement, FRP wraps offer an attractive choice. Corrosion is an expansive process and FRP jackets can provide confinement activated by lateral expansion of the concrete section.

In this paper, the effectiveness of jacketing substandard rectangular columns with FRP wraps for enhanced deformation capacity is experimentally investigated. The tests concern nonseismically detailed reinforced concrete columns subjected to cyclic uniaxial flexure under constant axial load. The level of the latter is selected relatively high to investigate the effect of cyclic damage and of the retrofitting on the axial load capacity of the column. The effect of important parameters of the retrofit design, such as the number of layers and the fiber material, is also studied experimentally in a systematic way. Last, but not least, the performance of this retrofitting scheme in columns with corrosion of the reinforcement is investigated.

RESEARCH SIGNIFICANCE

FRP jackets are becoming very popular for rehabilitation of concrete columns not designed and detailed for earthquake resistance. Experimental results on the effectiveness of the technique are abundant for circular columns, and to a limited extent for square columns, but are scarce for columns with rectangular sections, where the effectiveness of FRP wraps in confining the wide side of the section may be questioned. In addition to focusing on rectangular columns, the paper studies experimentally in a systematic way the effect of important parameters of the retrofit design, such as the number of layers and the fiber material. As FRP wrapping is often the technique of choice for both upgrading undamaged substandard columns and for the repair/strengthening of damaged ones, the paper also investigates the impact of previous damage left mostly unrepaired on the effectiveness of rehabilitation with FRP wraps. Most importantly, it studies the effect of reinforcement corrosion on the effectiveness of the retrofitting. This is an issue of major practical significance, as substandard columns in need of seismic rehabilitation are often old enough to also suffer from corrosion of the reinforcement. In that case, FRP wrapping is considered a practical means of restoring capacity lost due to corrosion and of upgrading earthquake resistance at the same time, while preventing future intrusion of corrosive agents.

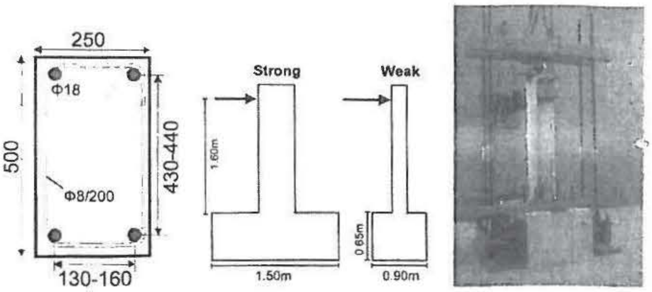

Fig. 1—Geometry of concrete columns and view of test setup.

SPECIMENS, MATERIALS, TEST SETUP, AND TESTING PROGRAM

A total of 20 column specimens were constructed and tested. All have the same geometry and reinforcement (Fig. 1). They are cantilever specimens with a height to the point of application of the lateral load (shear span) of 1.6 m. The cross section is rectangular, 250 x 500 mm, and reinforced with four 18 mm-diameter deformed (high-bond) bars at the corners. Structural depth varies between 465 and 470 mm in the strong direction of the column and between 190 and 205 mm in the weak direction. The column is fixed into a heavily reinforced 0.6 m-deep base, 1.5 x 0.9 m in plan, within which vertical bars are anchored with 90-degree hooks at the bottom.

To represent nonseismically designed and detailed members, specimens emulated old construction, as far as materials used and lack of earthquake resistant detailing. Ties used as lateral reinforcement consist of 8 mm-diameter plain (smooth) bars at 200 mm centers; they are closed with a 135-degree hook at one end and a 90-degree hook at the other. The 18 mm-diameter vertical bars have a yield stress of 559.5 MPa, a tensile strength of 682 MPa and uniform elongation at failure 13%. The corresponding values of the steel used for ties are 286 MPa, 350 MPa, and 13% (average values from three coupons). Concrete strength (measured on 150 x 300 mm cylinders) is intentionally selected low: at the time of testing it ranges from 16.7 to 20.4 MPa (refer to Table 1).

In half of the specimens, salt was added to the mixture at 3% of weight of water. These specimens were tested after 1 m at the bottom of the column had been subjected to accelerated corrosion of the reinforcement. In Table 1, these specimens have a C (= corroded) as the first letter, whereas for their uncorroded companion specimens, the first letter is U. Accelerated corrosion was achieved via an electrochemical circuit in which each longitudinal reinforcing bar was the anode and an external galvanized steel mesh was the cathode.[21] A 6 V fixed potential was applied between the anode and the cathode. Alternating wet-dry cycles of 60 and 12 h, respectively, were applied to the surface of the column, through burlaps saturated with water containing 3% of sodium chloride; this has been shown in the past[22] to produce corrosion products with high volumetric expansion. Stirrups were subjected to current through their contact to the vertical reinforcement. The evolution of corrosion was monitored by recording the current passing and applying Faraday's law to the integrated current. These conditions were maintained for approximately 3.5 months, at the end of which approximately 1 kg of steel mass in each specimen had been converted to oxides. Visual examination of exposed

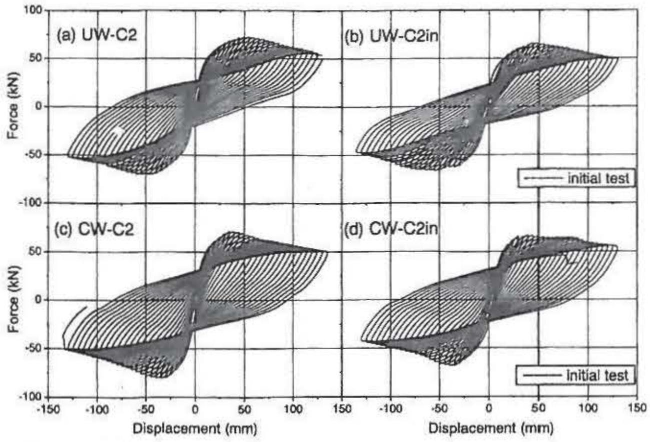

Fig. 4—Force-deflection loops of specimens retrofitted with two CFRP wraps, with or without prior damage, weak direction: (a) uncorroded specimen without initial damage; (b) uncorroded specimen with initial damage; (c) corroded specimen without initial damage; and (d) corroded specimen with initial damage.

deformation capacity are not adversely affected by corrosion. As a matter of fact, the opposite seems to be the case.

Figure 3 and 4 refer to the effect of initial damage on the effectiveness of retrofitting with two CFRP layers. Compared with an undamaged column, a column retrofitted after having been cyclically damaged beyond yielding of the reinforcement exhibits more rapid strength loss and lower deformation capacity. The difference may be attributed to the fact that, as FRP wrapping took place without repair of the damage (other than the treatment of the column surface necessary for application of the FRP), concrete has already undergone some permanent lateral expansion in the absence of the FRP jacket and, when confined afterward, it reached its crushing strain with less activation of the FRP wraps and benefit from it. The difference in performance between previously damaged and undamaged columns is much larger in the strong direction, where, due to its narrower compression zone, the column benefits most from confinement by the FRP.

Figure 5 and 6 refer to the effect of the number of layers and the type of fiber material in the FRP jackets, in specimens without damage prior to FRP wrapping. They show that replacement of CFRP by GFRP with the same extensional stiffness in the circumferential direction leads to approximately the same performance, confirming that FRP extensional stiffness controls confinement. The five GFRP layers, with their double tensile strength and ultimate strain relative to the two CFRP layers, provided slightly lower strength overall but a little better deformation capacity. The same figures demonstrate that increasing the number of CFRP layers from two to five does not materially improve member deformation capacity and strength. The benefit from the FRP extensional stiffness and its effect on confinement seems to have a limit, beyond which the magnitude of FRP thickness and stiffness do not seem to matter very much.

Regarding the effect of reinforcement corrosion on retrofitted columns, Fig. 3 and 5 and Table 2 show that in the strong direction retrofitting improved the conventionally defined deformation capacity of columns with corroded reinforcement by a mere 50% on average, versus 130% in the companion columns without corrosion. Columns with corroded reinforcement failed in that direction always by fracture of longitudinal bars, whereas fracture of a vertical

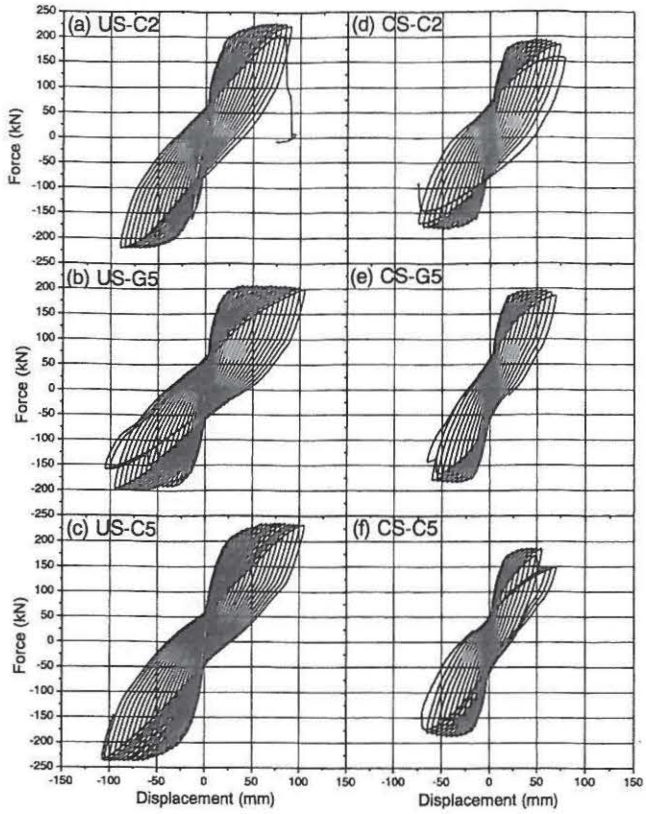

Fig. 5—Effect of number and material of FRP laminates on force-deflection loops of specimens without prior damage, strong direction: (a) uncorroded specimen with two CFRP layers; (b) uncorroded specimen with five GFRP layers; (c) uncorroded specimen with five CFRP layers; (d) corroded specimen with two CFRP layers; (e) corroded specimen with five GFRP layers; and (f) corroded specimen with five CFRP layers.

reinforcing bar was observed only in one of the columns with noncorroded reinforcement. In absolute terms, retrofitted columns with corroded reinforcement had in the strong direction on average 70% of the deformation capacity of their uncorroded counterparts. Corrosion seems to cause reduction of the elongation capacity of reinforcing bars and their early rupture, preventing full use of the strong confining effect of FRP wraps and setting a limit to the improvement of the overall deformation capacity by retrofitting.

Figure 4 and 6 and Table 2 suggest that in the weak direction retrofitted columns with corroded reinforcement have on average and in absolute terms only approximately 20% less deformation capacity than their uncorroded counterparts, as they never failed by fracture of longitudinal bars. Compared with the unretrofitted ones, in the weak direction retrofitted columns with corroded reinforcement had on average a gain in deformation capacity of 35%, versus 80% of the uncorroded columns.

Figure 7 shows the evolution during the test of the mean axial strain at the opposite sides of the column within the bottom 250 mm of its height (as derived from the individual LVDT measurements on opposite sides of the column), at the top for the unretrofitted uncorroded control specimens, and for all corroded columns below. Positive strains include the effect of bar pull-out, smeared over the gage length of 250 mm. The very small magnitude of the difference between the positive displacements measured over the

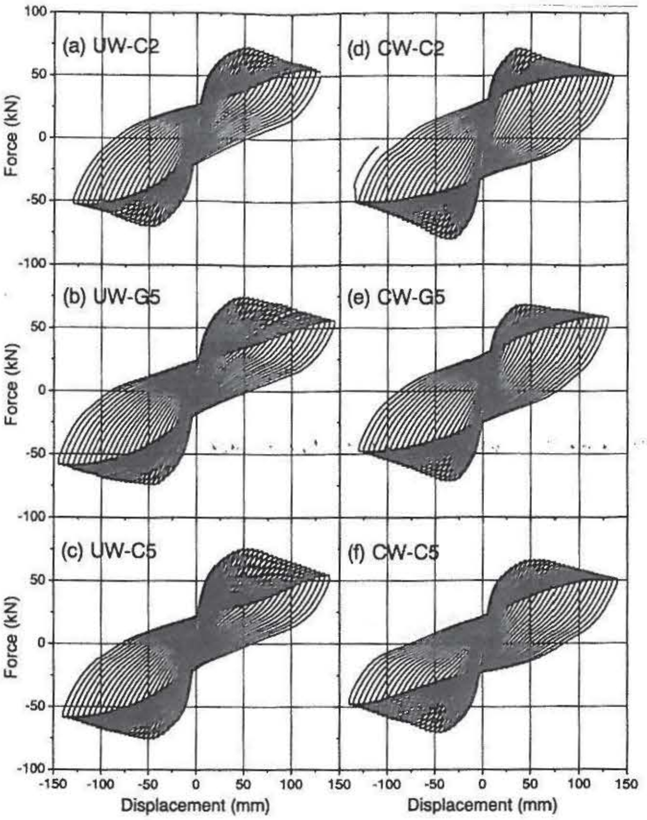

Fig. 6—Effect of number and material of FRP laminates on force-deflection loops of specimens without prior damage, weak direction: (a) uncorroded specimen with two CFRP layers; (b) uncorroded specimen with five GFRP layers; (c) uncorroded specimen with five CFRP layers; (d) corroded specimen with two CFRP layers; (e) corroded specimen with five GFRP layers; and (f) corroded specimen with five CFRP layers.

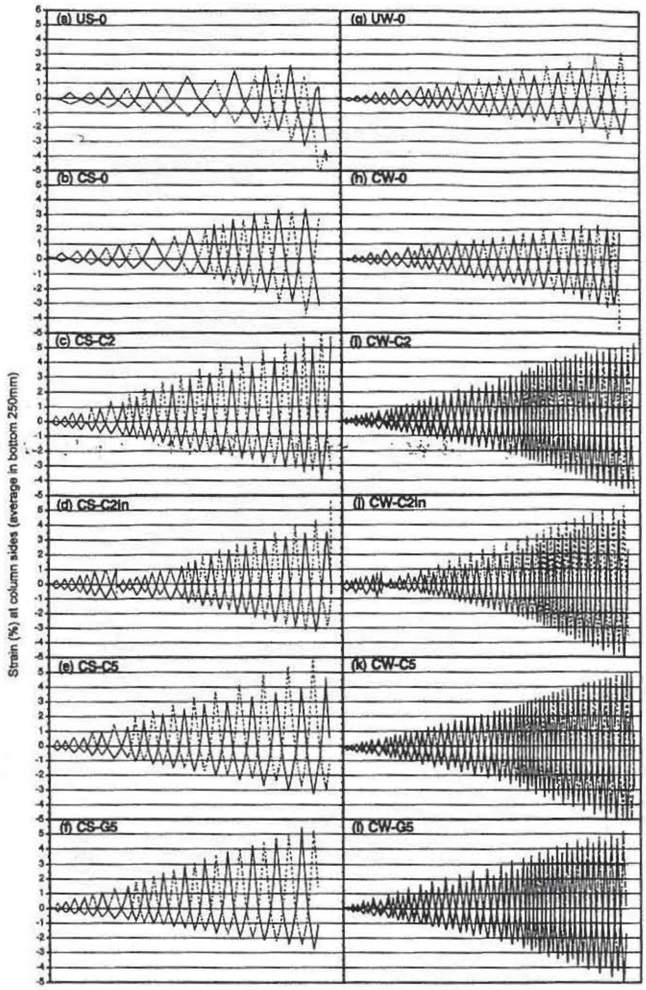

Fig. 7—Evolution of vertical strain at opposite sides of column (mean value over lower 250 mm from base): (a) to (f) columns tested in strong direction; (g) to (l) columns tested in weak direction; and (a) and (g): unretrofitted uncorroded control specimens; rest: corroded columns.

bottom 500 mm from those measured over the bottom 250 mm of the column suggests that the major part of these displacements (and hence of the positive strains in Fig. 7) is due to bar pullout, especially in the retrofitted columns. Negative strains reflect compressive deformation of the concrete in the lower 250 mm of the column and, near the end of some tests, reinforcing bar buckling. In the retrofitted columns the large magnitude of measured compressive strains (more than 4 to 5%, sometimes close to 6%) demonstrates the very large effect of confinement by the FRP.

It is expected that due to its more narrow compression zone (250 mm), retrofitted columns tested in the strong direction benefit more from confinement than those tested in the weak direction, where the 500 mm-wide compression zone is less well confined near the center. The very effective confinement of the narrow compressive zone may well explain the failure by rupture of a vertical bar in all four strong direction columns with corroded reinforcement and in one of those with uncorroded reinforcement, before failure of the compression zone. Failure of columns tested in the weak direction was never due to bar rupture and always had something to do with the compression zone. Nonetheless, even those columns sustained extreme vertical compressive strains with average values over the bottom 250 mm higher than 5% (refer to Fig. 7(k) and (l)). This shows that confinement by the FRP may be very effective even over a 500 mm-wide column.

Axial load was maintained constant during each test. In unretrofitted columns, the gradual loss of lateral load resistance during the cycle that led to failure was accompanied by some loss of axial load resistance, evidenced by the difficulty to maintain the axial load constant. Nonetheless, it was possible to increase their axial load well beyond the initial value, after they reached their ultimate lateral deformation and lost all their lateral load resistance. So, after failure, unretrofitted columns retained a large part of their axial load capacity. Retrofitted columns maintained constant axial load (and practically lateral force) capacity up to ultimate deformation and often beyond. Nonetheless, if the test ended with fracture of the FRP wrap the column was shattered and lost abruptly all its axial load capacity. Failure by bar rupture did not have such severe consequences on axial load capacity.

The evolution of the mean axial strain at the center of the section over the bottom 250 mm above the base (as derived from the average of the linear variable differential transformer (LVDT) measurements on opposite sides of the column) is an indication of those phenomena within the plastic hinge region that affect axial load resistance. Figure 8 shows this evolution for all columns with corroded reinforcement (C specimens) as a function of tip deflection. The change

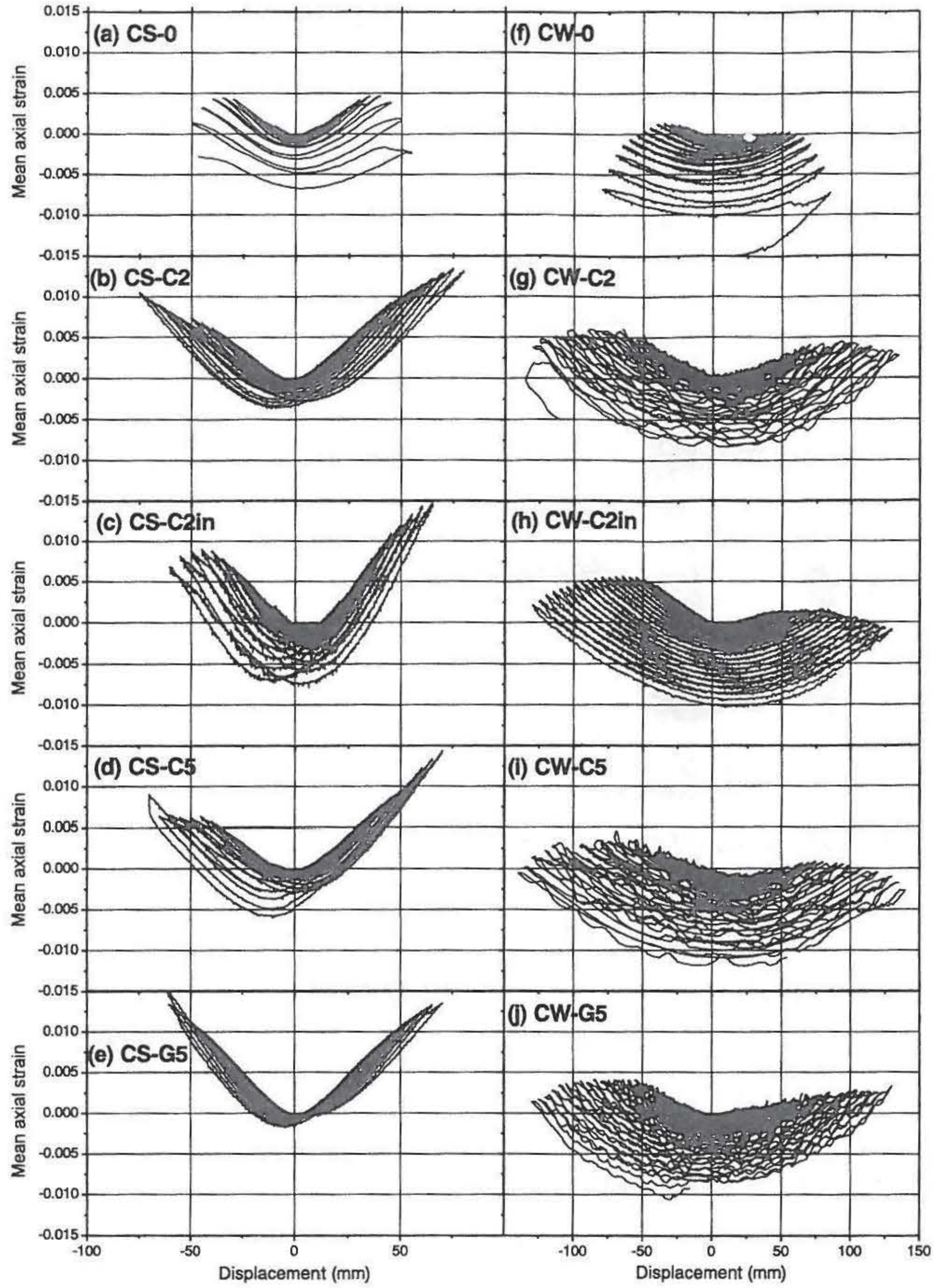

Fig. 8—Evolution of vertical strain at center of section (mean value over lower 250 mm from base). Corroded columns: (a) to (e) tested in strong direction; and (f) to (j) tested in weak direction.

of column length almost in proportion to lateral deflection is a direct consequence of flexure according to the plane-sections hypothesis. If less than half of the cross section is in compression, the less deep the compression zone and the larger the column elongation in each deflection cycle are. This is confirmed by the present results, which show larger mean elongation per half-cycle with respect to the neutral position (zero deflection) in the retrofitted specimens than in the unretrofitted ones, especially when confinement by the FRP is largest and hence the compression zone less deep. What is most interesting is the ratchetting axial shortening with cycling of deflections. Columns with low axial load (normalized axial force $\nu = N/A_c f_c'$ less than 0.15) develop ratchetting axial elongation during lateral-load-cycling, owing to the accumulation of positive plastic strains in the reinforcing bars on both sides of the column, turning into axial shortening when failure approaches with bar buckling and concrete crushing.[23] For higher axial load levels, as in the present case, there is instead ratchetting axial shortening after load cycling past yielding, indicative of the accumulation of permanent compressive strains in the concrete. As evidenced in Fig. 8(a) and (f), in the unretrofitted specimens that fail gradually with bar buckling on both sides and concrete crushing all over the section, mean compressive strains above 0.5 or even 1% take place over the bottom 250 mm of the column around failure. These strains are associated with the difficulty to maintain the axial load constant at that stage but did not prevent the application of a higher load level after the end of the test. Confinement by the FRP limited the magnitude of axial shortening in the retrofitted columns, especially in those that ultimately failed by rupture of vertical bars, Fig. 8(b) to (e), suggesting that vertical compressive strains in the concrete did not approach critical levels. (The uncorroded columns tested in the strong direction, that failed by FRP fracture like those tested in the weak direction, exhibit larger axial shortening, like that of Fig. 8(g) to (j). The larger strains in Fig. 8(c) include those due to the initial damage of the column; the uncorroded predamaged columns, not shown in Fig. 8, exhibit similar behavior.) The large magnitude of mean compressive strains in Fig. 8(g) to (j) suggests that concrete has undergone very large permanent strains inside the FRP wraps. These vertical strains, which are shared by the FRP wraps due to the surface bonding, often caused its local buckling.

CONCLUSIONS

Conclusions drawn on the basis of test results presented in this paper may be categorized, first, to general ones about the effectiveness of FRP wraps for seismic strengthening of deficient rectangular columns (with or without corroded reinforcement) and, second, to those referring specifically to the impact of reinforcing bar corrosion on the cyclic behavior of columns, retrofitted with FRPs or not. The general conclusions on the effectiveness of FRPs for seismic strengthening of rectangular columns are the following:

- Deformation capacity and hysteretic response improve considerably when nonductile regions are encased in continuous FRP jackets with either carbon or glass fibers. This improvement is due to increased strain capacity of the confined concrete, to enhanced restraint of bar buckling by the FRP jacket, as well as to suppression of the effects of shear on deformation capacity. FRP wrapping causes only a marginal increase in member strength without modifying member preyielding stiffness;
- Unretrofitted columns exhibit a gradual loss of lateral and axial load resistance during the cycle that leads to failure; after ultimate deformation they retain most of their axial load capacity although losing their lateral load one. Retrofitted columns maintain constant axial load (and practically lateral force) capacity up to ultimate deformation but lose it abruptly when they fail explosively by fracture of the FRP wrap. Failure by bar rupture does not have such severe consequences on axial load capacity;
- Changing the type of material (glass fibers versus carbon fibers), while maintaining the same extensional stiffness of the FRP jacket in the circumferential direction, leads to approximately the same performance, confirming that FRP extensional stiffness controls confinement. The five GFRP layers, with their double tensile strength and ultimate strain relative to the two CFRP layers, provided slightly lower strength overall but a little better deformation capacity;
- Overall, increasing the number of CFRP layers from two to five does not materially improve member deformation capacity and strength. The rule about the importance of FRP extensional stiffness for confinement, confirmed when five GFRP layers were used instead of two CFRP layers, does not seem to apply beyond a certain—relatively low—limit of FRP thickness and stiffness;
- As far as confinement is concerned, FRP wraps were found to have a larger overall effect for loading in the strong direction of the column—where the lower drift capacity is due to larger depth and lower shear span ratio—as the more narrow compression zone lends itself better to confinement by the FRP and improvement in strain capacity. This was confirmed by the columns that failed by fracture of the FRP—the increase in deformation capacity in the strong direction was 90%, versus approximately 55% in the weak direction, except when permanent lateral expansion of the concrete had already taken place due to load cycling prior to wrapping of the FRP (refer to the next point). It was also confirmed by the fact that in five out of eight retrofitted columns tested in the strong direction, failure was due to bar rupture, before failure of the compression zone, whereas no bar rupture was observed in the eight retrofitted columns tested in the weak direction. Nonetheless, the very large compressive strains measured before failure of the columns tested in the weak direction show that confinement by the FRP may be quite effective even over a 500 mm-wide compression zone; and
- Compared with a previously undamaged column, one retrofitted with FRP wraps after being cyclically damaged beyond yielding of the reinforcement exhibits more rapid strength loss and lower deformation capacity. The difference may be due to the fact that, as FRP wrapping took place without repair of the damage, concrete had already undergone some permanent lateral expansion in the absence of the FRP jacket and, when confined afterward, it reached its crushing strain with less activation of the FRP wraps and benefit from it. The difference in performance between the previously undamaged and the damaged column is much larger in the strong direction, where, due to its narrower compression zone, it benefits more from confinement by the FRP.

Conclusions about the impact of reinforcing bar corrosion on the cyclic behavior of columns retrofitted with FRPs are the following:

- Despite the fact that the reduction in bar diameter and the loss of cross-sectional area seem insignificant visually, reinforcing bar corrosion reduces the strength of the column, retrofitted or not, as this strength is controlled by the flexural capacity at the base and affected by the loss in longitudinal steel area. Nonetheless, in the unretrofitted columns deformation capacity and hysteretic behavior are not adversely affected by reinforcing bar corrosion. As a matter of fact, the opposite was the case in the pairs of unretroffited columns tested in the present study;
- Retrofitted columns with corroded reinforcement failed in the strong direction always by fracture of the longitudinal bars. Fracture of a vertical reinforcing bar was observed only in one of the companion retrofitted columns with noncorroded reinforcement. As a result, in the strong direction, FRP wrapping improved the deformation capacity of columns with corroded reinforcement by a mere 50% on average, versus 130% in the companion columns without corrosion. In absolute terms, retrofitted columns with corroded reinforcement had in the strong direction on average 70% of the deformation capacity of their uncorroded counterparts. It seems that corrosion reduces the ductility of reinforcing bars, preventing full use of the strong confining effect of FRP wraps in that direction and setting a limit to the improvement in overall deformation capacity that can result from this type of retrofitting;
- In the weak direction, retrofitted columns with

corroded reinforcement never failed by fracture of longitudinal bars and in absolute terms had on average about 20% less deformation capacity than the uncorroded ones. Compared with the unretrofitted columns, retrofitted ones with corroded reinforcement had on average a gain in deformation capacity of 35%, versus 80% of the uncorroded columns; and

- Overall, although wrapping with FRP significantly improves seismic performance of columns that suffer from both lack of seismic detailing and of corrosion of the reinforcement, such corrosion materially reduces the effectiveness of FRP wraps as a strengthening measure. From the practical point of view, this may be the single most important finding of this work.

ACKNOWLEDGMENTS

The General Secretariat for Research and Technology (GSRT) in Greece and NATO, through its Science-for-Peace program, provided financial support to this research. Sika granted the FRP materials.

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