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SEISMIC RETROFITTING OF COLUMNS WITH LAP-SPLICES THROUGH CFRP JACKETS

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SUMMARY

The effectiveness of CFRP wrapping as a seismic retrofit measure of rectangular columns with poor detailing, and in particular with lap splicing of bars at floor level was investigated. 12 cantilever column columns with smooth bars and hooked ends and another 12 with ribbed bars and straight ends, with or without CFRP wrapping, were cyclically tested to failure. In addition to the bond properties of the bars, parameters studied include the length of lapping, the number of FRP layers, and the length of the member over which FRP wrapping is applied. In unretrofitted columns with smooth bars and hooked ends, the low deformation capacity does not depend on lapping length, if it is at least equal to 15 bar-diameters. Unlike what happens for smooth bars with hooked ends, unretrofitted columns with straight ribbed bars lose deformation capacity when lapping decreases below 45 bar-diameters. In columns with smooth bars and hooked ends, no systematic effect of the number of layers and the length of application of the FRP, or even of the lapping, on the force and cyclic deformation capacity and the rate of strength degradation was found; nonetheless, a decrease in lapping seems to reduce energy dissipation in the retrofitted columns. In retrofitted columns with straight ribbed bars, 5 CFRP layers are more effective than 2 layers; nonetheless, the improvement in effectiveness is not commensurate to the number of CFRP layers. It seems there is a limit to what FRP wrapping can do: if the lapping of straight ribbed bars is as short as 15 bar-diameters, its adverse effects on force capacity and energy dissipation cannot be fully removed by FRP wrapping.

INTRODUCTION

Most existing buildings worldwide have been constructed prior to the introduction of modern codes for earthquake resistant design and, thus, are inherently vulnerable to earthquakes. The ductility deficit characterizing this class of buildings results to low deformation capacity systems, which, when subjected to deformation reversals well into the post-elastic region, respond with rapid loss of strength. In response to the pressing need for remedial measures enhancing the ductility of old-type members, conventional as well as more innovative materials are currently employed. The first category comprises jackets of cast-in-situ or sprayed concrete. Externally bonded FRP wraps for member rehabilitation belong to the latter category, with its main contribution being the enhancement of the (limited) confining action provided by

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existing sparse stirrups. Despite the fact that the cost-effectiveness and the scientific documentation of this new technology have not been fully established and many issues remain unresolved, encasing RC members in FRP jackets is rapidly becoming the method of choice.

Unlike concrete jackets, the effectiveness of FRP jackets in enhancing column deformation capacity is under intensive study worldwide, owing to certain advantages they offer over RC or steel jacketing. The contribution of FRP-wrapping to the improvement of column deformation capacity has been investigated by several researchers: for square columns by Ma and Xiao [1], Zhang et al [2], Ye et al [3], Saatcioglu and Elnabelsy [4]; for rectangular columns by Saadatmanesh et al [5], Chang et al [6], Seible et al [7], Restrepo et al. [8], Bousias et al [9] and for circular ones by Haroun et al. [10], Ma and Xiao [11] and Seible et al. [12]. FRP retrofitting of circular or rectangular columns with inadequate lap-splices of ribbed bars with straight ends has also been studied by Saatcioglu and Elnabelsy [4], Saadatmanesh et al. [5], Chang et al. [6], Restrepo et al [8], Haroun et al [10], Ma and Xiao [11], Seible et al. [12], Osada et al. [13].

This paper presents the results of an experimental campaign focusing on the effectiveness of FRP jackets as a retrofitting measure for rectangular columns with smooth or ribbed bars inadequately spliced at floor level. The main parameters studied are: (a) the type of lap-spliced bars: ribbed/deformed with straight ends or smooth/plain with hooks; (b) the length of lapping; (c) the number of FRP layers, and (d) the length of the member over which FRP wrapping is applied.

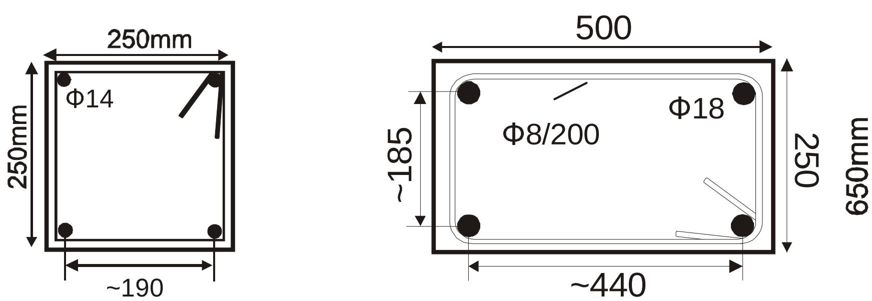

Figure 1 Specimen cross-section and reinforcement

EXPERIMENTAL STUDY

Test Specimens

The experimental program comprised 24 column specimens with dimensions, reinforcement detailing and materials typical of existing substandard RC buildings. The testing program included two column geometries, representing non-seismically designed and detailed members (Figure 1):

- Type Q: a 250mm-square cross-section, reinforced longitudinally with four-14mm smooth bars (Figure 1(a)).
- Type R: a 250×500mm cross-section, reinforced longitudinally with four-18mm ribbed bars (Figure 1(b)).

The column height at which the lateral load is applied is the same for the two cases and equal to half a typical story height, i.e. 1.6m. The purpose of selecting the aforementioned specimen geometries was twofold: first, to represent typical column geometry and reinforcement detailing dating before the application of modern seismic design codes, second, to include both flexure dominated members (high shear-span-ratio L/h, as in type Q specimens, equal to 6.4) and possibly flexure-shear dominated ones (as in type R specimens, with L/h=3.2).

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

Starter bars with 180-degree hooked ends are provided at the base of type-Q columns, which have smooth bars as longitudinal reinforcement. They are lap-spliced over 15- or 25-bar diameters with the bars starting at the column base (specimens Q-0L1, Q-0L2).

In type-R specimens, with ribbed bars, lapping of straight starter bars with the straight bars starting at the column base is provided over a 15-, 30- or 45-bar diameter length (columns R-0L1, R-0L3, R-0L4, respectively).

Table 1 Characteristics of specimens and summary of test results

Specimen	Lapping	Layers / Height of FRP jacket	Concrete strength (MPa)	Axial load ratio $\nu=N/A_c f_c$	$M_{y,exp}$ kNm	Drift at "failure"* (%)	Maximum drift during test (%)
Q-0L0	-	-	27.0	0.44	73.8	2.2	2.5
Q-0L1	$15d_b$ - 0.21m	-	30.3	0.41	76.0	2.5	2.8
Q-0L2	$30d_b$ - 0.42m	-	30.3	0.42	82.4	1.6	1.9
Q-P2L0H1	-	2 / 0.30m	25.6	0.40	86.3	5.0	6.5
Q-P2L0H2	-	2 / 0.60m	25.6	0.45	84.1	4.7	5.9
Q-P4L0H1	-	4 / 0.30m	28.2	0.45	90.9	no failure	6.6
Q-P4L0H2	-	4 / 0.60m	28.2	0.44	88.5	no failure	6.9
Q-P2L1H2	$15d_b$ - 0.21m	2 / 0.60m	30.0	0.40	86.4	6.0	6.6
Q-P4L1H2	$15d_b$ - 0.21m	4 / 0.60m	30.0	0.40	87.2	6.8	6.8
Q-P4L1H1	$15d_b$ - 0.21m	4 / 0.30m	27.5	0.44	93.3	6.2	6.9
Q-P2L2H2	$30d_b$ - 0.42m	2 / 0.60m	30.0	0.43	91.4	6.0	6.2
Q-P4L2H2	$30d_b$ - 0.42m	4 / 0.60m	30.0	0.42	97.5	6.9	6.9
R-0L0	-	-	31.0	0.26	306.4	2.5	2.8
R-0L1	$15d_b$ - 0.27m	-	18.0	0.23	230.9	1.9	2.8
R-0L3	$30d_b$ - 0.54m	-	18.0	0.28	287.0	1.9	3.1
R-0L4	$45d_b$ - 0.81m	-	18.0	0.28	281.0	2.5	2.8
R-P2L0	-	2 / 0.60m	32.9	0.23	335.1	4.4	4.4
R-P2L1	$15d_b$ - 0.27m	2 / 0.60m	26.9	0.30	266.1	3.4	4.7
R-P2L3	$30d_b$ - 0.54m	2 / 0.60m	26.9	0.28	315.1	4.7	5.3
R-P2L4	$45d_b$ - 0.81m	2 / 0.60m	26.9	0.28	317.3	5.6	5.6
R-P5L0	-	5 / 0.60m	32.9	0.23	328.2	5.3	5.3
R-P5L1	$15d_b$ - 0.27m	5 / 0.60m	27.0	0.28	295.4	5.0	5.6
R-P5L3	$30d_b$ - 0.54m	5 / 0.60m	27.0	0.29	334.9	5.6	5.6
R-P5L4	$45d_b$ - 0.81m	5 / 0.60m	27.0	0.29	332.5	5.6	5.6

***** 'Failure' defined conventionally as drop in resistance below 80% of peak resistance during test

A heavily reinforced 0.6m-deep base was constructed to anchor the columns to the laboratory strong floor, providing proper anchorage of the vertical bars (90°-hooks are provided at the far end of the ribbed starter bars and 180°-hooks at that of the smooth ones). Columns were subjected to cycles of tip deflections with peak values increasing at 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 monitor better the cyclic behavior of the specimen up to failure. The mean value of the normalized axial load, $\nu=N/A_c f_c$, 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 (Figure 2). Whenever base moment results are given in the paper they include the second-order moment produced at the base of the column.

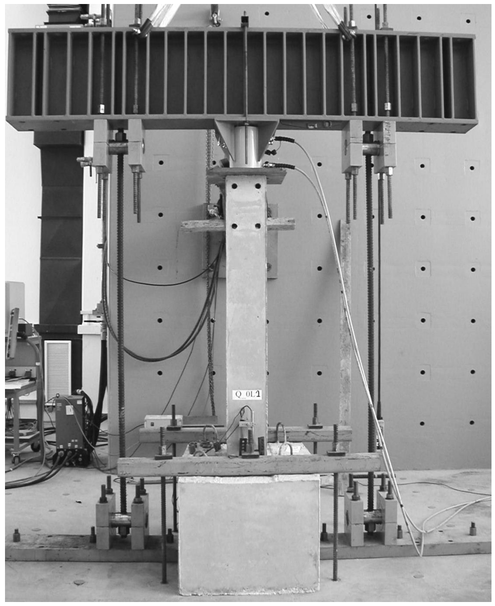

Figure 2 Test setup

The columns were tested after retrofitting with wraps of Carbon-Fiber Reinforced Polymer (CFRP) sheets. The sheets of practically uni-directional CFRP were attached to the column via epoxy resin, after thoroughly cleaning the column surface from loose material and rounding the corners of the section. The latter has been proven to be very important in earlier studies to avoid stress concentration at the corners of the cross-section, ultimately leading to premature FRP rupture. The CFRP wrapping started at a distance of about 10mm from the base. A CFRP lap length of one full side of the cross-section was provided at the end of the wrap. Each layer of CFRP has a nominal thickness, t_f, of 0.13mm, an Elastic Modulus E_f = 230 GPa and a tensile strength of 3450MPa (failure strain ε_f = 1.5%) in the (main) direction of the fibers.

To investigate the effect of FRP wrapping on the strength and deformation capacity of deficient lap-splices, different number of layers of CFRP are employed and over different heights from the column base. The notation used for the specimens includes specimen type (Q or R), the number of layers of FRP wraps used (denoted by P2, P4 and P5 for 2, 4 and 5 layers, respectively), the length of the zone at the column base over which the composite material is applied (H1 if CFRP is applied over the lower 0.6m, H2 if over the lower 0.3m), and the reinforcement lapping length (denoted by L1, L2, L3 and L4 for 15-, 25-, 30- and 45-bar diameters, respectively). It is noted that 2 FRP layers is the practical minimum. Similarly, with a wrapping length of just 0.3m and P-Δ moments included, the bending moment at the base of the column is about 20% higher than at the cross-section at the end of the wrapping; this 20%difference barely covers the increase in column flexural capacity due to confinement by the FRP and steel strain hardening. This poses the risk that column yielding may take place above the FRP, before the full column flexural capacity is attained at the base. Column deformation capacity may then be controlled by the limited ductility of the unconfined column above the FRP, instead of the well confined region where plastic hinging may first have taken place.

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

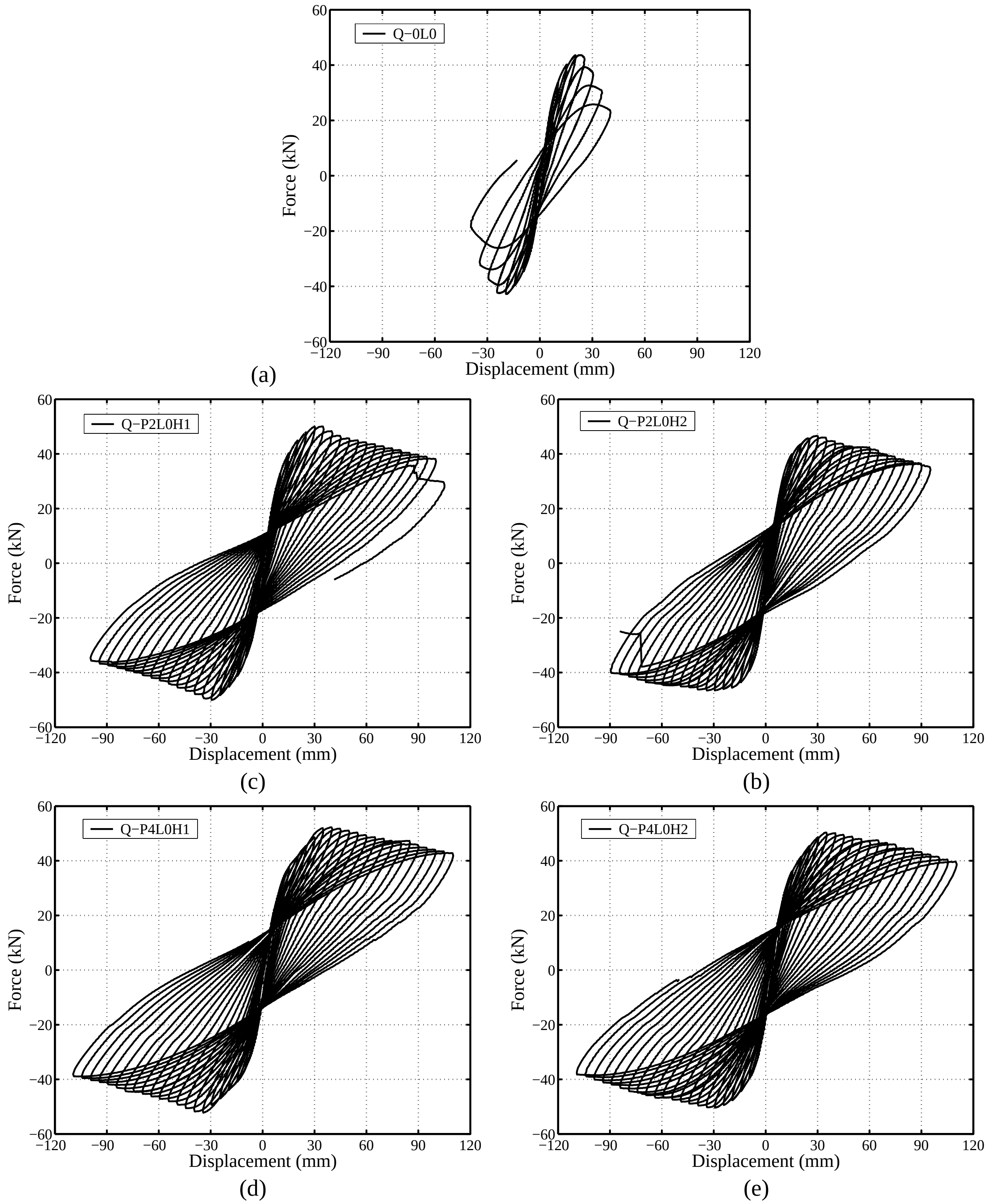

Figure 3 Q-type columns without lap splices: (a) Q-0L0, un-retrofitted; (b) Q-P2L0H1, 2 CFRP layers over 0.6m; (c) Q-P2L0H2, 2 CFRP layers over 0.3m; (d) Q-P4L0H1, 4 CFRP layers over 0.3m; (e) Q-P4L0H2 4 CFRP layers over 0.6m

TEST RESULTS

Q-type columns

Unretrofitted specimens
Force-displacement loops of type-Q specimens are presented in Figure 3(a), for the specimen without laps (Q-0L0) and in Figures 5(a) and (b) for those with lap-splices (Q-0L1, Q-0L2).

The behavior and failure of the control specimen (Q-0L0) was controlled by flexure, attaining a displacement ductility around 3. The concrete cover and part of the core concrete over the lower 200mm of the column disintegrated; bar buckling was evident after concrete cover spalled off. The behavior of specimens Q-0L1 and Q-0L2 with 15 and 25-bar diameters laps, respectively, was also controlled by flexure. Before yielding of the column, cracking parallel to the (hooked) corner bars took place and spalling of the concrete cover appeared and spread below and above the splice level. Loss of concrete cover led to buckling of the longitudinal reinforcement at low drifts (2.5% and 1.6%, for Q-0L1 and Q-0L2, respectively). Member resistance after that point dropped suddenly, as evidenced by the rapid collapse of the load-deformation loops in Figures 5(a) and (b). Damage was concentrated in the splice area, as shown in Figure 4 after the end of the tests.

Figure 4 Failure of non-retrofitted type-Q specimens:
Left: Q-0L1 (15-bar diameter lap); Right: Q-0L2 (25-bar diameter lap)

The force and cyclic deformation capacity of the two columns with lap splices were not noticeably inferior to those of the column with continuous, un-spliced bars. The only respect in which columns with lap splices show inferior behavior is in their more rapid strength degradation after peak resistance. It seems, therefore, that lap splicing of smooth bars with hooked ends does not impair flexural strength, nor it reduces much further the - already low - deformation capacity of these poorly detailed columns. Lapping of the hooked ends of the bars by as little as 15-bar diameters seems sufficient for the force transfer.

Retrofitted specimens
The pattern is very different in the companion specimens retrofitted with FRP wrapping. All retrofitted specimens, regardless of the number of the layers of FRP material and the lapping length, show behaved far better than their un-retrofitted counterparts. In general, member deformation capacity increased by a factor of about 2.5, achieving a drift ratio at conventional failure (20% drop in resistance with respect to peak resistance) from 4.7% to above 7%, and invariably sustaining of close to 7% during the test.

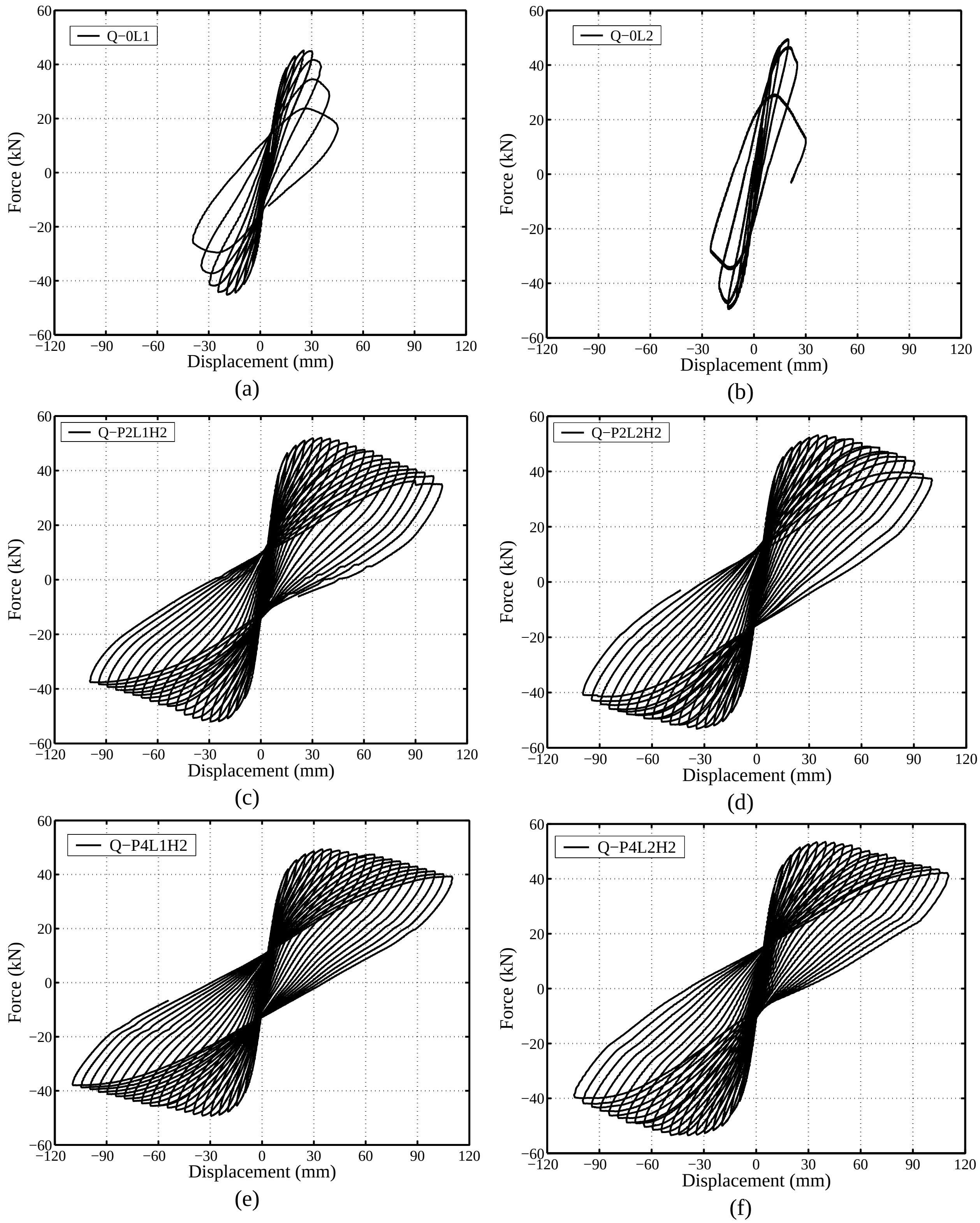

Figure 5 Q-type columns with short or long lap-splices - wrapping with 2 or 4 CFRP layers: (a), (c), (e): short lapping; (b), (d), (f): long lapping;(a), (b): un-retrofitted; (c), (d): retrofitted with 2 CFRP layers; (e), (f): retrofitted with 4 CFRP layers.

As shown in Figure 3 and in Table 1, the increase in force capacity and the post-peak strength deterioration in the column without lap splices is about the same, irrespective of the length of application and the layers of the FRP. Deformation capacity is slightly improved if 4 layers of CFRP are used instead of 2.

Columns with either short lapping lengths (denoted by L1 - Figures 5(c),(e)) or long ones (L2, see Figures 5(d),(f)), retrofitted with 2 or 4 layers of CFRP over the lower 0.6m of the column, had also very satisfactory performance. Specimen Q-P2L1H2 (Figure 5(c)) sustained reversed deformation cycles up to 6% drift before failing by rupture of the FRP during the last cycle of applied displacement. The companion specimen with the same lapping length but retrofitted with 4 layers of CFRP (Q-P4L1H2) had the same peak resistance (Figure 5(e)), but a slower rate of strength degradation after the peak. No sign of rupture of the FRP jacket was observed before the end of the test at 6.8% drift ratio. When the FRP jacket was removed after the end of both tests, the concrete enclosed by the jacket was found thoroughly fragmented. The pattern observed in columns with short lapping does not change for the longer lapping length - Q-P2L2H2 and Q-P4L2H2, Figures 5(d) and (f), respectively: very stable behavior, with both specimens exhibiting the same force resistance and a very gradual strength degradation after peak force. In both specimens the FRP jacket ruptured at the end of the test.

The effect of the length over which the FRP wrapping is applied (0.6m versus 0.3m) is studied through the three pairs of specimens: (a) the two pairs of columns Q-P2L0H1 (Figure 3(b)) and Q-P2L0H2 (Figure 3(c)), or Q-P4L0H1 (Figure 3(d)) and Q-P4L0H2 (Figure 3(f)) without lapping; and (b) that of Q-P4L1H1 (Figure 6(a)) and Q-P4L1H2 (Figure 6(b). In column Q-P4L1H1 the 4 CFRP layers applied over the lower 0.3m of the column cover 1.4 times the length of lapping. No systematic effect of the length of application of the FRP was found; nonetheless, it should be emphasized that, with the large increase of flexural capacity observed between first yielding and peak resistance, the 0.3m of application of FRP are at the limit of inducing plastic hinging (and possibly then failure) above the FRP wrapping, before strength degradation sets in after the peak.

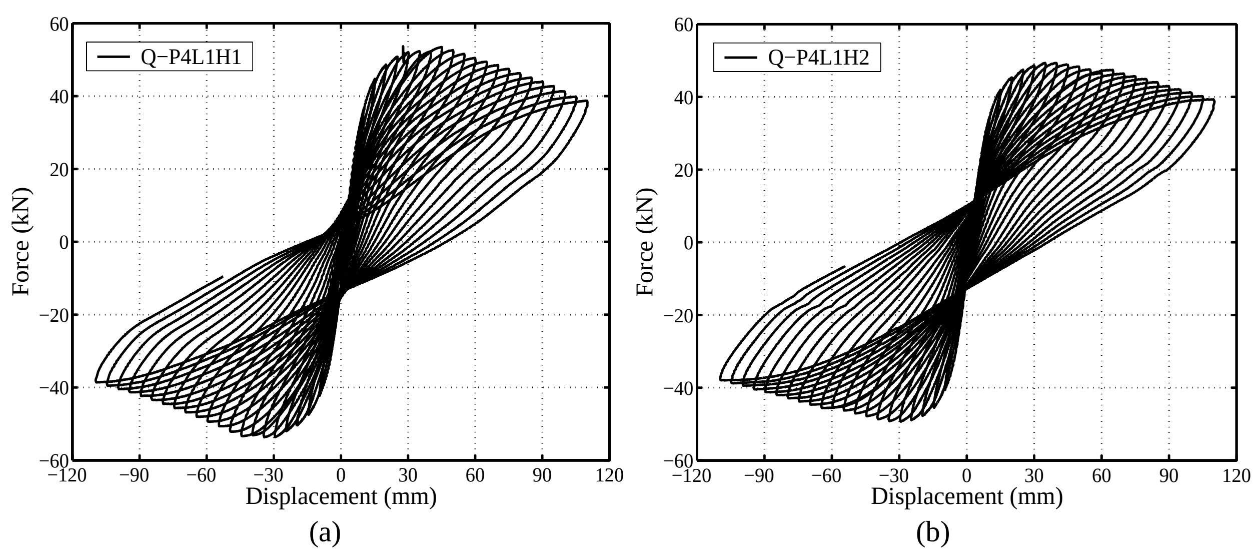

Figure 6 Q–type columns with short lapping and 4 FRP layers applied over: (a) 0.3m; (b) 0.6m.

Comparing the behavior of columns with short lapping (Figures 5(a), (c), (e)), long lapping (Figures 5(b), (d), (f)), or continuous bars (Figures 3(b)-(e)), all retrofitted with 2 or 4 CFRP jackets, it is concluded that force and cyclic deformation capacity and rate of strength degradation is not influenced by the existence and length of the lapping. Nonetheless, energy dissipation seems to be slightly affected, as evidenced by the reduction in the width of hysteresis loops as we go from continuous bars (Figures 3(b)-(e)), to long lapping (Figures 5(b), (d), (f)) and then to short lapping (Figures 5(a), (c), (e)).

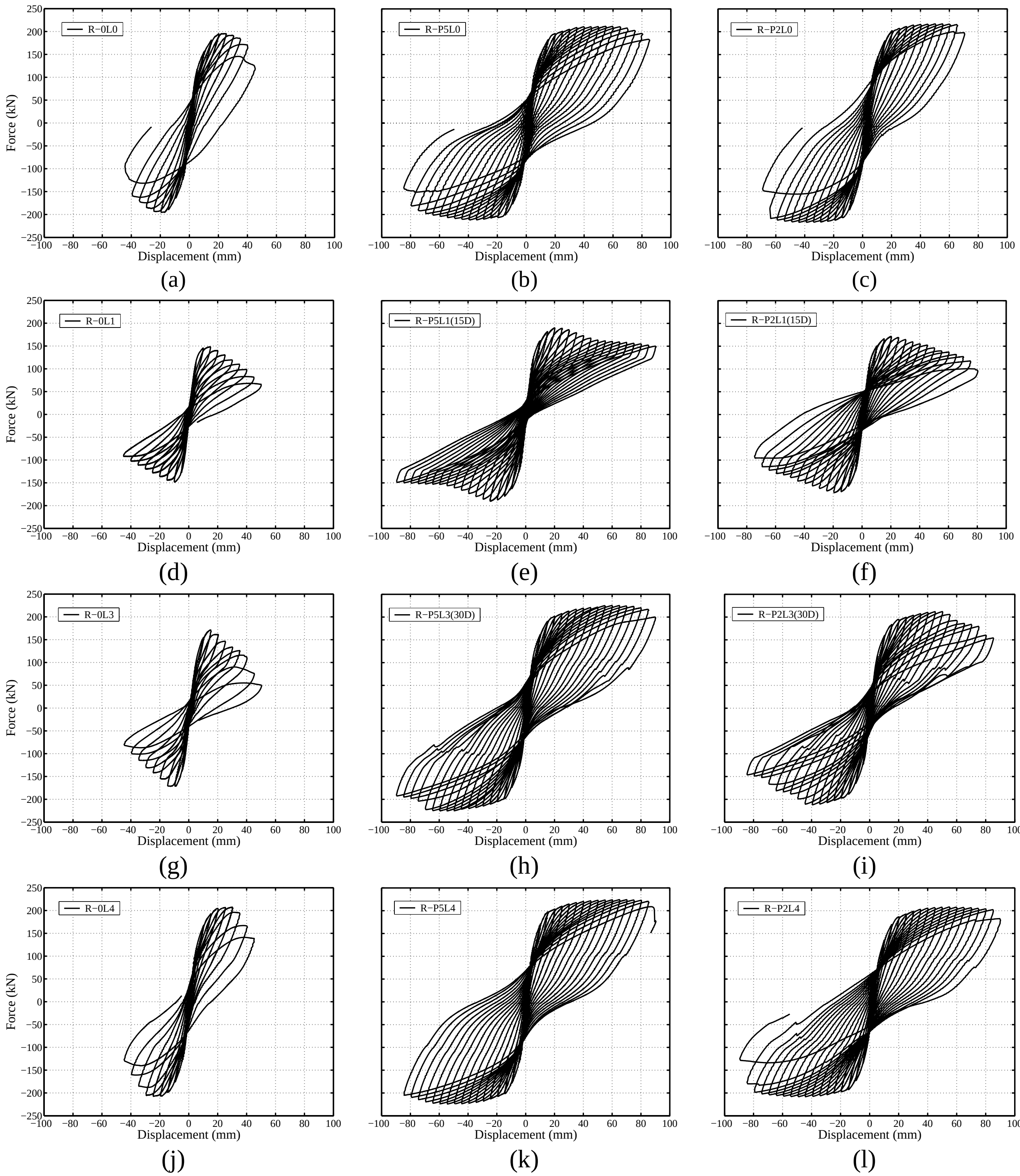

Figure 7 Effect of lap-splice length in R–type columns, un-retrofitted (left): (a) R-0L0, (d) R-0L1, (g) R-0L3, (j) R-0L4; retrofitted with 5 CFRP layers, (center): (b) R-P5L0, (e) R-P5L1, (h) R-P5L3, (k) R-P5L4; retrofitted with 2 CFRP layers (right): (c) R-P2L0, (f) R-P2L1, (i) R-P2L3, (l) R-P2L4

R-type columns

Unretrofitted specimens

Column R-0L0 of the group of type-R specimens serves as the unretrofitted control without lapping of the longitudinal reinforcement. It yielded in flexure but later exhibited a mixed flexure-shear failure mode, with a sudden drop in resistance at a deflection of 45mm (Figure 7(a)), bar buckling, inclined cracking and disintegration of the concrete above the base. On the basis of the criterion of 20%-drop in lateral force resistance the deformation at failure is 40mm (2.5% drift ratio, Table 1).

Three columns were tested with different lap splice lengths: 15 bar-diameters (R-0L1), 30 bar-diameters (R-0L3) and 45 bar–diameters (R-0L4). Their behavior is shown in Figures 7(d), (g), (j). The response is conditioned by the presence and length of lap splices. The column with the short lapping (R-0L1) has the lowest strength of all three. Unlike specimen R-0L4, which has a 45-bar diameter lap, columns R-0L1 and R-0L3 did not reach the full theoretical flexural strength of the end section. The experimental strength of specimens R-0L1 and R-0L3 was 80% and 95%, respectively, of the theoretical flexural capacity, while specimen R-0L4 and the control, R-0L0, reached 110% of the theoretical strength.

(a) (b) (c)

Figure 8 Failure of R-type columns with lap-splices: (a) short - R-0L1, (b) medium - R-0L3, (c) long - R-0L4

In columns R-0L1 and R-0L3 concrete splitting took place early along the plane of lapped bars, followed by crushing ahead of the end of the starter bars, due to the high bearing stresses there (due to the sequence of construction starter bars are usually near the corner of the stirrups and closer to the external surface than the continuing bars). During the following cycles of increasing deflections, spalling and shedding of concrete cover over the lapping took place. Lateral force capacity decreased rapidly after that, due to insufficient force transfer over the lapping. The drift ratio at the conventionally defined failure (reduction of peak cycle resistance below 80% of the maximum resistance in the direction of loading) was 1.5% for both specimens R-0L1 and R-0L3, irrespective of the lapping length. Lap length affected peak resistance, which is lower by 30% in the column with a 15-bar diameters lapping, or by 13% in that with the 30-bar diameters one, with respect to the column with splicing or with a 45-bar diameter lapping. Specimen R-0L4 (45-diameters lap-splice length) performed much better than the other two columns with lap-splices. Strength and deformation capacity of column R-0L4 are the same as those of the control column with continuous longitudinal bars. Splitting cracks appeared along the lapping in this specimen too, but ultimately failure was not conditioned by the splice. This column sustained cycling of horizontal displacements in about the same way as the one with continuous reinforcement, and with similar rate of cyclic strength deterioration after peak load.

Retrofitted columns

Four specimens similar to the previous ones (one without lap-splices and three with 15-, 30- and 45-bar diameter splicing) were tested after wrapping with 5 layers of CFRP. The force-deflection loops of all four are shown on the right column of Figure 7 (Figures (b), (e), (h) and (k)). In column R-P5L1 (with 15-diameter lapping) retrofitting restored member strength to above 90% of that of the control specimen with continuous reinforcement in Figure 7(a), while pre-yield stiffness remained unaffected. In the two other columns with lap splices, strength increased well above that of the unretrofitted column. The deformation capacity of all three retrofitted columns with lap splices was much higher than in the unretrofitted column without lap splices. An interesting observation on the three retrofitted specimens was that no crushing of concrete in the area ahead of the starter bars occurred, even in specimen R-P5L4 in which CFRP was applied over a length 0.6m, i.e. shorter than the lapping length (0.81m), in other words not providing confinement of the concrete at the end of the starter bar. Improvement in bond conditions along the 0.6m-long confined part of the lap splice reduces the force to be transferred by direct bearing of the head of the starter bar against concrete and with it the possibility of local crushing there.

Regardless of the lap-splice length, all columns tested after retrofitting sustained drift ratios of at least 3.4% at conventionally defined failure (see Table 1). The improvement of performance in comparison to the unretrofitted column is due to the confinement of concrete, especially in the splice region. Despite the lateral expansion of the compressed concrete inside the CFRP jacket, the jacket itself did not rupture in any of the specimens of the group.

Figures 7(c), (f), (i) and (l) show test results from specimens with 2 layers of CFRP, without lapping (R-P2L0) and with short to medium lapping length (R-P2L1, R-P2L3, R-P2L4). Two layers is the practical minimum for retrofitting. The retrofitting effect of 2 layers is less than that of 5 layers; nonetheless, the reduction is not commensurate to that of the number of layers. For the specimen with 30-bar diameter laps, which had shown very satisfactory deformation capacity and energy dissipation when retrofitted with 5 CFRP layers, wrapping with just 2 FRP layers is clearly not sufficient. Another interesting observation is that no matter the number of layers, 2 or 5, wrapping with FRP cannot fully remove the deficiency of very short lapping of straight bar ends: although columns R-P5L1 and R-P2L1 have greater deformation capacity than the unretrofitted column without lap splices, they had lower force resistance and low energy dissipation – as evidenced by their narrower loops. It seems therefore that adverse effects of a lap length of at least 30 bar diameters can be removed by FRP wrapping; on the contrary if the lapping is as short as 15 bar diameters, some of its adverse effects cannot be removed by FRP wrapping.

CONCLUSIONS

The effectiveness of CFRP wrapping as a seismic retrofit measure of rectangular columns with poor detailing, and in particular with lap splicing of bars at floor level was investigated. In addition to the bond properties of the bars, parameters studied include the length of lapping, the number of FRP layers, and the length of the member over which FRP wrapping is applied.

The tests of 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.

In FRP-retrofitted columns with smooth bars and hooked ends, no systematic effect of the number of layers and the length of application of the FRP, or even of the existence and length of lapping, on the force and cyclic deformation capacity and the rate of strength degradation was found. Nonetheless, a decrease in lapping seems to reduce energy dissipation in the retrofitted columns.

In FRP-retrofitted columns with straight ribbed bars, 5 CFRP layers are more effective than 2 layers; nonetheless, the improvement in effectiveness is not commensurate to the number of CFRP layers. It seems there is a limit to the improvement that FRP wrapping may bring about: if the lapping of straight ribbed bars is as short as 15 bar-diameters, its adverse effects on force capacity and energy dissipation cannot be fully removed by FRP wrapping.

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