EXPERIMENTAL STUDY ON SEISMIC REHABILITATION OF CONCRETE COLUMNS BY PRESTRESSED CARBON FIBER BELTS

Kourosh NASROLLAHZADEH NESHELI[1] and Kimiro MEGURO[2]

ABSTRACT: Six square columns with shear span to depth ratio of 2.5 were constructed to model shear deficient columns and tested under constant axial compression and reversed cyclic lateral load, simultaneously. The retrofit technique consisted of wrapping the column with carbon fiber strips/belts along the potential plastic hinge zone. By prestressing the carbon fiber belts for two of the specimens, the effects of active confinement were compared with those of passive confinement. According to test results, while the original column exhibited brittle shear failure, all retrofitted columns developed ductile flexural response.

Key Words: concrete column, carbon fiber belt, seismic retrofit, ductility, prestressing

INTRODUCTION

In order to reduce earthquake disaster, three countermeasures are recognized, as follows: Mitigation/Prevention, Preparedness/Emergency Response, and Recovery/Reconstruction Plan. Recent damaging earthquakes such as Northridge (1994), Kobe (1995), Kocaeli (1999), and Bam (2003) have clearly revealed that the highest priority for seismic hazard reduction is mitigation and structural issues. In other words, various problems generated after the quake might not have become so severe if structural damages were much less. By preventing building collapse, the number of dead and injured will be drastically reduced, and also, the costs of other activities such as rescue activities, debris removal, temporary shelter, refugee camps, and permanent residence reconstruction will be decreased. Therefore, seismic rehabilitation of the existing buildings and bridges is the key issue for earthquake hazard reduction in both developing and developed countries.

The retrofit techniques for the reinforced concrete (RC) columns, which are arguably the most critical component of many structures, are aimed at increasing the confinement for the concrete. This follows from the well-known fact that lateral confinement enhances the strength and, more importantly, ductility of RC columns. Therefore, brittle failure can be prevented and the structure will be capable of maintaining large lateral load-carrying capacity up to large story drift. This saves human lives by sustaining gravity load during earthquake and preventing collapse of buildings.

Among the existing confinement techniques for concrete columns, fiber reinforced polymer (FRP) materials are increasingly being considered for use as wraps/jacket/casings, due to their high strength-to-weight and stiffness-to-weight ratios, corrosion and fatigue-resistance, and overall durability. However, unlike steel jackets, where the confining pressure is constant after yielding the steel, the induced confinement by FRP materials is continuously increasing because of non-yielding properties of such materials. On the other hand, the steel yielding happens at relatively low amount of concrete dilation, while in the case of FRP, the high strength is not mobilized unless the lateral strain in the confined concrete is very high. In most cases in which premature local failure of fibers due to

[1] Post-Doctoral Research Fellow, The University of Tokyo / Assistant Professor, University of Tehran / Consultant, Building and Housing Research Center (BHRC)
[2] Professor, The University of Tokyo

stress concentration can be prevented, the concrete crushing occurs before the FRP sheet is fully utilized. Thereby, it becomes all too natural to think of prestressing the FRP wraps before applying it as a confining device, hoping that a more efficient use of expensive composites can be achieved. By doing so, the confinement is no longer limited to passive mechanism but includes the active one, as well.

On the other hand, reported experimental results show that similar levels of lateral pressure for similar types of concrete do not yield similar performance. Therefore, it has been suggested that concrete be referred to as a restraint-sensitive material, rather than a pressure-sensitive material. This approach pronounces the lateral stiffness of the confining device as a very important factor in enhancing the seismic performance of concrete columns. In fact, the confining pressure is dependent on the dilation characteristics of concrete, which in turn are affected by the lateral stiffness of confining device.

Based on the above-mentioned two paragraphs, a question may be raised, as follows: what would be the difference between seismic performances of two concretes which are confined by fibrous materials with two different levels of initial lateral pressure (say zero, and also, some prestressing value) while keeping the lateral stiffness of the two cases the same as each other? In other words, what is the effect of active confinement provided by prestressing of FRP in comparison with that of passive confinement? This paper is trying to shed more light on this point through an experimental program.

The idea of seismic retrofitting concrete columns by external prestressing has also been applied to high-strength steel by several researchers (Gamble et al. 1996, Yamakawa et al. 2000 and Saatcioglu 2003). Some researchers adopted lateral pre-tensioning of FRP using resin injections under pressure or using an expansive agent to apply pressure on the jacket (Priestly et al. 1995 and Saadatmanesh 1995). The method proposed by the authors adopts a different technique, since it uses a simple prefabricated steel device to manually prestress the FRP. Moreover, the technique is applied to the fibrous strips instead of continuous sheets.

OUTLINE OF EXPERIMENTAL PROGRAM

Six column specimens with the shear span to depth ratio of 2.5, which were square with dimension of 250 mm and height of 625 mm, were cast horizontally using wooden formworks and were tested as vertical cantilever columns under reversed cyclic lateral displacement and constant axial compression, simultaneously. Details of each column specimen are presented in **Table 1**, and properties of materials are listed in **Table 2**. In **Table 1**, M/VD refers to shear span-to-depth ratio, and axial force ratio is calculated as the axial stress applying on the gross sectional area of the column divided by the concrete cylindrical strength.

Table 1. Details of column specimens

Test column	M/VD	Axial force ratio	Concrete cylindrical strength (MPa)	Carbon fiber belts	Prestressing level in the carbon belts
R04M1-0	2.5	0.2	18	-	-
R04M1-C/0				2-ply@75 mm	0
R04M1-C/6				2-ply@75 mm	Fu/6
R04M2-0	2.5	0.4	18	-	-
R04M2-C/0				2-ply@75 mm	0
R04M2-C/6				2-ply@75 mm	Fu/6

Note: Fu refers to ultimate tensile strength of carbon fibers.

Table 2. Properties of materials

Type of material	Thickness (mm)/ Cross sectional area (mm^2)	Yield strength (MPa)	Tensile strength (MPa)	Ultimate strain (%)	Young modulus (GPa)
Carbon fiber sheet	0.176 mm	-	3800	1.55	240
Steel bar Φ 12	113 mm^2	380	580	20	195
Steel bar Φ 22	380 mm^2	395	625	17.5	200

The concrete cylindrical strength was considered as a low value so as to represent the old buildings constructed in developing countries. The scale factor for these columns was about 2.4 to model the low story concrete buildings which were designed in accordance with old seismic codes and were basically shear deficient columns because of poor arrangement of internal steel hoops. The columns were reinforced longitudinally with twelve deformed Φ12 bars distributed evenly around the perimeter of the square cross section. Steel hoops with diameter of 4 mm spaced at 100 mm were used as internal transverse reinforcement. **Figure 1** shows the arrangement of steel reinforcement in the test columns.

Lateral loading cycles included three successive cycles at each drift angle range of R= 0.5, 1.0, 1.5, 2.0, 2.5, 3.0%. To investigate the behavior under large deflections, the loading test continued for larger drifts of R= 4%, 5%, 6%, and etc. with one cycle for each. The loading test continued until a type of failure occurred, for instance, a large drop in lateral capacity of the column or rupture of carbon fiber strips. The specimens were divided into two groups to address two different levels of axial load. Each group consisted of a non-retrofitted column, representing as-built column, and two retrofitted versions of that, one with non-prestressed strips and another with prestressed carbon strips. With reference to **Table 1**, it can be seen that carbon fiber belts which are used for all retrofitted columns have the same number of plies, the same intervals and the same mechanical characteristics. Therefore, for all rehabilitated specimens, the lateral stiffness provided by the confining material would be quite similar and the only difference comes from different levels of initial confining pressure.

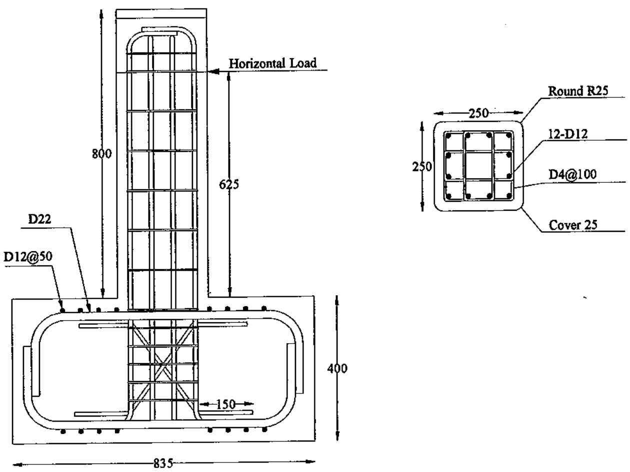

Figure 1. Arrangement of longitudinal/transverse steel bars in test columns

DETAILS OF PRESTRESSING TECHNIQUE

In this paper, an innovative technique is proposed so that carbon fiber strips are prestressed manually using a simple wrench (see **Figure 2**). The technique is as follows: a 3-cm wide strip is cut from a carbon fiber sheet and impregnated with epoxy resin along only 100 mm lap joint of both cut ends to form a loop, which is straightened to form a two-ply belt. Both ends of the two-ply belt (i.e. two-ply strip), after being straightened, look like eye-hook, through which crossbar can be put. It should be explained that crossbar refers to a piece of steel which has a threaded hole at its both ends. When the two-ply strip is wound around the column, its both ends can be clamped together by putting a couple of crossbars into the end eye-hooks, and then, passing bolt through the threaded hole of the crossbar. Then, prestressing can be given to the strips by manually screw driving the bolts of crossbars.

Before wrapping the column with carbon strips, the corners of square section had been rounded up to 2.5 cm to avoid stress concentration and were well prepared by grinding and primer so that smooth surface during prestressing procedure was provided. The prestressing was gradually increased by fastening the bolts of prestressing device, and continued up to about a sixth of ultimate strength of fibers. This value was selected for prestressing because it seemed that higher values might cause some local damage to the strip fibers considering that the strips should follow the perimeter of the square section and were in direct contact with the concrete surface. The strain in the strips was monitored by strain gauges pasted on the surface of the strips. For the level of prestressing which was used in this study, the relaxation during several days after applying the initial prestressing was negligible. The intervals of strips were selected as 7.5 cm, which was enough to accommodate the prestressing device (i.e. couplers) between two successive strips. The position of couplers was changed for every other strip, as indicated in **Figure 2**. For each specimen five strips were used, that were distributed within the bottom part of column with about height of 37.5 cm, which was equal to 1.5 times the dimension of cross section.

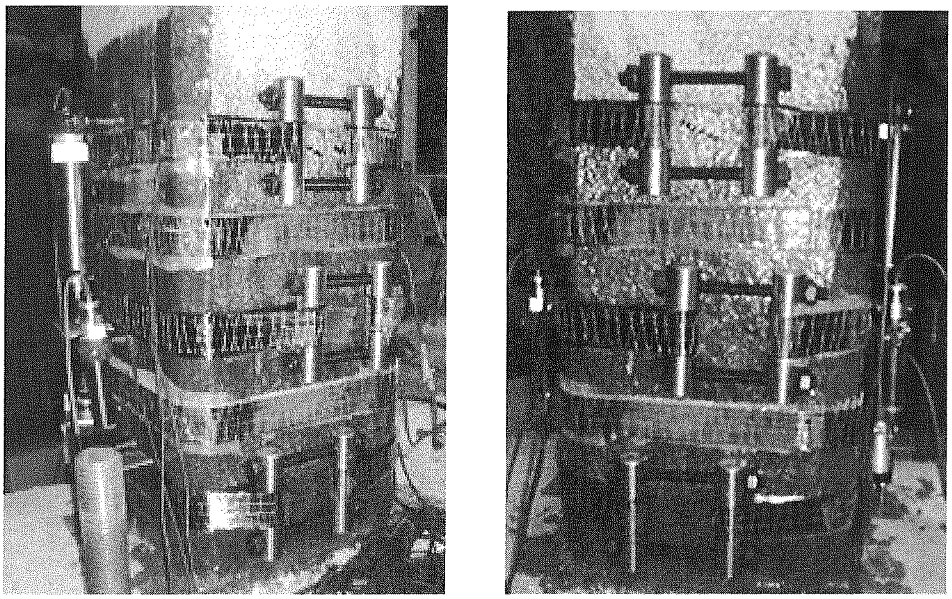

Figure 2. The prestressing technique

EXPERIMENTAL RESULTS

Lateral capacity versus drift angle

Figure 3 shows the cyclic curves for the test specimens in terms of lateral capacity versus drift angles. It should be noted that P-Δ effect was taken into account in these curves. As it can be seen from the **Figure 3**, the test column R04M1-0, which was not retrofitted, failed in a brittle shear mode due to the poor arrangement of internal transverse reinforcement, as expected. Diagonal cracks occurred at the drift angle of about R= 1.0% and propagated with the progression of the test. The concrete cover next to the base peeled off at about R= 2.5%. The lateral capacity of this column suddenly dropped when a diagonal crack widened at a drift angle of about 3%, that was a relatively low drift comparing with what was observed as the maximum drift achieved by the retrofitted versions of this test column.

The test specimen called as R04M1-C/0 was the same as the original column, i.e. R04M1-0, but was retrofitted by only five two-ply carbon fiber belts which were distributed evenly along the bottom 37.5-cm of the column. This column was retrofitted by use of non-prestressed carbon fiber belts, as can be implied from "/0" appeared in the last part of the specimen name. Thereby, the only available external confinement for this column was passive one. Comparing with the original column, R04M1-C/0 showed a much better response in terms of increased maximum lateral strength, and more importantly, the considerable deformation ductility, as indicated in **Figure 3**. The specimen could maintain its lateral capacity up to about R= 7.0% with no drop. Although R04M1-C/0 experienced the first shear crack at early stages, i.e. about R= 1.0% that was almost the same stage as for the original column R04M1-0, diagonal cracks did not propagate thanks to the induced external lateral pressure by carbon strips. In other words, the retrofitting scheme could stop the drop in the lateral capacity and provided a desirable ductile flexural response. The cyclic test continued until one of the strips (the second strip from the bottom) failed at about R= 9.0%. After this stage and at R= 10%, another strip failed and longitudinal steel bars buckled due to losing their cover concrete and lack of any confining device. Although the corners of cross section had been rounded up to 2.5 cm before wrapping the column with carbon strips, the failure of the strips initiated from the corners, indicating the concentrated lateral pressure at those critical areas of the square section.

The column R04M1-C/6 was the same as R04M1-C/0 except that its carbon belts were prestressed up to about a sixth of the ultimate strain of the carbon fibers, that was about 2500 microns (see the **Table 2**), and could be implied from "/6" which appeared in the last part of the specimen name. This prestressing level seemed to be a maximum value which could be achieved practically on site due to the fact that higher prestressing values might cause some local damage to the fibers during the prestressing procedure and might facilitate the fibers rupture during the cyclic test. Although for this particular type of carbon fiber, i.e. in the form of sheet, a sixth of ultimate strain was concluded as the maximum prestressing, the higher prestressing levels may be achievable for other types of fibrous composite materials. For instance, the authors could easily apply a prestressing level of about a third of ultimate strain for aramid fiber straps in a companion research. The fact is that softer fibrous materials, such as aramid fibers, tend to be more suitable for prestressing than carbon fibers with a higher Young's modulus. A high modulus of elasticity of fibers, on one hand, means a lower elongation for a specific prestressing level, and on the other hand, means a tendency for premature failure of fibers during the prestressing procedure. In order to transmit the tensile forces, prestressing requires the FRP systems to be locked or anchored at both ends. This would be done much more easily with the tough aramid fibers rather than with the brittle carbon fibers. It should be noted that in the innovative prestressing technique proposed in this paper, the fibrous strips are in direct contact with the concrete surface. The concrete surface was well prepared by grinding and using primer before wrapping with carbon fiber strips so as to provide a smooth surface during prestressing procedure. However, the direct contact between surface aggregates and fibers, especially at the higher prestressing levels and consequently under the resulting higher interacting pressure between concrete and fibers, may cause some local damage to the fibers. In this regard, carbon laminates behave better than carbon sheets because the fibers in the laminates have been protected by the pre-cured epoxy resin matrix. As a result, the forces are evenly transmitted into the fiber bundles. Which is why

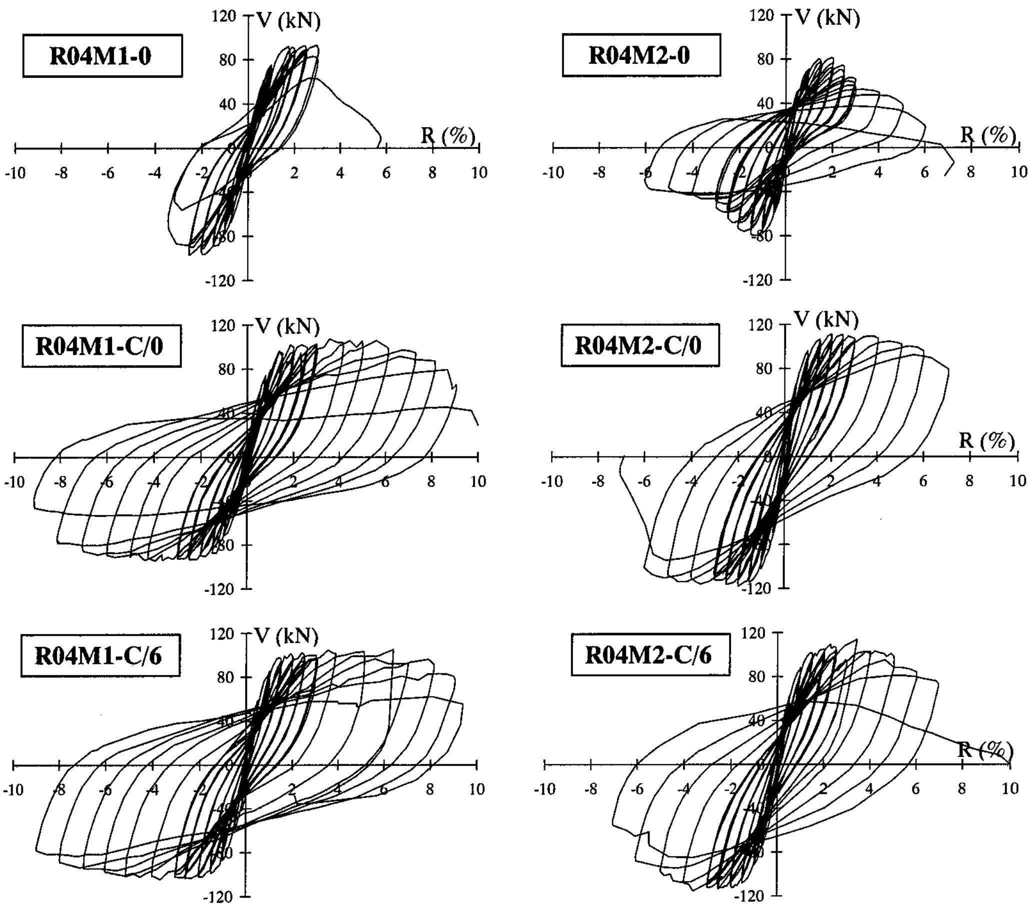

Figure 3. Measured lateral strength (V) versus drift angle (R)

the prestressed laminates are widely used for the purpose of flexural strengthening of the bridge slabs and concrete beams. It is, however, clear that for the purpose of confinement, specifically for non-circular sections, the application of such stiff laminates would not be that practical, and would not offer a considerable confining pressure.

Because of the prestressing which was introduced to the belts in R04M1-C/6, the external confinement in this test column was not limited to only passive confinement but included the active confinement as well. With reference to **Figure 3**, it can be concluded that the peak strength and deformation ductility for R04M1-C/6 did not show considerable difference from those of R04M1-C/0. In other words, an increase in the initial lateral pressure can not lead in considerable upgrading of seismic performance unless the lateral stiffness of confining device is increased.

The above-mentioned observation is important as it helps us understand the initial confining pressure can be appreciated if it is accompanied with some increase in lateral stiffness at the early stages of cyclic loading. This conclusion can be verified by some other observations. For instance, the past research carried out by the author (Nasrollahzadeh Nesheli et al. 2001) demonstrated that by locating steel angles between FRP belts and concrete surface at the corners of square section, the prestressing of belts could lead in remarkable increase in shear strength, and more importantly, in ductility of the columns. For the case of the past research with steel corner angles, the aramid straps were used, and for the reasons which mentioned earlier, higher prestressing levels could be utilized.

However, the main source of difference between the results comes from the combination of high prestressing level with some definite increase in lateral stiffness provided by the steel corner angles. It should be noted that for square sections, in which the confinement effects work mainly through the corners of the cross section by arching action, it would be good enough if the increase in lateral stiffness is provided only at the corners of cross section.

The observed damage in terms of cracks at the final stages of cyclic loading test was less in some parts in R04M1-C/6 comparing with the non-prestressed version, i.e. R04M1-C/0. This limited level of damage can be explained by the difference between the actively and passively confined concretes. Although introducing prestressing to the carbon fiber belts without increasing lateral stiffness can not prevent the initiation of cracks, it can limit widening of the cracks once they appear. On the other hand, very high level of prestressing would not necessarily limit the damage level. This is because when the cracks appear and propagate, a certain amount of pre-tensioning would be useful so as to avoid widening the cracks; however, the pre-tensioning values higher than that may cause the two adjacent sides of cracks to be overlapped. Overlapping the two sides of a crack under too much prestressing values has been reported elsewhere (Nasrollahzadeh Nesheli 2001), and can cause some sort of additional damage. In this capacity, as we are concerned with earthquake-damaged concrete columns, where the cracks propagated after the quake, external prestressing can provide a quick solution in limiting the level of further damage under aftershocks or even future quakes. Reduction of damage level in the columns during an earthquake plays a major role in decreasing the cost, time, and efforts for repair activities after the earthquake.

Next three columns were tested under higher axial force ratio of 0.4, indicated by "M2" as appeared in the specimen name. These three specimens were considered in the test plan, firstly to assess the effectiveness of the proposed retrofit technique under high compression and corresponding governing modes, and secondly to evaluate the results which were obtained based on the first three specimens with low axial force ratio and then to see whether those results can be reproduced.

With reference to **Figure 3**, R04M2-0 showed a better response comparing with R04M1-0 in terms of arriving at larger lateral deflections as a result of higher axial compression acting on R04M2-0. However, lateral load in push direction at initial stages was applied beyond the predefined drifts due to a malfunction in the loading jack. That is why the peak strength of R04M2-0, that had experienced some more initial damage, was less than that of R04M1-0. The first crack in the specimen R04M2-0 appeared horizontally at the interface of the column and the stub at R=0.5%. At R=1%, another horizontal crack occurred in the bottom part of the column at a forth of the column height and was located in the side which was perpendicular to the lateral loading direction. This horizontal crack inclined diagonally with the progression of test, indicating the mode of failure as shear cracking after flexural failure. Concrete cover started to peel at R=1.5%. Some of longitudinal bars lost their cover at R= 2.5%, and consequently buckled at R= 4%. At R=3%, where a large part of concrete cover near stub peeled off, some vertical cracks which were aligned along longitudinal bars appeared, showing bond degradation.

The retrofitted column R04M2-C/0 showed a much better response in comparison with the original column, i.e. R04M2-0, as the peak strength and deformation ductility increased a lot. From the observed crack pattern, the failure mode was judged as flexural failure. The test continued until R=7% (push direction), when one of the strips (the second one from the bottom) failed. In the pull direction of R=7%, another strip (the first one from the bottom) failed, and later, the third strip from the bottom failed. Based on these observations, it was concluded that the bottom three strips out of five strips were more effective in providing additional confinement for the plastic hinge area of the column. Thereby, it was expected that by providing just three carbon fiber belts distributed in the bottom part of the column, the increase in the seismic performance could be still appreciated. Such a low amount of consumed fibrous materials in the form of strips seemed to be an attractive option for retrofitting in developing countries as it could save consumption of the expensive composites. For the column R04M2-C/6 which was retrofitted by prestressed carbon fiber belts, the hysteretic curve was similar to the curve of R04M2-C/0 and therefore the resulted deformation ductility was almost the same. This observation, once again, shows that prestressing effects can be appreciated if it is combined with increase in lateral stiffness. The cyclic test for R04M2-C/6 continued till a belt failed at R=7%.

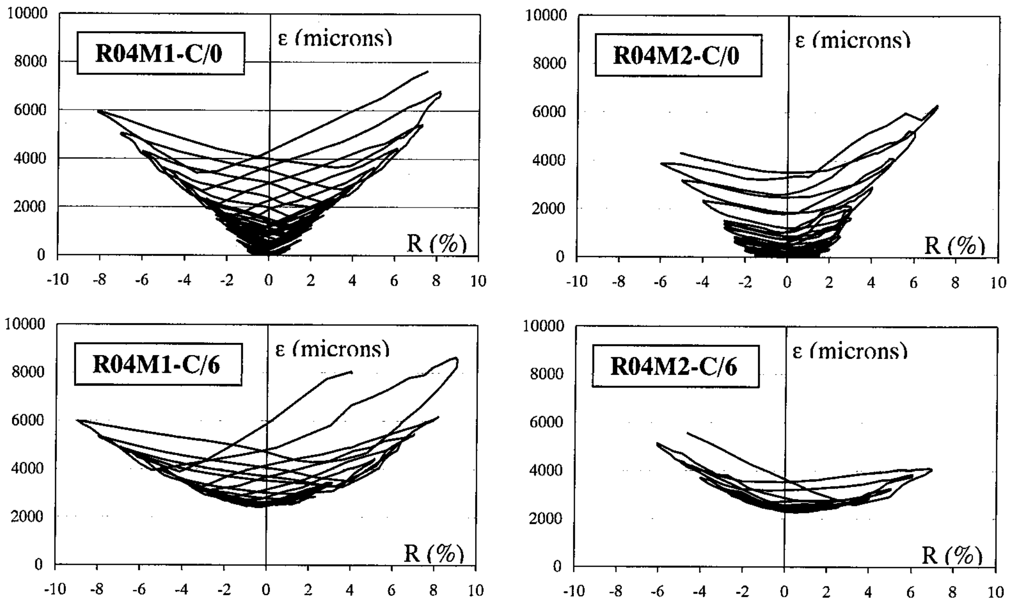

Figure 4. Measured strain (ε) variation in carbon fiber belts

Variation of strain in carbon fiber belts

Figure 4 demonstrates the strain variation in one of the carbon fiber belts located in the bottom part of the four retrofitted test columns. For the columns which were retrofitted by non-prestressed strips, lateral strain at low drift angles could not get any considerable increase. This phenomenon could be predicted as passive confinement could be mobilized only after the concrete dilation became a relatively high value. This would be considered as a problem for passive confinement which could not avoid the initiation of cracks at early stages of cyclic lateral loading, as explained earlier.

On the other hand, from **Figure 4** it is seen that the maximum lateral strain observed in the belts of R04M1-C/0 and R04M2-C/0 during cyclic loading test could not go beyond about 7000 microns. It was, however, not expected to arrive at the same value mentioned in **Table 2** as for tensile strength of fibers because in this case the strips followed the perimeter of a square section, and also, they were in direct contact with the concrete surface. But another limitation which mainly limited the increase in the strip strain was related to dilation tendency of the concrete. The strain of 0.7% as a limit for passive confinement provided by carbon fiber sheets had been already reported (BDPAJ 1999). Considering the above-mentioned observations, it became all too natural to think of introducing a prestress to the carbon fiber belts so that the initial lateral strain could get an appreciable value at the early stages of cyclic loading, and on the other hand, a better use from the whole strength capacity of composite materials could be made. However, as mentioned earlier, the increase in initial confining pressure should be combined with some increase in lateral stiffness of the confining device so as to upgrade strength and ductility of retrofitted column in a considerable amount. According to **Figure 4**, the variation range of strain for the belts prestressed up to 2500 microns (i.e. the specimens R04M1-C/6 and R04M2-C/6) became less than that of the non-prestressed belts (i.e. the specimens R04M1-C/0 and R04M2-C/0) while still the maximum values were not that different. This pronounces, once more, the dilation tendency of the confined concrete as the single most important factor in developing lateral strain in confining device. In this capacity, it seemed that prestressing value of 7000 microns could have been more realistic; however, as mentioned before, it was not practically possible to arrive at such high levels of prestressing for the carbon fiber strips used in this study.

CONCLUSIONS

Six column specimens with shear span to depth ratio of 2.5, were tested under reversed cyclic lateral deflections and constant axial compression, simultaneously. The retrofit scheme consisted of wrapping the column with carbon fiber belts/strips along the potential plastic hinge of the column. Moreover, an innovative technique for prestressing of the strips was proposed. The technique was simple, yet efficient, and could be implemented manually using a wrench. The test results demonstrated that by providing a few carbon fiber belts, which were two-ply and 30 mm wide, uniformly distributed next to the base of the cantilever column, seismic performance could be improved a lot. While the original non-retrofitted column exhibited brittle shear failure, all retrofitted columns developed ductile flexural response. However, as the cyclic curves for the actively and passively-retrofitted columns were almost the same in terms of deformation ductility and also lateral strength, it was concluded that the initial confining pressure could be appreciated if it was accompanied with some increase in lateral stiffness of the confining device. On the other hand, external prestressing could avoid widening the cracks, and therefore, could limit the level of concrete damage at final stages of cyclic loading. In this regard, external prestressing seemed to be a beneficial technique for retrofitting earthquake-damaged columns, where the cracks already appeared.

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