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# External Prestressing Concrete Columns with Fibrous Composite Belts

**by K.N. Nesheli and K. Meguro**

**Synopsis:** Five square columns were constructed to model shear-deficient columns and tested under constant axial compression and reversed cyclic lateral load, simultaneously. The retrofitting scheme consisted of wrapping the column along its end parts, i.e. around the plastic hinge area, by use of FRP in the form of three-centimeter wide belts. Both carbon and aramid/epoxy belts were used in this study. Moreover, for two of the specimens, the FRP belts were prestressed before applying the lateral load to the columns, and thereby, the effects of active confinement in addition to passive confinement were investigated. The proposed prestressing technique is an innovative method and can be applied manually. According to test results, while the original column exhibited brittle shear failure, all retrofitted columns developed ductile flexural response. Despite the different initial confining pressures, yet the same lateral stiffness of the confining device, the deformation ductility of all retrofitted columns was similar.

Keywords: AFRP; CFRP; concrete column; ductility; prestress; seismic retrofit

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## 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), Hanshin-Awaji (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 designed in accordance with inadequate old seismic codes so as to meet the requirements of current seismic design standards 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. 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 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 confinement, 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 the 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 the 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 [1, 2, 3]. Some researchers adopted lateral pre-tensioning of FRP using resin injections under pressure or using an expansive agent to apply pressure on the jacket [4, 5]. 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 FRP belts instead of continuous sheets.

## RESEARCH SIGNIFICANCE

This paper presents results of an experimental study on passive and active (prestressed) composite systems for improved seismic performance of concrete columns. Considering that the prestressed passive confinement system is relatively new, there is a need to conduct research for addressing the related design concerns of external prestressing concrete columns. Among these are, the effects of different initial confining pressure, yet the same lateral stiffness of the confining device, on deformation ductility of retrofitted columns. This issue has been investigated by conducting cyclic loading test on five square columns which were retrofitted by carbon and aramid/epoxy belts.

## OUTLINE OF EXPERIMENTAL PROGRAM

Five 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 the Note 2 of the Table 1, M/VD refers to shear span-to-depth ratio, and the axial force ratio is calculated as the axial stress applying on the gross sectional area of the column divided by the concrete cylindrical strength, and is equal to 0.2 for all specimens.

The concrete cylindrical strength was considered as a low value so as to represent the old buildings constructed in developing countries. The geometrical 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 fibrous composites. The specimens were divided into two groups to address two different types of FRP materials, i.e. carbon/epoxy belts (which were cut from a carbon fiber sheet) and aramid/epoxy belts (which were straps with twisted aramid fiber bundles). Each group consisted of two retrofitted columns, one with non-prestressed belts and another with prestressed belts. With reference to Table 2, it can be seen that the modulus of elasticity for aramid fibers is half of that for carbon fibers. On the other hand, thickness of aramid/epoxy belt is about twice that of carbon/epoxy belt. Considering that both types of the belts were three-centimeter wide and two-ply, and also, had the same intervals in all retrofitted specimens (see Table 1), it could be concluded that the lateral stiffness provided by confining material was quite similar for all four retrofitted columns. The only difference amongst the retrofitted columns comes from different levels of initial confining pressure.

## DETAILS OF PRESTRESSING TECHNIQUE

In this paper, an innovative technique is proposed so that FRP belts are prestressed manually using a simple wrench (see Figure 2). The technique is as follows: a 3-cm wide belt (either carbon or aramid/epoxy) is cut in a desirable length needed for wrapping around the column cross section, and then, is 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, after being straightened, look like eye-hook, through which crossbar can be put. It should be explained that, herein, crossbar refers to a metallic device with a threaded hole at its both ends. When the two-ply belt 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 belts by manually screw driving the bolts of crossbars. The implementation of the prescribed prestressing method is simple, yet effective in arriving at high prestressing levels, and can be applied on site without using heavy machinery.

Before wrapping the column with FRP belts, the corners of square section were rounded up to 2.5 cm to avoid stress concentration, and also, to generate corner's hoop stresses. After rounding, the corner concrete surface was well prepared by grinding and primer so as to provide smooth surface to facilitate prestressing of the belts. It should be explained that although the larger corner radius is more desirable for non-circular sections to increase the area of effectively confined concrete, the amount of concrete cover brings a limit to the amount of corner radius. Considering our specimens were scaled down by a geometrical scale factor of 2.4 and regarding the existing cover concrete, the 2.5-cm corner radius was a maximum value in practice. The prestressing was gradually increased by fastening the bolts of prestressing device, and continued up to either about a sixth of tensile strength of fibers for carbon/epoxy belts or about a third of fiber strength for aramid/epoxy belts. The strain in the belts was monitored by strain gauges pasted on the surface of the belts. 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 belts were selected as 7.5 cm, which was enough to accommodate the prestressing device (i.e. couplers) between two successive belts. The position of couplers was changed for every other belt, as indicated in Figure 2. For each specimen five belts were used, and were distributed within the bottom part of the column with about height of 37.5 cm, which was equal to 1.5 times the dimension of cross section.

For carbon/epoxy belts used in this study, the prestressing level of about a sixth of the ultimate strain 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. It should be noted that in the proposed prestressing technique, the belts are in direct contact with the concrete surface and also the prestressing is applied before the belts are impregnated with the epoxy resin. The concrete surface was well prepared by grinding and using primer before wrapping with the belts so as to provide a smooth surface during prestressing procedure. However, the direct contact between surface aggregates and belts, 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. On the other hand, for the aramid/epoxy belts (with twisted aramid fiber bundles), the higher prestressing levels may be achieved, for instance, the prestressing level of about a third of tensile strength could be easily applied in the present paper. In terms of handling the belts and applying the prestressing in the way which has been suggested in here (i.e. forming a two-ply belt from a loop, wrapping around the column, and anchoring with steel device and then prestressing manually), the softer fibrous composites, such as aramid/epoxy belts, tend to be *easier to work with* rather than carbon/epoxy belts 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 the current paper is not aimed at comparing the prestressability of aramid-based composites with that of carbon-based composites. The two different materials were utilized for arriving at different levels of initial confining pressure. Although handling aramid-based belts is easier, aramid-based composites possess high sensitivity to creep for long-term applications.

For practical applications, it is recommended that after prestressing, the belts should be protected from the environmental effects, e.g. moisture and high temperature. This can be done by using mortar layers or other encapsulating methods. Moreover, common protective measures (e.g. mortar or architectural covering) should be employed to avoid the possibility of damages to the FRP belts due to vandalism and traffic impact.

As the prestressed confinement is relatively new, the current research is intended to shed more light on some of its design-related concerns for improved seismic performance. In the next stages and for practical application, the technique needs to be improved. For instance, the prestressing metallic device, which is in direct contact with carbon/epoxy belts, may cause galvanic corrosion. This phenomenon can be avoided by using some protective measures, using other material types (instead of metallic ones) for prestressing device, or even removing the metallic device after application of prestressing and fixing two ends of the belts by paste.

## EXPERIMENTAL RESULTS

### Lateral capacity versus drift angle for carbon series

Figure 3 shows the cyclic curves in terms of lateral capacity versus drift angles for the three test specimens including the original column, that was non-retrofitted, and two columns of the carbon series. It should be noted that P-$\Delta$ 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/epoxy belts which were distributed evenly along the bottom 37.5-cm of the column. This column was retrofitted by use of non-prestressed carbon 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 diagonal 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/epoxy belts. 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 belts (the second belt from the bottom) failed at about R= 9.0%. After this stage and at R= 10%, another belt failed and longitudinal steel bars buckled because of losing their cover concrete and lack of any confining device. Although the corners of the cross section had been rounded up to 2.5 cm before wrapping the column with carbon/epoxy belts, the failure of the belts was initiated at the corners, indicating the relatively small corner radius and the concentrated lateral pressure at those critical areas of non-circular sections.

The column R04M1-C/6 was the same as R04M1-C/0 except that its carbon/epoxy 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. 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.

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. the test column R04M1-C/0. This limited level of damage can be explained by the difference between the actively and passively confined concretes. That is, active confinement 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 propagates, 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 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 earthquakes.

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.

## Lateral capacity versus drift angle for aramid series

Figure 4 shows the cyclic curves for the two columns retrofitted by aramid/epoxy belts. It should be mentioned that with the dry aramid fibers, the transfer of force from the locking device of the prestressing system into the fiber bundles is not that uniform. That means during the prestressing process, the fibers located in the center of the aramid fiber bundles exhibit greater elongation than the external fibers. For this reason, the twisted aramid fiber bundles were used in the belts for the purpose of prestressing. And as mentioned earlier, the higher prestressing values than the case of carbon series could be achieved.

For the column R04M1-A/0, which was retrofitted by non-prestressed aramid/epoxy belts, the first cracks occurred horizontally at the first cycle of R=0.5%. These cracks were placed at the column sides which were perpendicular to the direction of lateral loading, and hereafter, could be referred to as “web” sides. With the progression of the cyclic loading test and at R=1.0%, several new horizontal cracks were appeared in the web sides of the column. These horizontal cracks were distributed almost between every two successive belts, and later on, continued into another side of the column, called hereafter as “flange side” (i.e. parallel to the direction of lateral loading). Such a pattern of cracking demonstrated a desirable flexural failure mode. The horizontal cracks were also observed at the interface of the column-base in the web side, and widened at larger drift ratios. Visible damage in the form of spalling of the cover concrete was initiated from the second cycle of R=2.5%. This concrete damage was observed mainly between the base and the first two belts located next to the base. From R=3.0%, width of the horizontal cracks increased in a considerable amount. At R=9.0%, the cover concrete between the first two belts was damaged very much, and consequently, the strain in those belts increased a lot at this stage of loading test. Despite carbon series, until the end of the test, i.e. up to a large drift ratio of R=10%, none of the aramid belts failed.

Based on the observed damage, it was concluded that the bottom three belts out of five belts were more effective in providing additional confinement for the plastic hinge area of the column. Thereby, it was expected that by providing just three belts distributed in the end part of the column, the increase in the seismic performance could be still appreciated. Such a low amount of consumed fibrous composites in the form of belts seemed to be an attractive option for retrofitting in developing countries as it could save consumption of the expensive composites.

For R04M1-A/3, which was retrofitted by prestressed aramid/epoxy belts with the prestressing level of about 7000 microns, the measured cyclic curve was very similar to that of R04M1-A/0, and therefore the resulted deformation ductility was almost the same. Besides, the observed damage in the form of cracks was almost similar for the two columns at the initial stages of the test. However, the final damage in terms of spalled area of the concrete was less in the laterally prestressed column as the prestress could avoid widening of the cracks. This observation, which was similar to what was already explained for carbon series, implied while keeping the lateral stiffness of the confining device constant, the prestressing effects would be very limited. This conclusion can be verified by some other observations. For instance, the past research carried out by the authors [6, 7, 8] demonstrated that by locating steel angles between aramid/epoxy 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/epoxy belts 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. In this regard, it would be interesting to see (Figures 3 and 4) that all four columns retrofitted by either carbon or aramid/epoxy belts, and whether the belts prestressed or not, show a similar deformation ductility. It has been known, however, that passive confinement can not be appreciated in terms of enhancing flexural strength under low axial compression. The present research, through dealing with the retrofitted columns which developed flexural response, addressed, in more details, the effects of active confinement on lateral strength and, more importantly, on the deformation ductility of the retrofitted columns.

## Variation of strain in carbon and aramid/epoxy belts

Figure 5 demonstrates the strain variation in one of the belts located in the bottom part of the four retrofitted test columns. For the columns which were retrofitted by non-prestressed carbon or aramid/epoxy belts, lateral strain at low drift angles could not get a 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 (i.e. diagonal ones) at early stages of cyclic lateral loading, as explained earlier.

On the other hand, from Figure 5 it is seen that the maximum lateral strain observed in the belts of R04M1-C/0 during cyclic loading test could not go beyond about 7000 microns. Also for R04M1-A/0, except for the asymmetric variation of strain at larger drifts due to the sudden spalling of the concrete located between the two first belts in one of the web sides of the column from R=9%, the strains were less than 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 belts followed the perimeter of a square section, and also, they were in direct contact with the concrete surface. But another issue which mainly limited the increase in the belt strain was related to dilation tendency of the concrete. The strain of 0.7% as a limit for passive confinement provided by FRP sheets had been already reported [9]. Considering the above-mentioned observations, it became all too natural to think of introducing a prestress to the 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 composites 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 5, the range of strain variation for the belts prestressed up to 2500 microns (i.e. the specimen R04M1-C/6) became less than that of the non-prestressed belts (i.e. the specimen R04M1-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/epoxy belts used in this study. But instead, for the aramid/epoxy belts, the initial prestressing was selected as about 7000 microns. As can be seen from Figure 5 for R04M1-A/3, under the initial prestress of 7000 microns, the variation of strain was little during cyclic loading test, showing a suitable level for the initial lateral pressure.

## CONCLUSIONS

Five 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 and aramid/epoxy belts along the potential plastic hinge of the column. Moreover, an innovative technique for prestressing of the belts was proposed. The technique was simple, yet efficient in arriving at a desirable level for prestressing, and could be implemented manually using a wrench. The test results demonstrated that by providing a few carbon or aramid/epoxy belts, which were two-ply, 30 mm wide, and 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, it was concluded that despite the different initial confining pressures, yet the same lateral stiffness of the confining device, the deformation ductility of all retrofitted columns was similar. 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. As the prestressed confinement system is relatively new, the presented paper was aimed at surveying the effects of different initial confining pressure on seismic performance of concrete columns. However, for more detailed design information, and in the next stages, for practical application, further research is needed.

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**Table 1 – Test parameters**

| Test column | Retrofitting by external FRP belts | | |
|---|---|---|---|
| | Fibrous composite | Belt spacing | Initial prestress |
| R04M1-0 | - | - | - |
| R04M1-C/0 | 2-ply carbon/epoxy belt | 75 mm | 0 |
| R04M1-C/6 | 2-ply carbon/epoxy belt | 75 mm | Fuc/6 |
| R04M1-A/0 | 2-ply aramid/epoxy belt | 75 mm | 0 |
| R04M1-A/3 | 2-ply aramid/epoxy belt | 75 mm | Fua/3 |

Note 1: Fuc and Fua refer to tensile strength of carbon fibers and aramid fibers, respectively.
Note 2: Common details for all specimens are as follows: concrete cylindrical strength=18 MPa, axial force ratio= 0.2, shear span-to-depth ratio (M/VD) = 2.5.

**Table 2 – Properties of materials**

| Material type | 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 |
| Aramid fiber belt | 0.44 mm | - | 2900 | 2.5 | 120 |
| Steel bar $\phi$12 | 113 $mm^2$ | 380 | 580 | 20 | 195 |
| Steel bar $\phi$22 | 380 $mm^2$ | 395 | 625 | 17.5 | 200 |

Note: Both carbon and aramid/epoxy belts are 3-cm wide.

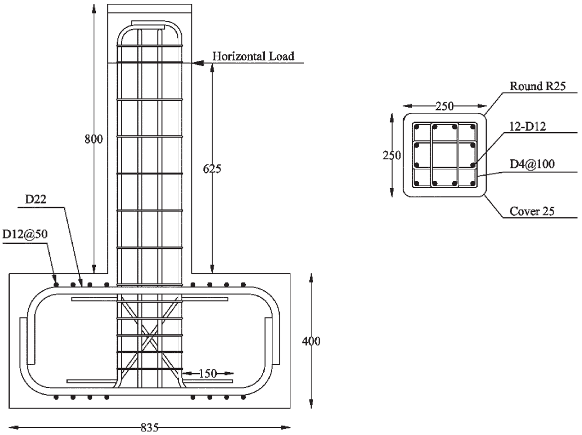

Figure 1 – Arrangement of internal steel bars in the model columns.

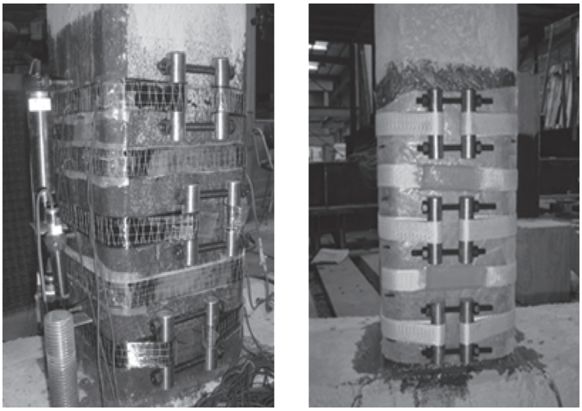

Figure 2 – Details of prestressing technique for carbon and aramid/epoxy belts.

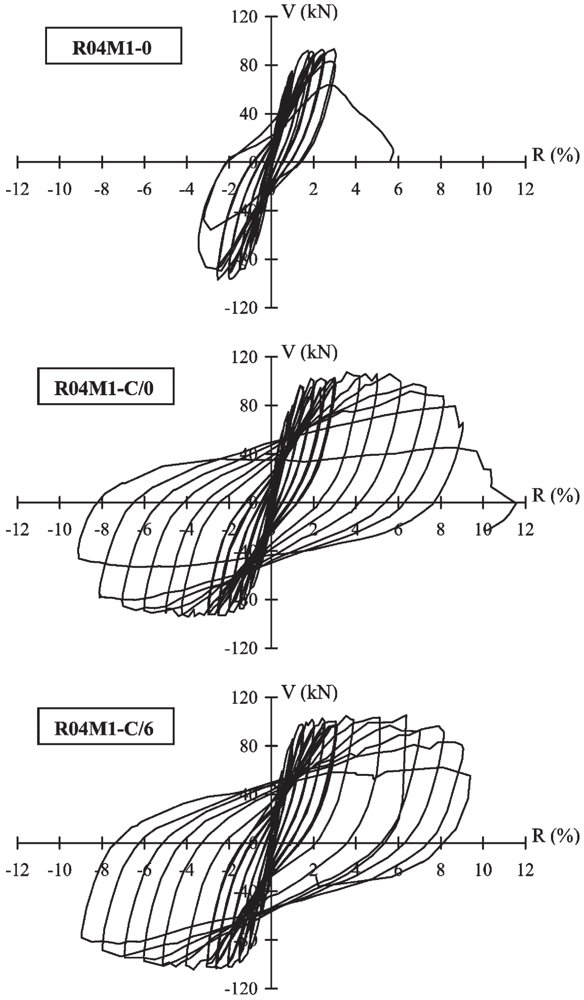

Figure 3 – Measured lateral strength (V) versus drift angle (R) for carbon series.

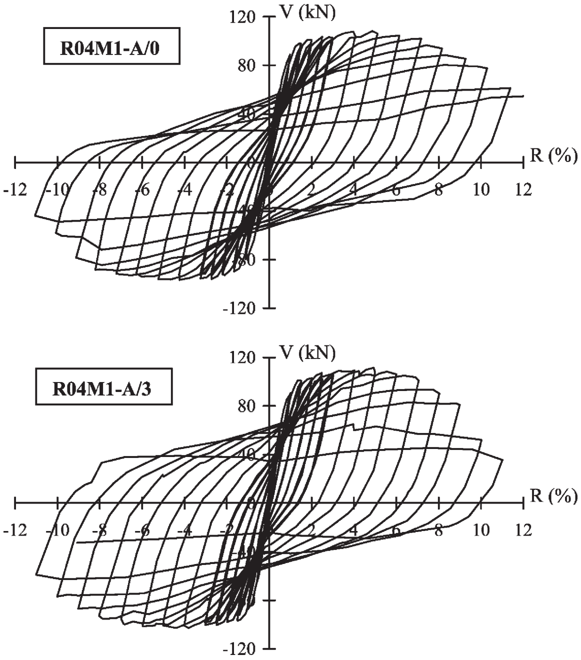

Figure 4 – Measured lateral strength (V) versus drift angle (R) for aramid series.

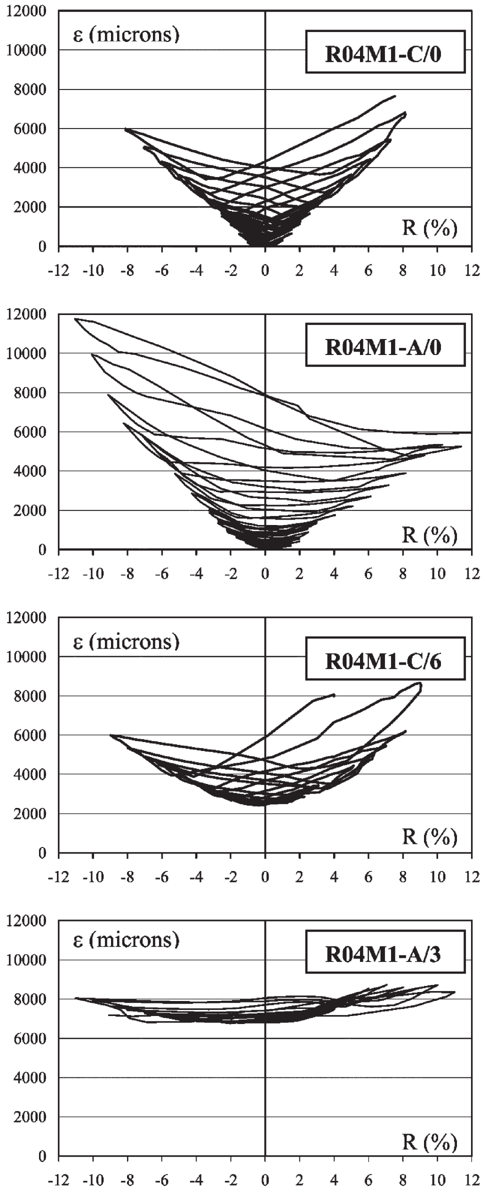

Figure 5 – Measured strain (ε) variation in carbon and aramid/epoxy belts.