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AN EXPERIMENTAL STUDY ON THE BEHAVIOUR OF REINFORCED CONCRETE COLUMNS USING FRP MATERIAL

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SUMMARY

An experimental study was conducted on the determination of strengthening reinforced concrete columns using FRP material. Four reinforced concrete cantilever columns of 200x400x1610 mm dimensions, representing the old construction practice, were tested. One lap-spliced and one continuous longitudinally reinforced as build control columns, and their strengthened columns were tested under constant axial load and reversed cyclic lateral load. FRP sheets were wrapped around the potential hinging zones. Test results showed that lap-splicing dominates the behaviour where no difference in force-deformation relationship between control and strengthened columns were observed. However, the columns with continuous longitudinal reinforcement showed significant increase in ductility.

INTRODUCTION

Repair, rehabilitation and strengthening of existing structures have become a major part of construction activity in the World. Although many traditional methods can be adopted, the application of fiber reinforced plastic (FRP) sheets, impregnated with epoxy resin, to reinforced concrete structures for strengthening purposes has received considerable attention due to its high-strength, light weight, applicability, and resistance against corrosion.

Existing reinforced concrete frame buildings often lack adequate seismic resistance due to deficiencies in columns, such as inadequate lap-splice in the longitudinal reinforcement, lack of confinement in potential plastic hinge regions, and inadequate shear strength. For ease of construction, longitudinal bars of older reinforced concrete building columns were typically spliced just above the floor level at potential plastic hinge region and the lap length being only 20 times the bar diameter or even less, and inadequately confined by transverse reinforcement. As a result, they usually experience splice or bond failure before the bars develop yield strength [1]

In the study of Sheikh, circular columns with 356-mm-diameter were subjected to a constant axial load and reversed cyclic lateral load. The main variables investigated were axial load levels, spacing of spirals,

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thickness and type of the FRP material. The test specimens were divided into three groups. The first group of specimens, which had four columns, had the traditional longitudinal and spiral reinforcements. The second group, including six columns, was strengthened with carbon fiber-reinforced polymers (CFRP), or glass fiber-reinforced polymers (GFRP). In the third group, including two columns, columns were damaged to a certain extent, repaired with fiber-reinforced polymers under axial load, and then tested. It was observed from the test results that ductility, energy dissipation capacity and the strength of the columns were increased in the strengthened columns. It was concluded that the FRP composites are very effective for the rehabilitation of the damaged columns [2].

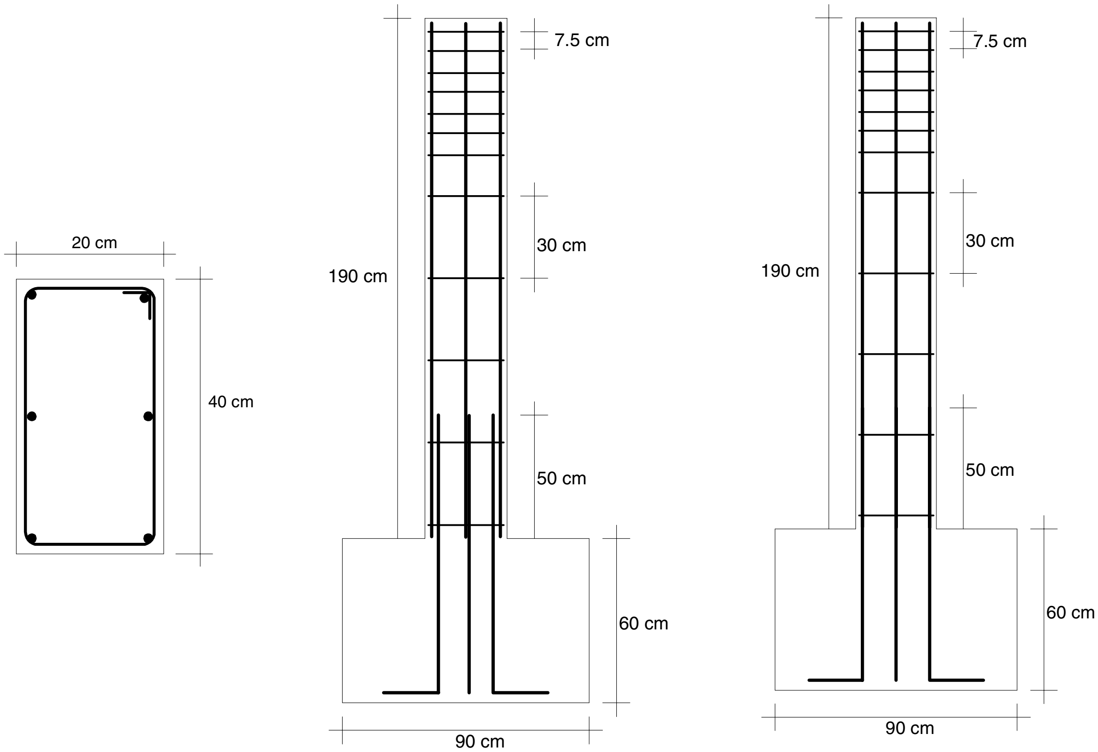
Saadatmanesh conducted a series of tests on four columns in order to observe the effects of type of columns and FRP wraps. Two circular and two rectangular columns were prepared and tested until failure under reversed cyclic loading. The columns were repaired with prefabricated FRP wraps, and retested under similar loading. The tests results indicated that, all repaired columns performed extremely well under the simulated earthquake loading. The repaired columns exhibited relatively larger lateral displacement at low load levels compared to the control column specimen. In all repaired specimens the rate of stiffness degradation under large reversed cyclic loading was lower than that of the corresponding original columns [3].

EXPERIMENTAL STUDY

Specimens

Four full-scale rectangular reinforced concrete columns were designed and constructed, all having the same size and reinforcement details, representing the old practice in most residential buildings. The cross-sectional dimension of the specimen was 200x400 mm. and the height of the column was 190 cm. The compressive strength of the concrete was determined around 16 MPa. The columns were prepared in two groups and in each group had two specimens that were cast as lap-spliced and as continuously longitudinal reinforcement. The lap length was selected to be 50 cm, corresponding to 35 times the re-bar diameter. Figure 1 illustrates the reinforcement details for lapped and continuous longitudinal reinforced columns.

Here, a standard 3-meter storey height representing full-length of the column is simulated in a single curvature, as cantilever, i.e. corresponding to half of the length of the storey height. 6- 14-mm-diamater plane re-bars were used as longitudinal bars and 8-mm-diamater plane stirrup re-bars at 300 mm on centres were used as transverse reinforcement. The hook detailing of the stirrups was made with 90°-angles. In order to prevent any damage during the testing, in close proximity to the tip of the column, where the lateral load is applied, the spacing of the transverse reinforcement was decreased to 75 mm, providing proper confinement.



(a) (b)

Figure 1. Details of test specimens

From each group, one specimen was tested as a control specimen and the other one is strengthened with CFRP sheets. Properties of the reinforcements were given in Table 1.

Table 1. Mechanical properties of plain re-bars.

	8-mm-diamater re-bar	14-mm-diamater re-bar
Area	50.27 mm^2	153.94 mm^2
f_y	360 Mpa	319 MPa
f_u	490 Mpa	450 MPa
ε_r	31 per cent	33 per cent

One column from each group of specimen was strengthened. Figure 2 shows picture of column strengthened with FRP. The epoxy was prepared by mixing two components as suggested by the manufacturer and the fiber sheet was on to the column surface accordingly. The 500-mm-part of the column specimens from the level of foundation were wrapped with 3 and 4 layers of FRP sheets around the continuous and lap spliced columns, respectively.

Figure 2. Application of CFRP sheets onto column surface

Testing

The columns were tested under constant axial load and reversed cyclic lateral load. Lateral load was applied by computer-controlled dynamic actuator, which has a capacity of 250 kN. At each displacement level, three cycles were applied. Figure 3 illustrates the loading history chart. As seen from the chart, after the drift level of 2 and 3 percent, some sub levels were repeated in order to compare the stiffness degradation between the same drift ratios. An axial load was applied by using manually controlled hydraulic ram, which has a capacity of 600 kN. The constant axial load was transferred to the column by means of a steel axial loading frame, which was positioned on top of the column, and the ram was placed inside the frame. Four pre-stressed cables, two on each side, were fixed from the top of the frame and connected to the bottom of the column level to a one-directional swivel system. A schematic drawing of test set-up is shown in Figure 4.

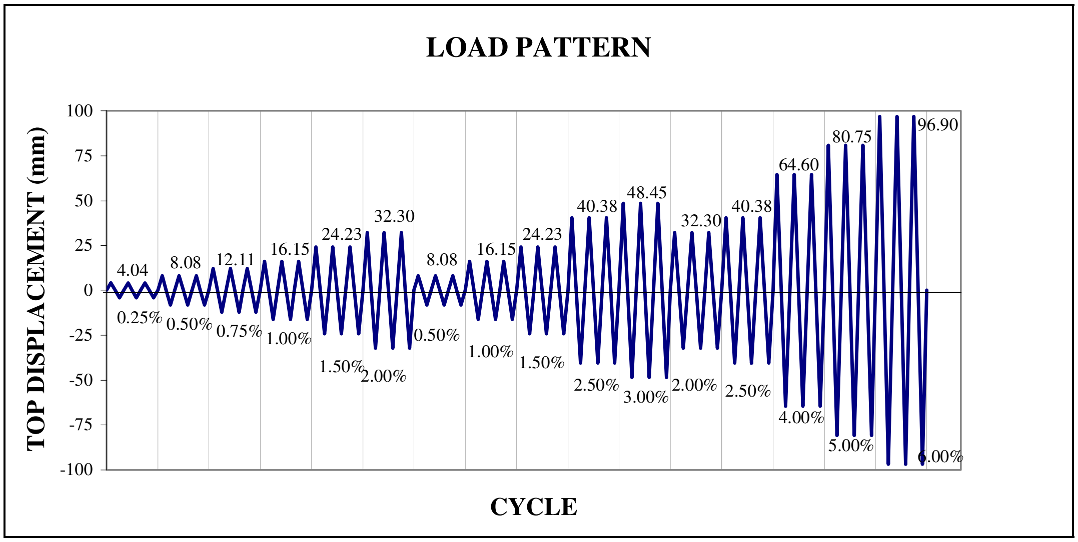


Figure 3. Loading pattern

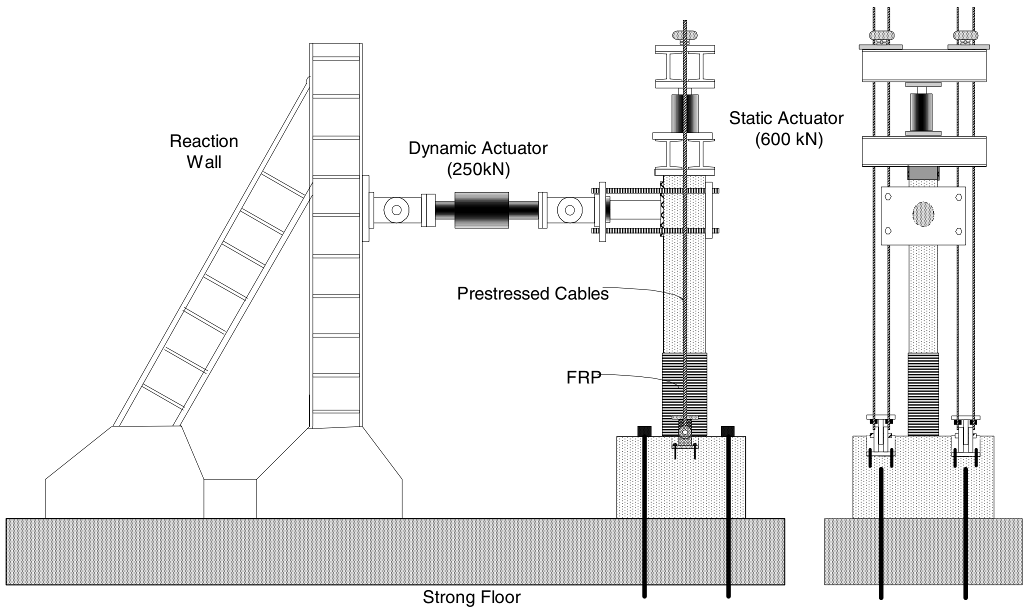


Figure 4. The test set-up

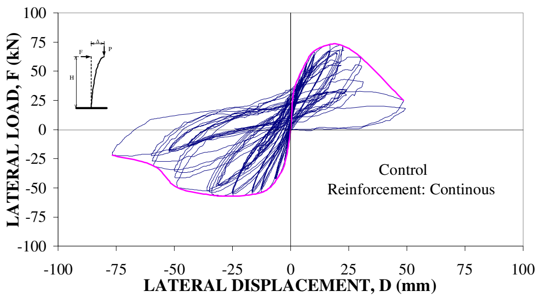
RESULTS AND DISCUSSION

Column with Continuous Bar, Without Strengthening (*Control-L0C0*)

Prior the application of lateral load, the column was first loaded with a constant axial compressive force of 350 kN, which corresponded approximately to 25 per cent of the ultimate axial load carrying capacity. Observations during testing indicated that the first crack was formed at 0.75 per cent drift level. The cracks were widened during the subsequent cycles at the same displacement. At the 1.0 per cent and 1.5 per cent drift levels, new cracks appeared and continued to widen. The new diagonal cracks caused decrease in the load capacity from 77 kN to 70 kN at 1.5 per cent. Spalling of concrete cover was observed at the base of the column at 2.0 per cent drift level. After the completion of 2.0 per cent level, 0.5 per cent, 1.0 per cent and 1.5 per cent drift levels were re-applied to the column. At these cycles, the cracks were widened further. At 2.5 per cent drift level, the cover concrete experienced extensive spalling. Buckling of the column longitudinal bars followed the crushing of the concrete. Figure 5a shows the lateral load versus top displacement graphics and the backbone curve. It may be observed from the Figure 5b that the test was ended with the crushing of the concrete ,buckling of longitudinal reinforcements.

Column with Continuous Bar, Strengthened with FRP Sheets (*L0FRP*)

The first cracking occurred when the specimen was subjected to a drift level of 1.5 per cent. Up to this drift cycle, there was no crack observed. New cracks formed at 2.0 per cent drift level. Shear cracks appeared near the base at 2.5 per cent drift level. The load did not increase significantly after the drift level of 1.0 per cent, but some spalling and crushing of concrete were observed at the base. Load-Displacement diagram and envelope curves are shown in Figure 6a. The damages, which the column experienced at the end of the test, are shown in Figure 6b.

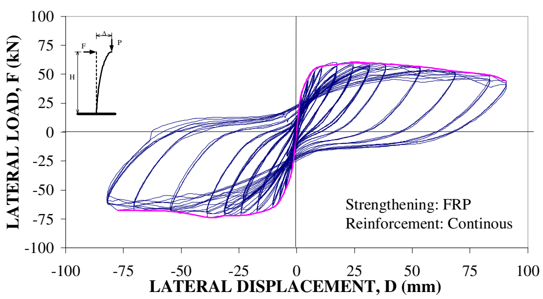


(a)

(b)

Figure 5. Test of control column reinforced with continuous reinforcement

After the test, FRP layers were removed from the column to see further damages occurred. Only, minor cracks were observed near the bottom section of the column and the rest remained undamaged.



(a)

(b)

Figure 6. Test of strengthened column reinforced with continuous reinforcement

Column with Lapped Bar, without Strengthening (*Control-L50C0*)

The control lapped-spliced column was subjected to the same loading program as described in preceding section. Load-Displacement diagram is shown in Figure 7a. At the first cycle, a drift of at 0.25 per cent was applied. The cracks formed around the lapped region. In the following cycles, these cracks widened and new horizontal cracks were formed. Crushing of concrete was observed during the cycles at 1.0 per cent drift level. The bond between the reinforcement and concrete was lost and the lateral force was decreased. Slipping of the reinforcements of dowels and column re-bars were observed and thus high degree of pinching effect was experienced. The picture showing the damage on the column is shown in Figure 7b.

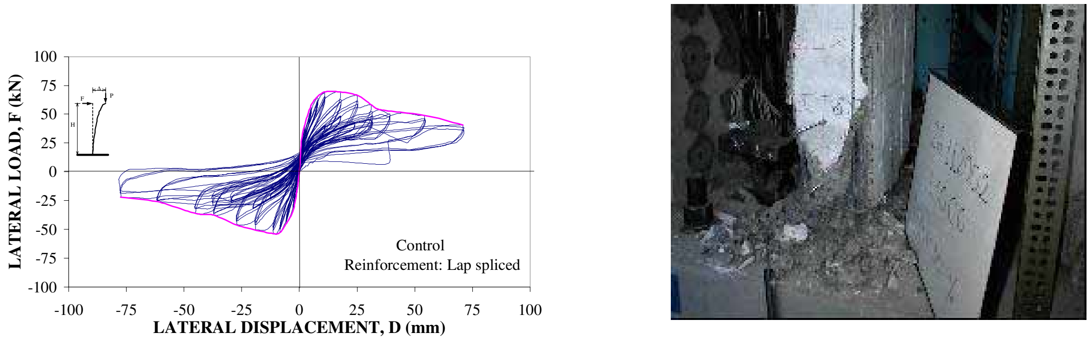


Figure 7. Test of control column reinforced with lap-spliced reinforcement

Column with Lapped Bar, Strengthened with FRP Sheets (*L50FRP*)

Similar to the column with continuous bar, cracks were observed at the base of the column. During the 0.50 per cent drift cycles, first cracks were observed. Due to the FRP sheets, there was no crack observed on the surface of the column. The test ended at the cycles of 6 per cent drift while cracking at the column base was observed. Similar behaviour was observed with the control column that was reinforced with lap-splice longitudinal reinforcement. Figure 8a shows the load displacement and the backbone curve of the specimen, and the picture from the specimen at the end of the test are illustrated in Figure 8b.

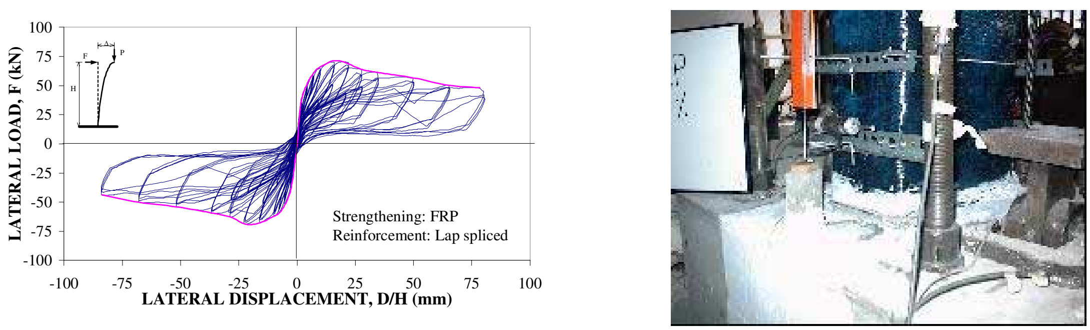


Figure 8. Test of strengthened column reinforced with lap-spliced reinforcement

Table 2. Summary of Test Results

Specimen		L0C0	L0FRP	L50C0	L50FRP
P_{max} (kN)	Push	72.57	60,34	69,52	70,56
	Pull	-56,98	-73,77	-53,96	-69,1
$P_{first\ crack}$ (kN)		51,58	32,38	40	68,19
Δ_{max} (mm)	Push	15,86	26,13	16,63	19.55
	Pull	-24,38	-37,22	-10,3	-21.79
$\Delta_{firstcrk}$ (mm)		12,52	2,32	2,26	15,98

A direct comparison of lateral load displacement peak envelopes of the control specimen and the strengthened columns with continuous re-bars is provided in Figure 9. The tests have been terminated at the highest shear strength, when the column failed or when the load carrying capacity dropped to 80 per cent of its maximum strength. It can be observed from the Figure 9. that up to a drift ratio of 1.0 per cent the columns L0C0 and L0FRP exhibited identical Lateral Load-Displacement response. The column retrofitted with CFRP sheets exhibited large ductility and high-energy dissipation. However, the maximum lateral load capacity did not change significantly, which is expected. Both specimens in this group, strengthened and control columns, had about 75 kN of lateral load capacity.

It can also be seen from the Figure 9 that the stiffness, strength, and the ductility characteristics of the column were improved significantly by the application of CFRP sheets.

In Figure 10, the Lateral Load-Displacement response envelope for the specimen with lap spliced re-bar was shown. A little, insignificant increment was seen in ductility and energy dissipation capacity of retrofitted column. As in the column with continuous bar, maximum load was about 75 kN in this group. The progression of damage was similar, for the specimens in lap-spliced columns. Initially, horizontal cracks were formed at the bottom of the column. Initial yielding of the column longitudinal reinforcement followed displacing the column further resulted in the formation of diagonal cracks at the column ends.

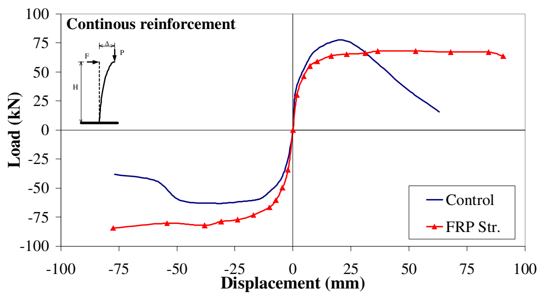


Figure 9

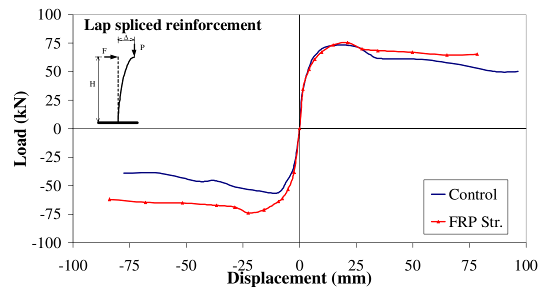


Figure 10

From the Lateral Load-Displacement diagrams of the columns, ductility can be calculated by using several methods. The most preferred one is based on reduced stiffness equivalent elasto-plastic yield method. In this method the yield displacement of the equivalent elasto-plastic system with reduced stiffness is found as the secant stiffness at either first yield or at 0.75 per cent of the ultimate lateral load, which ever is less [4].

Although the strengthened column with continuous reinforcement behaved in a ductile manner than the control column, the ductility of the strengthened lap-spliced column was not increased significantly. Due to the slippage of the longitudinal reinforcement at the lapped region, behavior of the specimen can not be improved by strengthening with FRP.

The energy dissipated in each cycle is the integration of tip force times the displacement for the cycle. Figure 11 shows the value of this integration for each cycle from the beginning of the experiment for each column. The dramatic effect of retrofitting was also reflected by the total energy that each column is dissipated. Evidently, the column with continuous bar and retrofitted with CFRP sheet produced the highest energy dissipation (L0FRP). Thus, at no retrofit and the column with spliced re-bar, the total energy dissipation had the smallest value (L50C0).

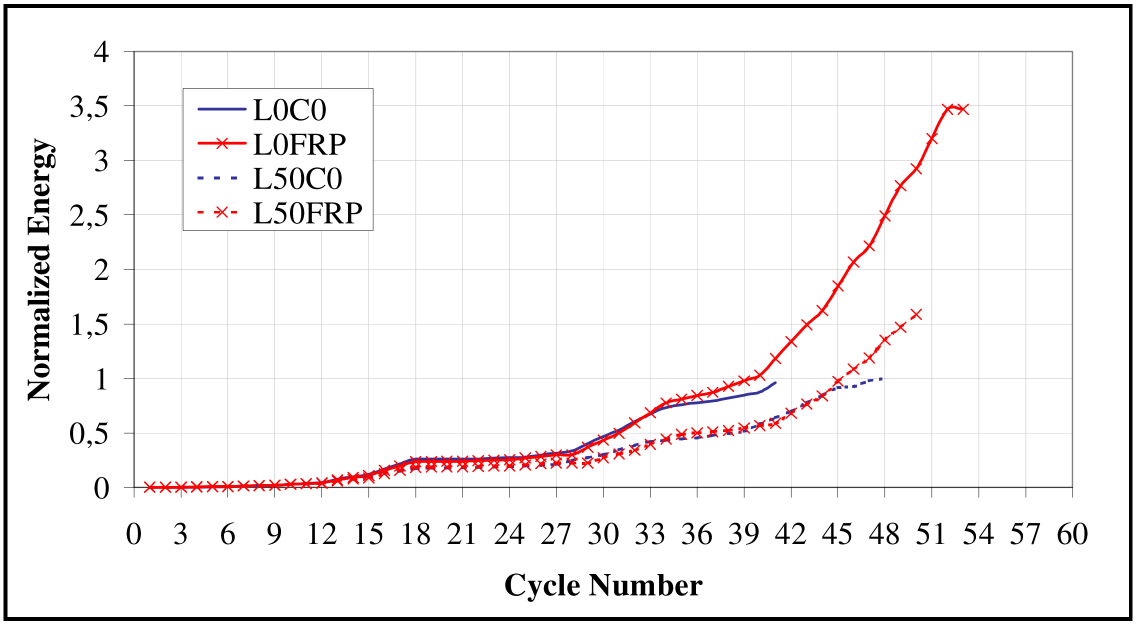


Figure 11. Energy dissipation of tested columns

CONCLUSION

The retrofitting technique using CFRP Sheets resulted in significant improvement in drift capacities of the columns with only continuous longitudinal re-bars. However, in lap-spliced longitudinal re-bars this retrofitting technique did not work properly. Applying CFRP directly cannot provide enough confinement stress to increase frictional force between the lap-spliced longitudinal reinforcements.

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