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SEISMIC RETROFITTING OF COLUMNS WITH LAP-SPLICES VIA RC JACKETS

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SUMMARY

The effectiveness of RC jackets for seismic retrofitting of rectangular columns with poor detailing, and in particular with lap splicing of bars at floor level, was investigated. Four cantilever columns with smooth bars and hooked ends and another 3 with ribbed bars and straight ends, were cyclically tested to failure, after jacketing. The tests of companion unretrofitted columns show that, for smooth bars with hooked ends, the low deformation capacity and energy dissipation does not depend on lapping length - at least for lapping as short as 15 bar-diameters. Unretrofitted columns with straight ribbed bars exhibit a remarkable loss of deformation capacity and energy dissipation with decreasing lap length, below 45 bar-diameters. RC jacketing of columns with smooth bars and hooked ends is very effective in increasing their resistance, cyclic deformation capacity and energy dissipation to levels sufficient for earthquake resistant construction and to those of a monolithic column without lap splicing. In columns with straight ribbed bars RC jacketing cannot fully re-instate cyclic deformation capacity and energy dissipation to that of a monolithic column, if the original column has very short lapping, e.g. in the order of 15 bar-diameters.

INTRODUCTION

Owing to their cost-effectiveness, concrete jackets have been, over the past two to three decades, by far the most widely-used technique for seismic upgrading of existing concrete members. This cost-effectiveness is due to a number of reasons, namely: (a) the familiarity of engineers and of the construction industry alike with the field application of structural concrete, (b) the suitability of concrete jacketing for simultaneous repair of serious seismic damage, involving local or more extensive concrete crushing, or even buckling of bars and fracture of stirrups, (c) the versatility and shape-adaptability of reinforced concrete to fully encapsulate existing concrete members and joints and provide structural continuity between different components, (d) the ability of a concrete jacket to have, through the appropriate reinforcement, multiple effects, i.e. to enhance member stiffness, flexural resistance, shear strength, deformation capacity and anchorage and continuity of reinforcement in anchorage or splicing zones. From

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the technical point of view, the multiple effectiveness of concrete jackets is what mainly differentiates them from the other techniques of seismic retrofitting individual concrete members.

Considering the benefits and popularity of RC jacketing, one cannot but note the scarcity of experimental results on the cyclic behavior of RC jacketed members, especially those concerning columns with deficient lap-splicing of longitudinal bars at floor level, which is the case in almost every old concrete building. Among the limited experimental data in the literature dealing with the behavior of RC jacketed columns (Bett et al [1], Rodriguez and Park [2], Gomez and Appleton [3], Ersoy et al [4], Yamamoto [5], Iliya and Bertero [6]), none includes members with lap splices.

The paper presents and discusses the results of an experimental program on RC jacket retrofitting of rectangular RC columns with deficient lap-splicing of their longitudinal - smooth or ribbed – reinforcement, at the base of the column.

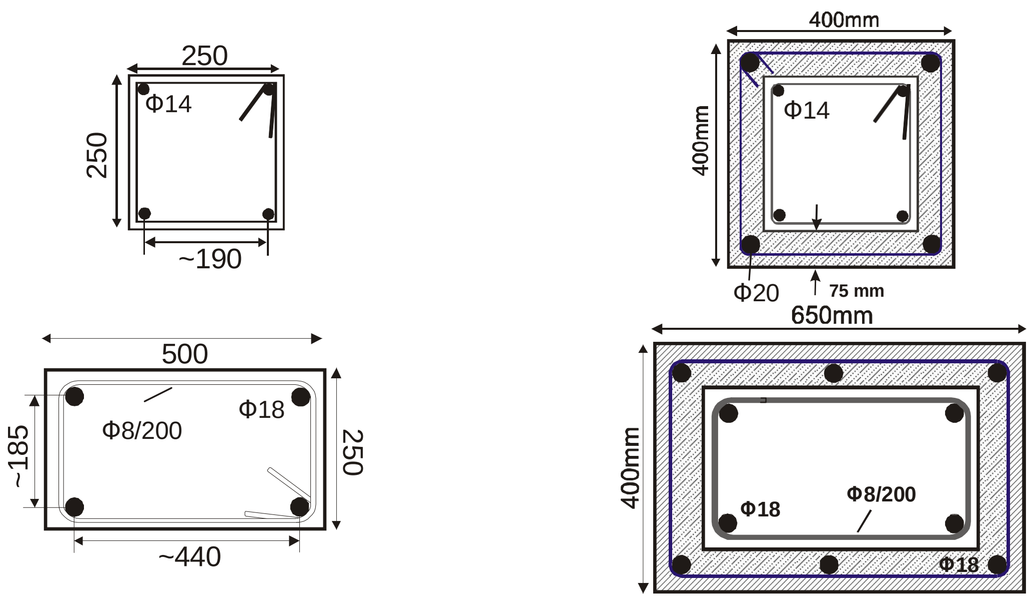

Figure 1 Cross - section of original test columns and of RC-jacketed ones

EXPERIMENTAL PROGRAM

Test Specimens

The experimental program comprises 14 column specimens with dimensions, reinforcement detailing and materials typical of old RC buildings without detailing for earthquake resistance. The testing program includes two column geometries (Figure 1):

– Type-Q: a 250mm-square cross-section, reinforced longitudinally with four-14mm smooth (plain) bars with nominal yield strength of 220MPa (Figure 1(a)).
– Type-R: a 250×500mm cross-section, reinforced longitudinally with four-18mm ribbed (high bond) bars with nominal yield strength of 500MPa (Figure 1(b)).

The distance from the column base at which the lateral load is applied is the same for the two cases and equal to about half a typical story height, i.e. 1.6m. The purpose of selecting the aforementioned specimen geometries was twofold: first, to represent typical columns before the application of modern seismic design methodologies, and second, to include both columns dominated by flexure before and after jacketing (shear-span-ratio L/h of 6.4 to 4, in type-Q specimens) and columns affected by shear, especially after jacketing (shear span ratio of 2.5 in type-R specimens after jacketing).

In both types of specimens transverse reinforcement consists of 8-mm smooth (plain) stirrups at 200mm centers, anchored by 135-degree hooks at one end and 90-degree hooks at the other. The 14mm-diameter smooth vertical bars of type-Q specimens have a yield stress of 313MPa and tensile strength of 442MPa (average values from three coupons); the corresponding values for the 18mm-diameter ribbed vertical bars of type-R specimens are 514MPa and 659MPa. The yield and ultimate stresses for the mild steel used for the ties are 425MPa and 596MPa. Concrete strength (on 150-by-300mm cylinders) at the time of testing ranges from 26 to 30 MPa (see Tables 1 and 2).

In type-Q specimens, with smooth bars as longitudinal reinforcement, starter bars with 180-degree hooked ends are provided at the base of the columns, with lap-splicing over a length of 15- or 25-bar diameters with the main bars of the column that start at the base section, again with a 180-degree hook (Figure 2, left).

In type-R specimens, with ribbed longitudinal bars, lapping of straight bar ends with the straight starter bars is provided over a 15-, 30- or 45-bar diameter length above the base section (Figure 2, center).

Figure 2 Laps at column base in type-Q specimen (left) and in type-R specimen (center); jacket reinforcement (right)

The specimens were cast into a heavily reinforced 0.6m-deep base, within which ribbed vertical bars were anchored with 90-degree hooks at the bottom and smooth bars with 180°-hooks. The behavior of the columns is studied under cycling of transverse displacements at amplitudes increasing in 5mm steps, under constant axial force. The load history with closely spaced single cycles was chosen over the usual protocols of 3 cycles at few ductility levels, to capture better the cyclic behavior of the specimen up to failure. The mean value of the normalized axial load, $\nu=N/A_cf_c$, during the test is listed at Table 1. The jack applying the axial load acted against vertical rods connected to the laboratory strong floor through a hinge. With this setup the P-Δ moment at the base of the column is equal to the axial load, times the ratio of the distance of the hinge from the column base to that to the point of application of transverse loads (i.e. times 0.5/1.6=0.3125). Results presented in the paper for bending moments include the P-Δ contribution.

Both types of specimens (Q and R) were tested after being retrofitted with a 75-mm thick concrete jacket. The jacket is reinforced longitudinally with four 20-mm ribbed bars in Q-type specimens, or six 18-mm bars in R-type specimens. These vertical bars were embedded in the column base at the time of casting of the original unretrofitted column. Jacket transverse reinforcement consists of 10-mm stirrups at 100mm centres, in both specimen types. Shotcrete with a mean compressive strength of 36MPa was used for the jacket. No special measures were taken for the connection of the jacket to the existing member, as in a parallel investigation of the authors on RC-jacketed columns without lap splices, positive measures of connection (such as roughening of the interface, steel dowels, or connection of the new corner bars to the old ones through welded steel inserts) were not found essential for the full composite action of the old and the new concrete.

With the addition of the RC jacket the total cross-sectional dimensions of the specimens became 400mm by 400mm in type-Q columns, or 650mm by 400mm in type-R columns, leading to shear span ratios in the direction of testing of 4.0 and 2.5 for type-Q and type-R columns, respectively.

A summary of the geometry and retrofitting schemes for the specimens tested is presented in Table 1.

Table 1 Characteristics of specimens

Specimen	Lapping	Concrete strength f_c in original column (MPa)	Jacket concrete strength f_c (MPa)	Axial load ratio $v=N/A_cf_c$ in original column	Axial load ratio $v=N/A_cf_c$ in jacketed column[2]	Yield moment with P-Δ (kNm)	Drift at "failure" (%)	Max. drift attained in test (%)
Q-0L0	-	27.0	-	0.44	-	73.8	2.2	2.5
Q-0L1	$15d_b$	30.3	-	0.41	-	82.4	2.5	2.8
Q-0L2	$25d_b$	30.3	-	0.42	-	81.3	1.6	1.9
Q- RCL0	-	26.3	55.8	0.35	0.079	244.5	5.3	7.2
Q- RCL0M[1]	-	30.6	-	0.18	0.18	262.4	5.3	6.2
Q-RCL1	$15d_b$	27.5	55.8	0.35	0.084	223.8	5.6	6.2
Q-RCL2	$25d_b$	25.6	55.8	0.38	0.084	227.0	5.3	5.6
Q-RCL1pd	$15d_b$	28.1	20.7	0.38	0.25	212.0	4.4	5.0
Q-RCL2pd	$25d_b$	28.6	20.7	0.40	0.27	254.4	5.3	5.9
R-0L0	-	31.0	-	0.26	-	306.4	2.5	2.8
R-0L1	$15d_b$	18.0	-	0.23	-	230.9	1.9	2.8
R-0L3	$30d_b$	18.0	-	0.28	-	287.0	1.9	3.1
R-0L4	$45d_b$	18.0	-	0.28	-	281.0	2.5	2.8
R-RCL1	$15d_b$	36.7	55.8	0.21	0.066	545.2	4.2	4.8
R-RCL3	$30d_b$	36.8	55.8	0.21	0.066	572.8	3.8	4.5
R-RCL4	$45d_b$	36.3	55.8	0.16	0.052	532.1	4.7	5.1

1 Specimen Q- RCL0M, has similar geometry and reinforcement as the final jacketed column Q-RCL0, but was constructed as monolithic.

2 The axial load ratio of the jacketed column is calculated on the basis of the concrete strength of the jacket

TEST RESULTS

Q-type specimens

Unretrofitted columns

The force-displacement loops of unretrofitted type-Q specimens are shown in Figure 3(a) for the specimen without laps (Q-0L0) and in Figures 3(b) and 3(c) for those with lap-splices (Q-0L1, Q-0L2). The behavior of the control specimen (Q-0L0) during testing was controlled by flexure; the concrete cover and part of the core concrete over the lower 200mm of the column disintegrated and steel bar buckling was evident after concrete cover spalled off. The response of specimens Q-0L1 and Q-0L2 with 15 and

25-bar diameters laps, respectively, was also controlled by flexure. Cracking parallel to the (hooked) corner bars was evident before yielding and spalling of the concrete cover appeared and spread below and above the end of the lapping. Loss of concrete cover led to buckling of the longitudinal reinforcement at low drifts, with member resistance dropping suddenly afterwards.

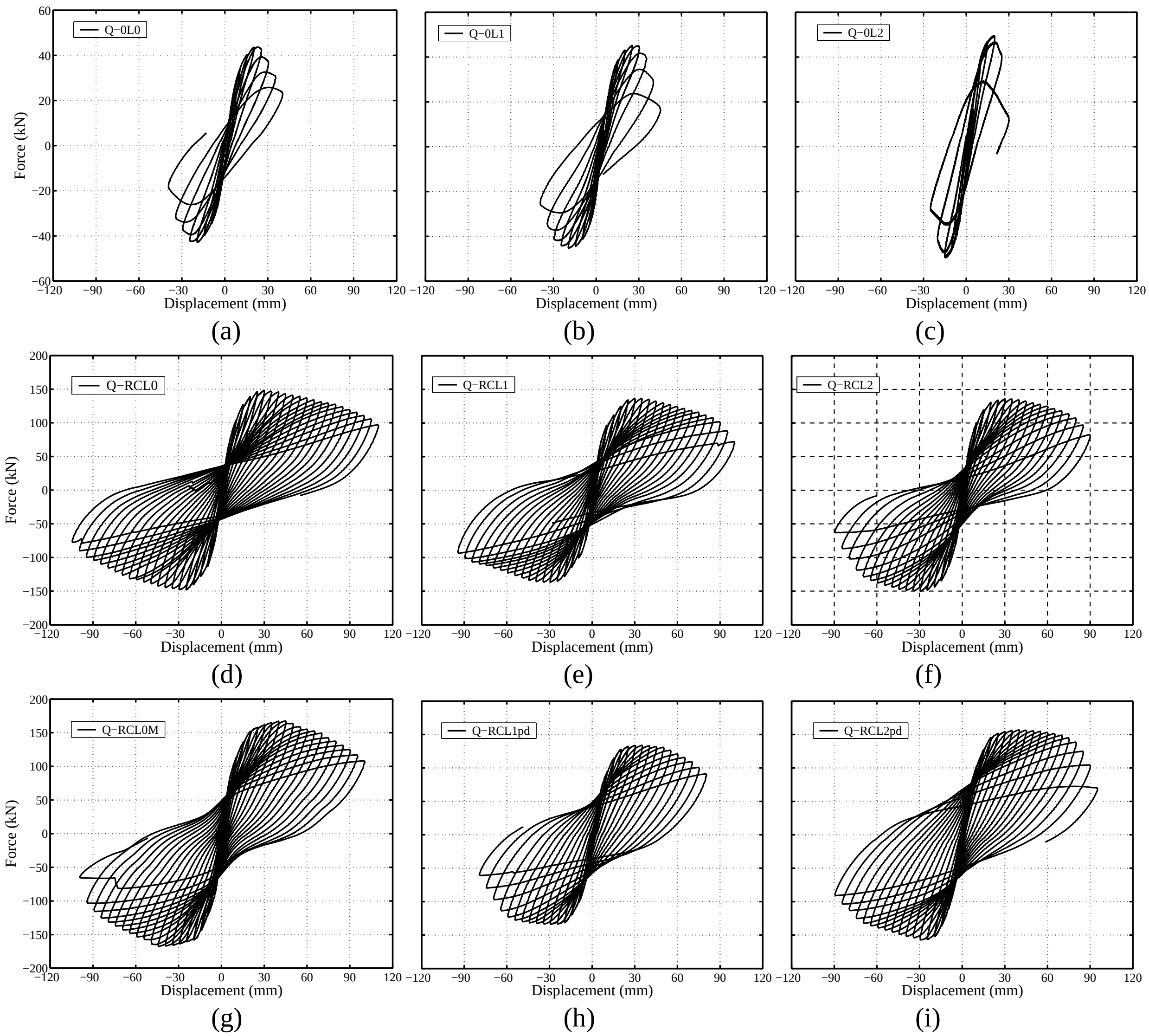

Figure 3 Q-type columns: (top) un-retrofitted: (a) Q-0L0, (b) Q-0L1, (c) Q-0L2; (middle row) RC-jacketed ones: (d) Q-RCL0, (e) Q-RCL1, (f) Q-RCL2; (bottom): (g) monolithic Q-RCL0M; (h) pre-damaged jacketed Q-RCL1pd, (i) pre-damaged jacketed Q-RCL2pd.

Retrofitted specimens

The response of the RC-jacketed column is completely different from that of the companion original columns. Peak resistance is almost the same, regardless of the lapping of longitudinal reinforcement in the original column. Comparison of (d) and (g) to (e) and (f) in Figure 3 shows that retrofitting by RC jacketing overshadows the sufficient or not lapping length in the original column. Resistance exhibits mild degradation with cycling, which is accelerated during the last cycles in the columns with lap-spliced reinforcement. Member deformation capacity increases impressively in all cases (by a factor of 3 at least) reaching ‘failure’ at drift levels equal to approximately 5.5%, both in columns with and without lap-spliced longitudinal bars. Noteworthy is the similarity of the behavior of all jacketed columns, with or without lap splicing, to that of column Q- RCL0M, which has similar geometry and reinforcement as the final jacketed column Q- RCL0, but has been cast as monolithic from the beginning. That column performs better than the jacketed ones only as far as peak resistance is concerned.

The effectiveness of RC jacketing in repair and retrofitting of pre-damaged columns with lap-splicing of smooth longitudinal reinforcement was examined through specimens: Q-RCL1pd and Q-RCL2pd, in which the lapping length of the reinforcing bars was equal to 15- to 25-bar diameters, respectively. The initial specimens were similar to specimens Q-0L1 and Q-0L2 and were subjected to the same loading history with those, beyond yielding and close to peak resistance. Jacket longitudinal reinforcement was fixed with epoxy resin in 0.40m-deep holes drilled in the column base. The force-displacement response of the RC jacketed columns shown in Figures 3(h) and (i) and summarized in Table 1 does not suggest a substantially inferior performance with respect to the retrofitting of the originally undamaged column. The slightly worse behavior of the pre-damaged column may be due to the significantly lower strength of the jacket concrete.

R-type specimens

Unretrofitted columns
Specimen R-0L0 served as the unretrofitted control specimen of the group of type-R specimens with continuous longitudinal reinforcement. The specimen yielded in flexure but exhibited a mixed flexure-shear failure mode, with sudden drop in resistance at peak deflection of 45mm accompanied by bar buckling, inclined cracking and ultimate disintegration of the concrete core above the base. The deformation at failure (Figure 5(d)) was 40mm (2.5% drift ratio) defined on the basis of the conventional rule of 20%-drop in lateral force resistance.

The un-retrofitted columns with lap-spliced longitudinal reinforcement included different lap lengths: 15-bar diameters (R-0L1), 30-bar diameters (R-0L3) and 45-bar diameters (R-0L4). The behavior of these specimens is shown in Figures 5(a) to (c). The effect of the presence and length of lap splices is clear. The specimen with the shortest splices (R-0L1) displays the lowest strength, as reversed cyclic loading caused early spalling of the concrete cover and rapid degradation of bond. Specimens R-0L1 and R-0L3 did not reach the full flexural strength of the end section, while specimen R-0L4, with the 45-bar diameter lap, did. The experimental capacity of specimens R-0L1 and R-0L3 was 80% and 95%, respectively, of the theoretical yield moment, whilst specimen R-0L4, as well as the control, R-0L0, reached almost 110% of the theoretical yield moment. The initial stiffness of all specimens with lap splices was similar to that of the member with continuous reinforcement, because during the early stages of loading slip between the lapped bars seems to be minimal. Due to slippage along the lap splice, the width of the hysteresis loops (and with it hysteretic dissipation) decreases, as lapping decreases. Although the column with the 45-bar diameter lapping has similar strength and deformation capacity as the control column with the continuous reinforcement, its hysteresis loops exhibit the detrimental effect of lap-splicing, albeit much less than in the two other columns.

Damage in specimens R-0L1 and R-0L3 appeared first as concrete splitting along the plane of lapped bars and progressed by crushing of concrete ahead of the end of the starter bars, due to high bearing stresses in that region. In the absence of dense stirrups, concrete crushing ahead of the starter bar end is promoted by the fact that (due to the sequence of construction) starter bars are usually located at the corner of the stirrups and hence closer to the concrete surface than the bars which start at the base and continue over the full column length. During the subsequent cycles of increasing displacement amplitude and due to the sparse stirrups, shedding of the concrete cover in the region of lapping took place. Member lateral force capacity decreased rapidly due to insufficient force transfer between starter bars and member longitudinal reinforcement, soon after cover concrete had spalled. The drift ratio at the conventionally defined failure (i.e. at reduction of peak cycle resistance below 80% of the maximum recorded lateral resistance in the direction of loading) was 1.5% in both specimens R-0L1 and R-0L3, regardless of the lapping length. Lap length affected peak resistance, which dropped by 30% in specimen with the 15-bar diameters lap splice, or by 13% in that with the 30-bar diameters one, in comparison to the specimen without lap splices or with 45-bar diameter ones.

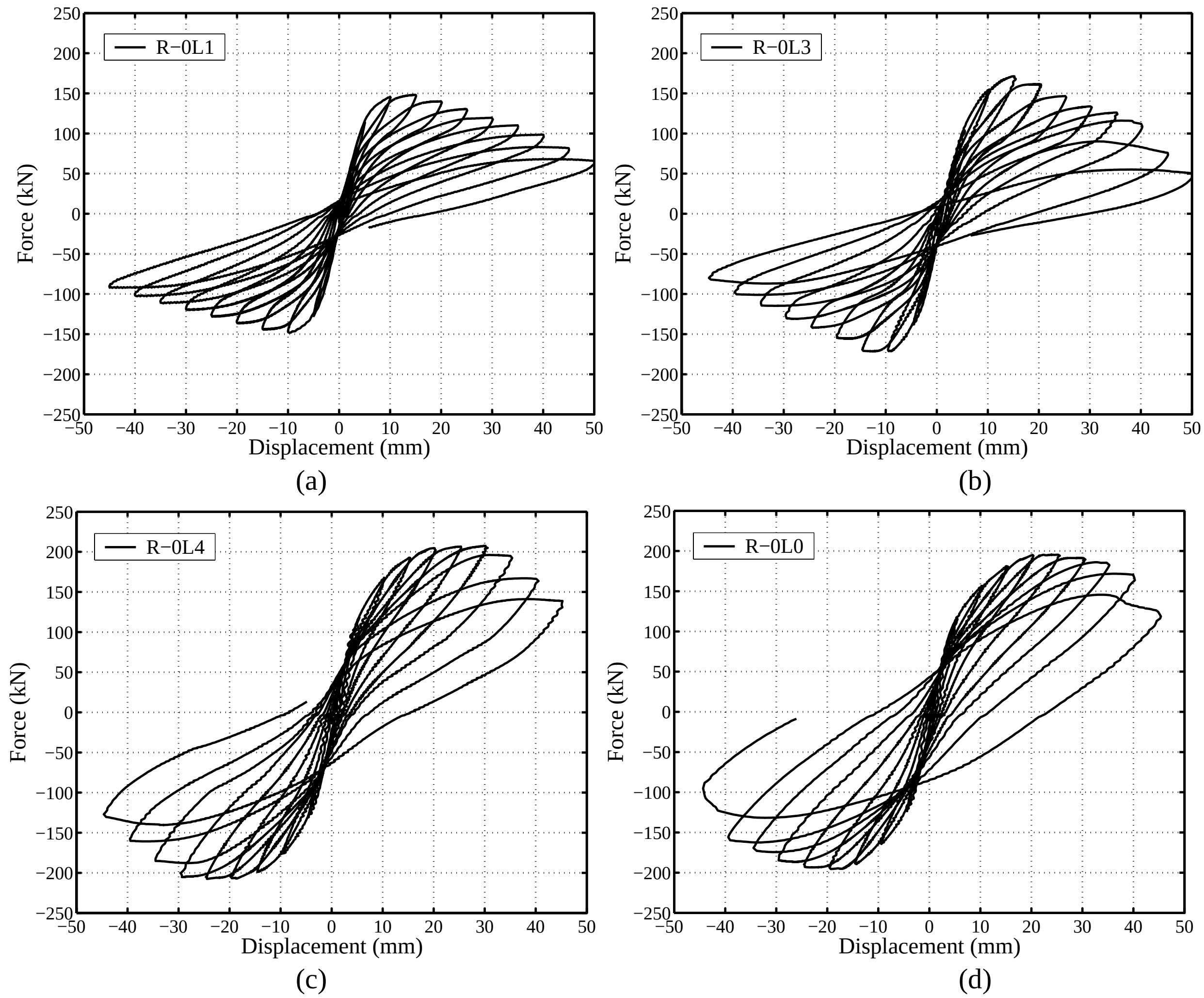

Figure 5 Effect of lap length un-retrofitted R-type columns: (a) R-0L1 (15-bar diameters), (b) R-0L3 (30-bar diameters), (c) R-0L4 (45-bar diameters), (d) no lap-splicing (R-0L0)

The behavior of column R-0L4 (45-diameter lapping) up to failure was much better than in the other two columns with lap-splices: its peak resistance and deformation capacity were the same as in the control column without lap-splicing. Splitting cracks appeared also along the lap length, but the behavior of the member afterwards was not conditioned by failure of the splice. Except for the reduced width of hysteresis loops, the column sustained cycling of horizontal displacements in more or less the same way as the one with the continuous reinforcement and with similar rate of strength decrease after peak load.

Retrofitted columns

The force-deformation loops of the jacketed columns are shown in Figure 6. Jacketing increased, as expected, the flexural strength of all columns. The jacketed columns reached or exceeded the theoretical flexural capacity of the monolithic column, with the lap-spliced bars assumed as continuous. In other words, the RC jacket seems to be quite effective regarding flexural resistance and mobilization of the strength of the insufficiently spliced bars. Strength enhancement is roughly equal in the three columns.

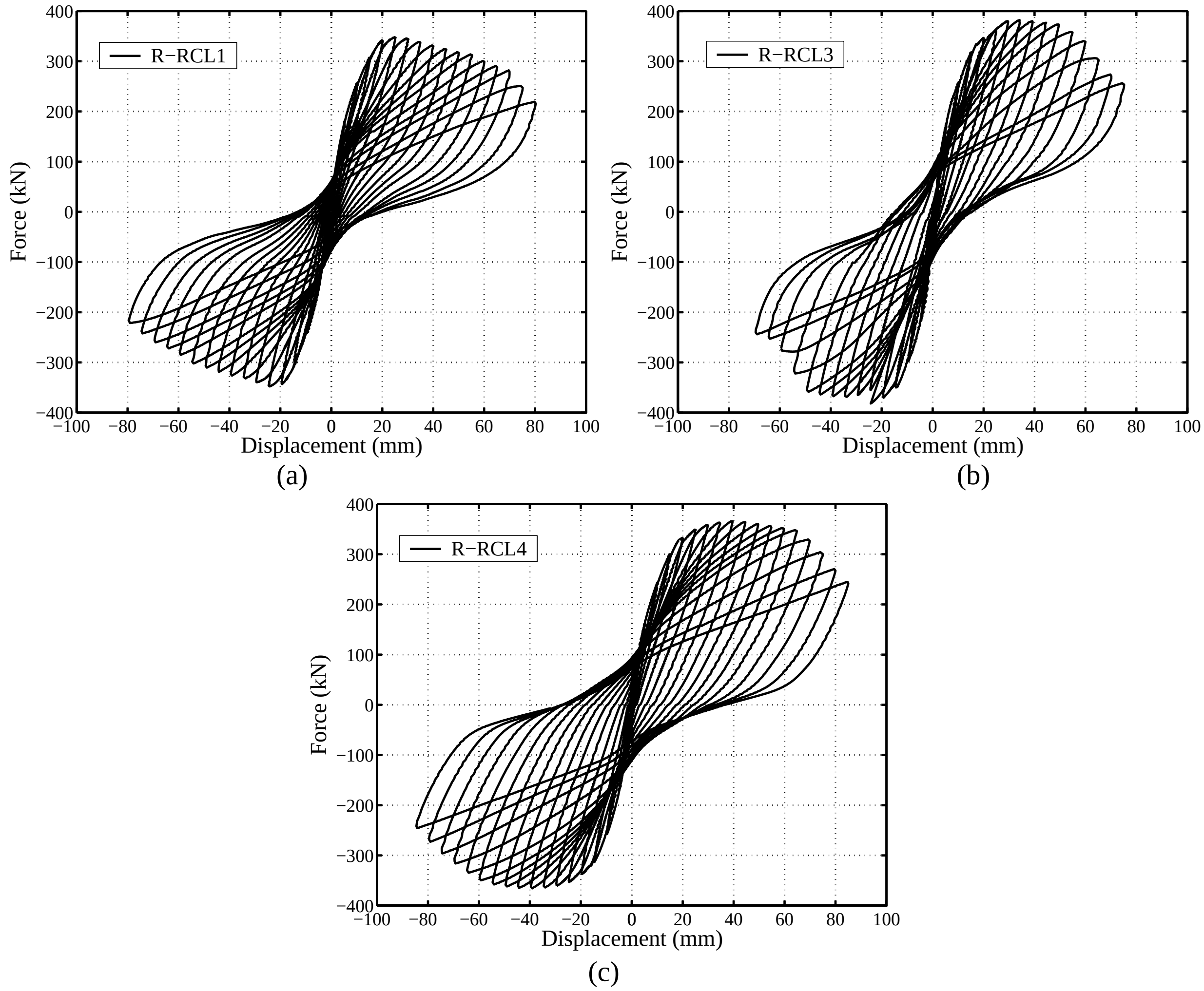

Figure 6 Effect of lapping in RC-jacketed R-type columns: (a) R-RCL1 (15-bar diameters), (b) R-RCL3 (30-bar diameters), (c) R-RCL4 (45-bar diameters)

Columns R-RCL1 (15-bar diameters lapping) and R-RCL3 (30-bar diameters lapping) yielded in flexure; peak resistance was attained at 1.5% drift (2.5 times that of column R-0L1 and 2 times that of R-0L3). Inclined cracking developed after peak resistance, with the opening of diagonal cracks increasing with displacement cycling. The jacket concrete disintegrated along a large part of the length of the corner bars, apparently due to bond stresses. As a result, column strength dropped rather rapidly and the column ultimately failed at a drift of 4.2%. Shear- and bond-dominated behavior may have contributed to the limited energy absorption capacity suggested by the rather narrow force-deflection loops in Figures 6(a) and (b). At the end of the test the column had disintegrated at the base. The main difference in the behavior of column R-RCL1 to that of R-RCL3 is that the latter maintained peak resistance for a few of cycles and exhibited an abrupt reduction thereafter, while in R-RCL1 resistance started dropping immediately after peak but at a slower rate. An immediate result of this behavior is the marginally lower drift at conventionally defined failure of column R-RCL3 (3.8% compared to 4.2% of R-RCL1).

The force-deformation response of column R-RCL4 (45-bar diameters lap splice length) does not differ appreciably from that of the other two retrofitted columns (Figure 6(c)). It yielded in flexure and, owing to the longer splice length, maintained its peak resistance for larger number of cycles. Shear cracking developed in this specimen as well, but there was no bond failure and damage concentrated mainly at the lower part of the specimen. Fracture of the jacket concrete in compression near the base extended through the whole width of the jacket, accompanied by disintegration of the concrete in the original column section and buckling of the bars, both in the jacket and in the original column (Figure 7(c)). Hysteresis loops are appreciably wider than in the retrofitted columns with shorter lapping.

(a) (b) (c)

Figure 7 RC-jacketed R-type columns after failure: (a) R-RCL1, (b) R-RCL3 and (c) R-RCL4

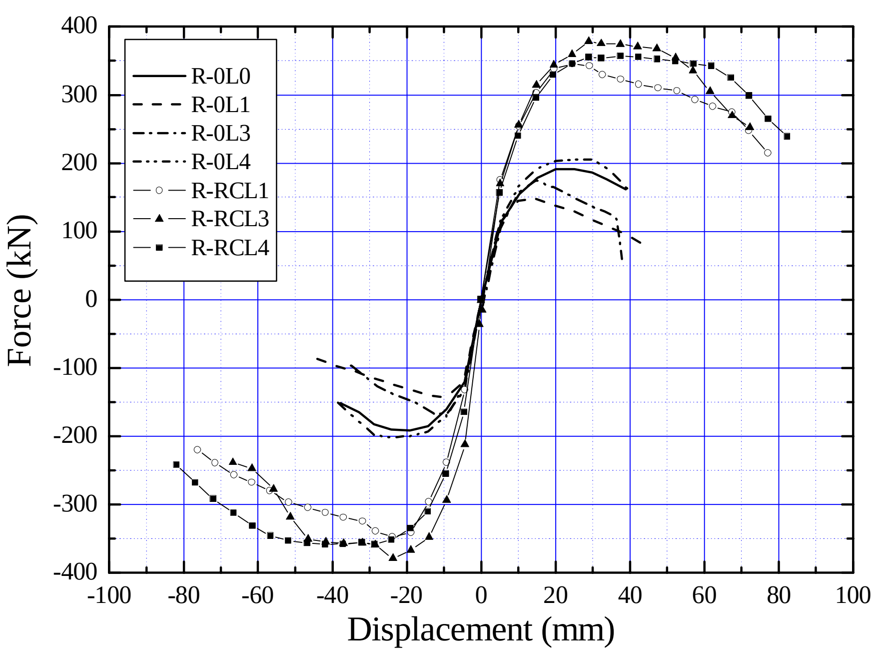

Figure 8 Comparison of envelope curves of un-retrofitted and retrofitted type-R columns

Figure 8 compares the envelope curves of the 4 un-retrofitted and the 3 RC-jacketed type-R columns. The improvement in strength and deformation capacity effected by the jacket is evident.

CONCLUSIONS

Old-type columns with smooth (plain) bars have rather low deformation and energy dissipation capacity under cyclic loading, which is however not impaired further by the lap-splicing of the smooth bars with their hooked ends at the base of the column (at floor level). A lap length as short as 15-bar diameters supplements sufficiently the hooked ends for the transfer of forces. RC jacketing of such columns increases their deformation capacity to levels more than sufficient for earthquake resistance. Like in the unretrofitted columns, the behavior of the RC-jacketed ones is practically unaffected by the presence and length of the lap splices. Jacketed columns, with or without lap splicing, have very similar behavior as a monolithic jacket with the same geometry and reinforcement as the final jacket column without lap splicing. The RC jacket is equally effective in repair and retrofit of a column with lap splices of smooth bars cyclically damaged to almost past peak resistance, as for retrofitting an originally undamaged column.

Columns with ribbed (deformed) bars lap-spliced at the base (at floor level) suffer from reduced cyclic deformation capacity and energy dissipation. If lapping is at least 45-bar diameters, cyclic deformation capacity is not significantly reduced in comparison to the column with continuous bars, and energy dissipation is acceptable. Lapping of straight bar ends by as little as 15-bar diameters reduces appreciably flexural resistance and results in rapid post-peak strength and stiffness degradation and in low energy dissipation capacity. Concrete jackets are effective in removing the adverse effect of lap-splicing of straight ribbed bars on strength and deformation capacity, even for very short lap lengths. Nonetheless, the adverse effect of a short lapping in the original column upon the hysteretic energy dissipation is maintained in the jacketed column.

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