



SEISMIC RETROFITTING OF EARTHQUAKE-DAMAGED CONCRETE COLUMNS BY LATERAL PRE-TENSIONING OF FRP BELTS

K. Nasrollahzadeh Nesheli¹ and K. Meguro²

ABSTRACT

Five square columns with two shear span-to-depth ratios of 1.5 and 2.5 were constructed to model half-scale shear-deficient columns and tested under constant axial compression and reversed cyclic lateral load, simultaneously. After being tested, two of the columns with different shear span-to-depth ratios were subjected to a certain level of damage in terms of crack pattern and also drop in the lateral capacity. Then, these earthquake-damaged columns were retrofitted by pre-tensioned carbon or aramid FRP belts, and once more, were tested under cyclic lateral loading and constant axial compression. As the confining devices, i.e. FRP belts, were pre-tensioned before applying the lateral load to the columns, both active and passive confinements were utilized. As an instant result of pre-tensioning, the initial cracks of the damaged column were closed. It should be noted that this retrofitting procedure is quick as it is carried out without any repair measures such as removal of damaged concrete or crack injection and so on. Moreover, the prestressing technique is an innovative method and can be applied manually using a simple wrench. According to test results, the lateral capacity of the original columns dropped suddenly, showing a brittle shear failure. When the damaged columns were retrofitted by pre-tensioned FRP belts, the lateral strength could be restored and the drop in shear capacity could be prevented up to large drifts, indicating a better seismic performance.

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) and Hanshin-Awaji (1995) 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

¹JSPS Post-Doctoral Research Fellow, University of Tokyo, Tokyo 153-8505, Japan & Assistant Professor, Dept. of Civil Engineering, Faculty of Engineering, University of Tehran, Iran

²Professor, Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

activities, debris removal, temporary shelter, refugee camps, and permanent residence reconstruction will be decreased. Therefore, seismic retrofitting of the existing buildings and bridges designed in accordance with inadequate old seismic codes is the key issue for earthquake hazard reduction in both developing and developed countries.

While retrofitting is most likely referred to the non-damaged existing buildings, there is also a need to upgrade the structures which are partially damaged following an earthquake. It goes without saying that rehabilitation of earthquake-damaged buildings can be a case only if the level of damage is not that high. In this capacity, the objective of rehabilitation can be either a permanent solution for enhancing the seismic performance of damaged buildings up to the desirable level of performance or as a temporary solution to avoid further damages to the earthquake-affected structures during the possible aftershocks or even upcoming quakes.

In this regard, an observation from the 1997 Kagoshima Ken-Hokuseibu earthquake can be mentioned as a good example. In this particular region of Japan, two different earthquakes occurred within just one and half months. The first earthquake with the magnitude of 6.5 and the epicenter depth of 12 km hit the region on March 26th in 1997 and the second earthquake with the magnitude of 6.3 and the epicenter depth of 9 km occurred on May 13th in 1997. It should be noted that the two earthquakes were independent (i.e. not aftershocks). According to a survey conducted after these two earthquakes for the performance of high school concrete buildings in the region, it was observed that several concrete columns were damaged during the first earthquake. Right after the first quake, the authorities of a high school provided rehabilitation measures by using steel bracing and so on, but the authorities of another damaged high school in the same region did not apply any retrofitting within one and half month after the event as they did not expect the second quake might come so soon. The difference could be seen when the second earthquake happened; the damages to the former building were very much limited, however, the damage in the latter was very high. Such an observation revealed the need for developing some sort of retrofitting techniques which firstly can deal with the earthquake-damaged columns rather than sound concrete, and secondly can be applied as quickly and easily as possible on site.

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. 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. In this paper, the FRP is used as belts (instead of conventional continuous sheets) for retrofitting of earthquake-damaged square columns. Moreover, the FRP belts are prestressed so as to utilize active confinement as well as passive confinement. Although the idea of seismic retrofitting of concrete columns by lateral pre-tensioning has been applied to high-strength steel by several researchers (Gamble 1996, Yamakawa 2000, and Saatcioglu 2003), the prestressed confinement FRP system is relatively new. Such an application is particularly useful for the earthquake-damaged columns, where the open cracks can be closed by the initial lateral pressure provided by prestressed FRP belts, and is being investigated in the current paper.

Details of Retrofitting Technique

An innovative technique is proposed in order that FRP belts are prestressed manually using a simple wrench (see Fig. 1). The technique is as follows: a carbon or aramid fiber belt 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. Each end of the straightened two-ply belt looks like an eye-hook, through which a steel rod (with threaded holes at its both ends) can be passed. When the two-ply belt is wound around the column, its both ends can be clamped together by putting a couple of rods into the end eyes of the belt, and then, passing bolts through the rod holes. Then, prestressing can be given to the belts by manually screw driving the bolts. Herein, prestressing is applied before the belts are impregnated with the epoxy resin (except for the 100-mm lap joint), and thereby, dry fibers are wrapped around the square section. Although dry fibers are used during prestressing procedure, it is recommended to impregnate the belts (after pre-tensioning) for long-term applications.

As shown in Fig. 1, for the specimens retrofitted by carbon fiber belts, the corners of square section were rounded up to 25 mm 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 25-mm corner radius was a maximum value in practice. On the other hand, for the specimens retrofitted by aramid fiber belts, the corners were not rounded but instead steel angles with the leg width and length of 50 mm and external radius of 20 mm were located at the section corners. The role of steel angles is to distribute corner's confining pressure and also provide frictionless surface during pre-tensioning procedure. Moreover, by using corner angles, there is no further need to prepare concrete surface as there is no direct contact between the belts and column.



Figure 1. Pre-tensioning technique for carbon (left) and aramid FRP belts (right).

The prestressing was gradually increased by fastening the bolts, and meantime, the fibers strain was monitored by strain gauges pasted on the surface of the belts. For the carbon fiber belts used in this study, the prestressing level equal to about a sixth of the tensile strength of fibers 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 damages to the dry fibers which were in direct contact with concrete surface. On the other hand, for aramid fiber belts, the higher prestressing levels equal to a third of fiber strength might be achieved as there was a gap between the belts and concrete surface. It should be explained that, however, the current paper is not aimed at comparing the prestressability of aramid-based composites with that of carbon-based composites.

Outline of Experimental Program

Table 1 shows the test parameters for five square columns with the dimension of 250 mm and two shear span-to-depth ratios of 1.5 and 2.5. The axial force ratio (i.e. the axial stress applying on the gross sectional area of the column divided by the concrete cylindrical strength) is equal to 0.2 for all specimens. The geometrical scale factor for these columns is about 2.4 to model the low-rise concrete buildings which were designed in accordance with old seismic codes and were basically shear deficient columns because of poor arrangement of internal steel ties. The column with shear span-to-depth ratio of 2.5 was retrofitted by use of three carbon fiber belts distributed evenly along height of 1.5D next to the base of the cantilever column (where D is the dimension of cross section, i.e. 250 mm). The columns with shorter shear span-to-depth ratio of 1.5 were retrofitted using the pre-tensioned aramid fiber belts, which were evenly distributed along total height of the columns and were located on steel angles at the corners of cross section (as indicated in Fig. 1).

Table 1. Test parameters.

Test column	RM1-0	ERM1-C75/6	RM-0	RM-A200/3	ERM-A65/3
Description of specimen	Non retrofit	Initially damaged & retrofitted	Non retrofit	Initially sound & retrofitted	Initially damaged & retrofitted
Shear span-to-depth ratio	2.5		1.5		
Concrete strength (MPa)	25		26	23	
Internal steel reinforcement	Ties	2 Φ 3.7 @ 100		Φ 3.7 @ 105	
	Longitudinal bars	12 Φ 12		12 Φ 13	
Retrofitting by FRP belts	Fiber type	-	carbon	-	aramid
	Belt interval	-	2-ply @75	-	2-ply @200
	Initial pre-tensioning	-	Fuc/6*	-	Fua/3*

*Fuc and Fua refer to tensile strength of carbon fibers and aramid fibers, respectively.

Note: For all columns, cross section is square (D = 250 mm), and the axial force ratio is 0.2.

Table 2. Properties of materials.

Type	Thickness per ply (mm)	Width (mm)	Cross section area (mm ²)	Tensile strength for fibers (Yield strength for steel) (MPa)	Young modulus (GPa)
Carbon fiber belt	0.176	30	5.28	3800	240
Aramid fiber belt	0.612	17	10.4	2000	120
Steel bar Φ 13	-	-	127	359	200
Steel bar Φ 12	-	-	113	380	195
Steel tie Φ 3.7	-	-	11	333	195

Table 2 lists the properties of materials. The columns were tested under constant axial compression and reversed cyclic lateral displacements. The lateral loading cycles included three successive cycles at each drift ratio range of $R= 0.5, 1.0, \text{ and } 1.5 \%$. In addition, the lateral loading continued for larger drift ratios of $R= 2.0, 2.5, 3.0, 4.0, \text{ and } 5.0 \%$, where the number of applied cycles depended on the level of observed damage, and also on the purpose of the test as will be explained in the next section.

Experimental Results

The non-retrofitted test column RM1-0 was tested under the drift ratios of $R= 0.5, 1.0, 1.5 \%$ (with three cycles for each), and $2.0, 2.5, 3.0 \%$ (with one cycle for each). Then the lateral displacement increased up to $R= 4.0\%$ when the shear capacity suddenly dropped, and at about $R= 4.5\%$ the drop in lateral strength of the column became more than half of the peak strength (see Fig. 2). Moreover, diagonal cracks appeared in the column face, showing a brittle shear failure. Hereafter, this earthquake-damaged column was about to be rehabilitated by pre-tensioned carbon fiber belts and re-tested under constant axial compression and reversed cyclic lateral displacements. But before re-testing, the corner concretes, which were peeled off during the first stage of the cyclic loading test, were repaired by using cement mortar so as to provide a smooth surface for placing the belts. This repair operation was very simple and quick as it was not accompanied with replacement of damaged concrete and also was not involved with crack injection and so on. In the next stage, only three carbon fiber belts with the intervals of 75 mm were wrapped around the column and distributed next to the base of the cantilever column. The lateral pre-tensioning strain equal to 2500 microns (i.e. a sixth of carbon fiber ultimate strain) was applied to the carbon fiber belts. As an instant result of the lateral pre-tensioning, the cracks, which remained open in the damaged column, were getting closed. Hereinafter, the retrofitted column was re-named as ERM1-C75/6 and was ready to be tested. It should be explained that “ER” in the name of specimen refers to emergency retrofit or rehabilitation to represent the fact that the above-mentioned retrofitting measure was not accompanied with the conventional repair operations which might take time and labor.

The rehabilitated column ERM1-C75/6 was tested under constant axial compression and cyclic drift ratios of $R= 0.5, 1.0, 1.5, 2.0\%$ (three cycles for each). Then the drift ratio was increased up to $R= 3.0\%$ where the lateral capacity dropped to about half of the peak strength. Fig. 2 shows the response of the column in terms of shear strength versus drift angle.

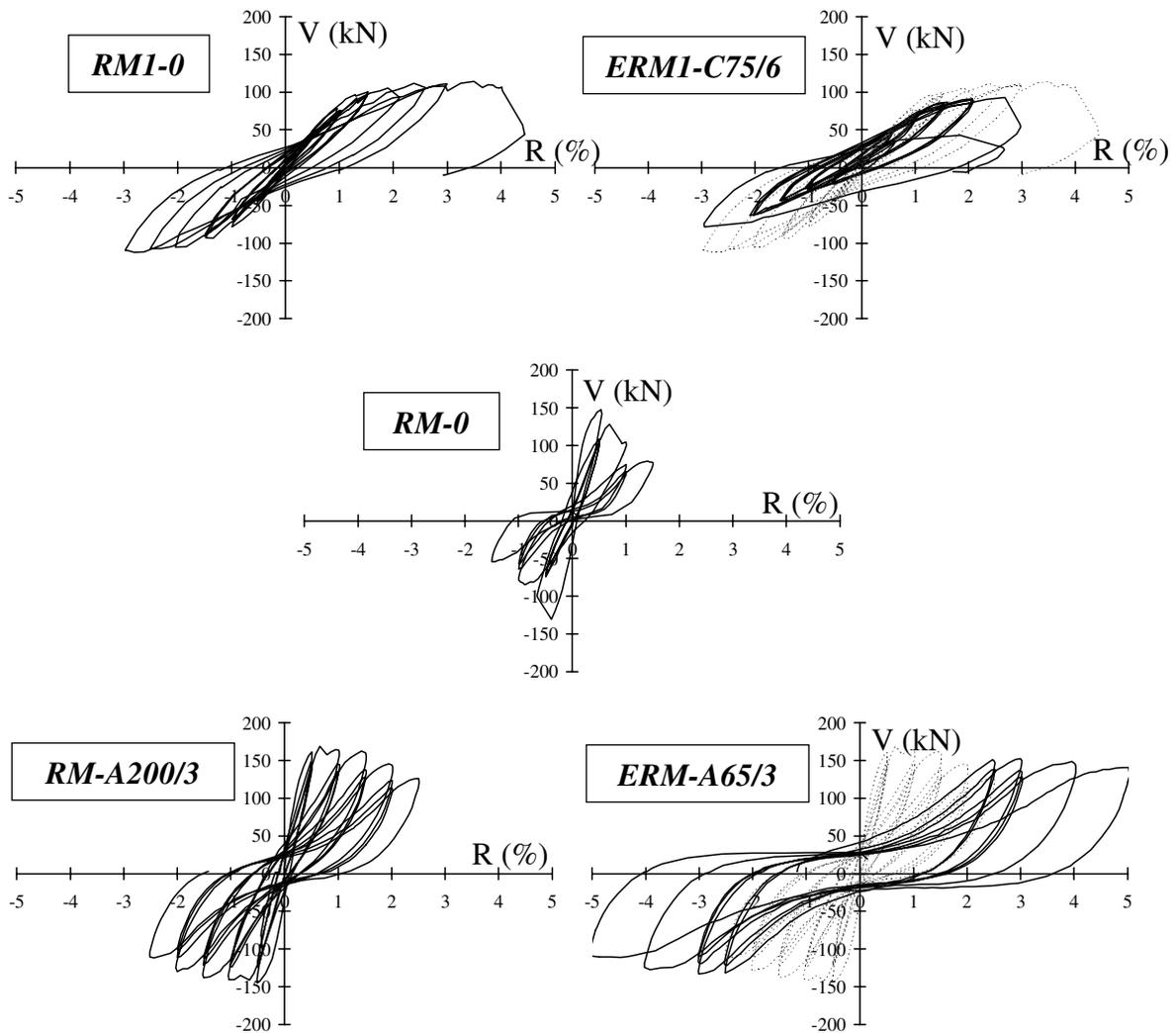


Figure 2. Measured lateral strength (V) versus drift angle (R) for test columns.

The dotted line in Fig. 2 demonstrates the response of the original column. As it can be seen, the initial damage existing in the column, however, affected the shear strength of ERM1-C75/6 so that it could not arrive at that of RM1-0. Although the initial damage in ERM1-C75/6 was relatively high, the rehabilitated column could maintain its shear capacity up to drift ratio of about $R=2.5\%$, indicating the efficiency of the proposed retrofitting measure for stopping the drop in the shear capacity of the damaged column.

The column RM-0, which was not retrofitted, failed in a brittle shear manner because of poor transverse reinforcement. According to Fig. 2, the lateral capacity of this column dropped suddenly during the cyclic loading test. Moreover, relatively large amount of diagonal cracks appeared at a low drift ratio of $R=1.5\%$.

The specimen RM-A200/3 was retrofitted with two-ply aramid fiber belts with the

intervals of 200 mm, while the end belt was located at 75 mm from the base of the column. Before applying axial load and lateral displacements to the column, the belts were pre-tensioned up to about a third of tensile strength of aramid fibers. Although the number of added belts to the column RM-A200/3, and consequently, the amount of retrofitting were not that much, the response of RM-A200/3 was improved in comparison with the non-retrofitted column, i.e. RM-0 (see Fig. 2). However, RM-A200/3 could not develop its flexural strength and finally failed in a shear mode due to the poor retrofit. Moreover, it was observed that the first shear crack occurred at $R=0.4\%$, and then, successive shear cracks happened with increasing the drift angle. At $R=2.0\%$ some parts of cover concrete peeled off because of joining the shear cracks to each other. During the cyclic loading test, hoops yielded but longitudinal bars did not yield, showing a shear failure mode. The lateral loading program included three cycles at each drift ratio range of $R=0.5, 1.0, 1.5, 2.0\%$. Then, the drift angle increased up to 2.5% (in push direction), in which the lateral load capacity dropped by more than 20% of the experimental peak shear strength. During the first cycle of $R=2.5\%$, and at the time that the lateral force became zero in the pull direction, the application of cyclic lateral displacements stopped. While keeping the axial force on the column, several new aramid fiber belts were added between the previous belts of the damaged column so that the intervals of the new arrangement of whole belts became as 65 mm. Then, the newly added belts were prestressed up to about a third of tensile strength of aramid fibers. Hereafter, the column was designated as ERM-A65/3 and its lateral loading test continued from the point that the test of RM-A200/3 had been stopped before. That means, the loading test of ERM-A65/3 started with some residual lateral displacements and also initial damage. It should be noted that during the whole procedure of applying new belts to the damaged column and furthermore during the test, the axial compression was kept as a constant value (as indicated in Table 1).

The loading cycles for ERM-A65/3 contained about two successive cycles at $R=2.5\%$, and three cycles at $R=3.0\%$ and one cycle at $R=4.0\%$ and 5.0% . Fig. 2 presents V-R curve for ERM-A65/3 as well as for RM-A200/3 (by the dotted line). In order to assess the efficiency of the retrofit procedure for the damaged column, the responses of the two columns RM-A200/3 and ERM-A65/3 are compared as follows: in RM-A200/3 and at $R=2.5\%$ (the first cycle in the push direction), shear capacity reached 126.1 kN, which was less than 80% of the experimental peak value of RM-A200/3, that is 169.1 kN. After emergency retrofit (i.e. the column ERM-A65/3), the lateral capacity increased up to 152.6 kN at $R=3.0\%$. This lateral capacity decreased to 141 kN at $R=5.0\%$ (push direction), that means the amount of decrease was equal to a small value of about 7% . Therefore, the procedure of emergency retrofitting could stop decreasing in the lateral capacity and could restore the lateral strength of the earthquake-damaged concrete column. However, the emergency retrofitted column ERM-A65/3 could not indicate its flexural strength because of the initial damage previously existing in the column; but the seismic response of the emergency-retrofitted earthquake-damaged column was definitely improved with respect to maintaining its lateral strength under large drifts.

It should be explained what we mean from “emergency retrofit” (as described above) is a technique to quickly retrofitting the earthquake-damaged concrete column. The main characteristic of this sort of retrofit is that the technique deals with the initially damaged column rather than sound concrete, and more importantly, the damaged and spalled concretes are not replaced by new concrete. From this standpoint, the emergency retrofit is described as a quick

technique, because the retrofit (or additional retrofit) would be applied without any repair operation, which might take time and labor. However, it should be noticed that the efficiency of emergency retrofit depends on the amount of initial damage existing in the column. In other words, in the case of severe damage, some repair operations such as replacing the damaged concrete with fresh concrete as well as crack injection are needed before applying retrofit to the column. For instance, in the case of ERM-A65/3, the initial damage was limited by the initial retrofit which was provided for RM-A200/3, and thereby, the emergency retrofit could be efficient for that level of damage which was caused by 20% drop in the lateral capacity of the shear-failed column. However, estimating different levels of damage is beyond the scope of this paper. On the other hand, what we expect from an emergency retrofit measure is not necessarily to develop a ductile flexural response for the earthquake-damaged column as there is no repair operation. Instead, what is looked for is to develop a technique to quickly bring the lateral capacity of damaged column into a stable condition in terms of maintaining the available shear strength up to relatively large drift ratios. Such retrofitting techniques would be of much use in high-risk seismic zones and would provide an attractive option for rehabilitation of the earthquake-damaged columns when the speed of applying a retrofit method is the first priority. While such an emergency retrofit seems to be more appropriate to be referred to as a temporary solution rather than a permanent one, it can provide an effective way so as to sustain the gravity loading capacity of the columns during aftershocks or even subsequent earthquakes.

Fig. 3 demonstrates the strain variations in the carbon or aramid fiber belts during the cyclic loading test. For the column ERM1-C75/6, in which the carbon fiber belts were prestressed up to about 2500 microns, the belt strain increased with progression of the test, as expected due to the lateral expansion of the concrete. However, the maximum lateral strain in the belts could not go beyond about 7000 microns till the end of the test. This limit for the lateral confinement provided by the carbon fiber belts pronounces the limitation of the dilation tendency of the concrete. Fig. 3 also shows the strain variation in aramid fiber belts for RM-A200/3 and ERM-A65/3 (i.e. before and after applying emergency retrofit). It can be seen that there was a sudden drop in the belt strain right after emergency retrofit was applied. This is because when the new prestressed aramid fiber belts were added to the column RM-A200/3, which had damaged during the first stage of the test, some of the existing cracks closed as an instant result of the newly introduced active confinement, and thereby, the strain in the previous aramid fiber belts suddenly dropped right after emergency retrofit. In addition, similar to ERM1-C75/6, there is a limit of 7000 microns for confinement strain in the aramid fiber belts.

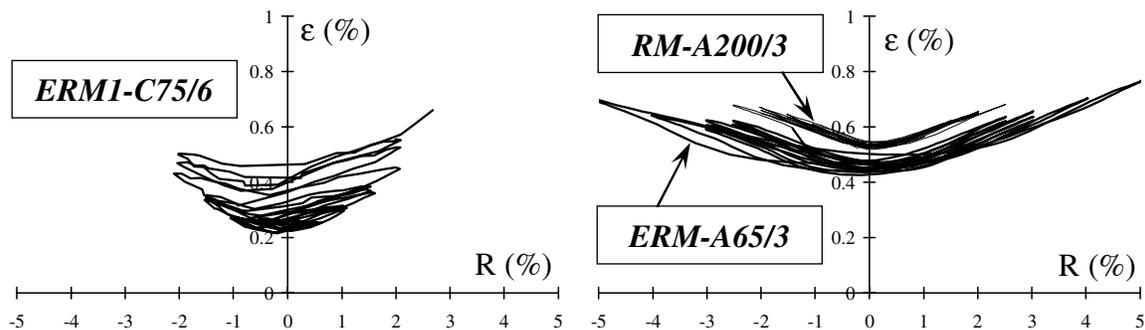


Figure 3. Measured strain (ϵ) in the FRP belts versus drift angle (R).

Conclusions

This paper presented experimental results for retrofitting of earthquake-damaged square concrete columns by use of lateral pre-tensioning of FRP belts. As in the proposed procedure neither the damaged concrete was replaced by new concrete nor any repair operation such as crack injection was employed, the technique was quick in application and was described as an emergency retrofit. One of the test columns with shear span-to-depth ratio of 2.5 was tested under constant axial compression and reversed cyclic lateral displacements up to drift ratio of 4% where its lateral capacity suddenly dropped. Thereafter, the damaged part of the column (i.e. the part next to the column base) was wrapped by a few prestressed carbon fiber belts. Another test column with shear span-to-depth ratio of 1.5 which was partially retrofitted was tested up to drift ratio of 2.5% where the lateral capacity dropped by 20% and some damages in the form of cracks appeared, and then once again, was retrofitted by additional prestressed aramid fiber belts. A summary of the test results for the retrofitted damaged columns is as follows:

- The so-called emergency retrofit measure could restore the lateral strength of the earthquake-damaged concrete column and could maintain its shear capacity up to large drift ratios. Moreover, because of lateral pre-tensioning, the initial cracks, which had appeared in the damaged column and remained open at the time of retrofitting, were instantly closed or their width was reduced. The efficiency of the proposed measure is, however, dependent on the level of the existing damage. In other words, in the case of severe damage some repair operations such as crack injection are needed before retrofitting.
- The maximum measured lateral strain in the FRP belts was about 7000 microns during the cyclic loading test. This strain level, which is due to a limit in dilation tendency of the concrete, is considered as a limit for confinement provided by the FRP belts.

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