SEISMIC RETROFIT OF BEAMS IN BUILDINGS FOR FLEXURE USING CONCRETE JACKETING

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ABSTRACT
For a reinforced concrete framed building designed for gravity loads, the sagging (positive) flexural capacity of a beam near the joint tends to be deficient due to inadequate amount and discontinuity of the bottom reinforcing bars. One way of retrofitting such beams is concrete jacketing. The present study investigated the effect of a certain scheme of jacketing on the positive flexural behaviour of beam specimens in the span region, and that of the beams of sub-assemblage specimens near the joint. The specimens were tested under monotonic and cyclic loads. From the tests, it was found that the strength, ductility and energy absorption capacities of the retrofitted specimens were higher than the corresponding reference specimens as per the prediction. A layered approach and an incremental nonlinear method were adopted for the analyses of the retrofitted beam and sub-assemblage specimen, respectively. The procedure of jacketing is described for professional practice.

Keywords: Beam, concrete jacketing, flexural capacity, retrofit, seismic force

1. INTRODUCTION

Recent earthquakes have exposed the vulnerability of existing reinforced concrete (RC) buildings with moment resisting frames. A common deficiency in a building that was designed for the gravity loads is the inadequate sagging (positive) flexural capacity of a beam adjacent to the beam-to-column joint. The longitudinal reinforcing bars (rebar) at the bottom of the beam tend to be discontinuous or spliced at an interior joint. For an exterior joint, the bottom bars may not be bent properly with adequate hook length. Pull-out of the bars (especially under low axial load in the column) lead to reduced capacity and deformability of the beam. The present study investigated an option of improving the positive flexural capacity of a beam near an interior joint by concrete jacketing. Concrete jacketing involves placing additional layer of concrete around the existing beam, with additional longitudinal bars and stirrups to enhance the flexural and/or shear capacities. The selected scheme of jacketing involved placement of additional bottom bars continuous at the joint, which were integrated with the additional longitudinal bars of the column for adequate moment transfer.

Another deficiency due to inadequate amount and spacing of stirrups in the potential plastic hinge regions adjacent to the joints, leads to reduced shear capacity and ductility of a beam. The stirrups are generally open, unless the beam is designed for torsion. These lead to absence of confinement of the core concrete, especially in absence of a slab adjacent to the side under compression. Although the present study did not address the deficiency in shear capacity, the jacketing scheme included additional stirrups. The use of closed stirrups in the jacket involves frequently spaced drilling of the existing beam or the supported slab. If the existing concrete is of low strength or the beam has small width, the drilling may worsen the member. Also, drilling may intercept the existing bars unless executed carefully with a rebar locator. Hence, to minimize drilling, the use of closed stirrups was precluded and an alternate method of anchoring the stirrups was conceived.

In the present study, first, slant shear tests were carried out to check the interface bond between the existing (old) and new concrete. Second, simply supported beam specimens were tested to investigate the constructability and effectiveness of the selected jacketing scheme in enhancing the positive flexural capacity in the span region. Finally, beam–column–joint sub-assemblages were tested to study the effect of jacketing of the beams on their positive bending near the joints.

2. LITERATURE REVIEW

Studies of strengthening of RC beams using concrete jackets, have been undertaken in different contexts. Here, the studies are grouped as per the strengthening for gravity loads and seismic forces. Liew and Cheong (1991) tested simply supported flanged beams retrofitted for positive flexural capacity in the span region, with two types of jacketing scheme. In the first type, holes were drilled through the web of an existing beam to place closed stirrups. In the second type, recesses were made in the flange to anchor open stirrups. Cheong and MacAlevey (2000) conducted tests on similar specimens, where open stirrups were placed through pre-located pipe inserts in the flanges and then secured with nuts at the threaded ends. Altun (2004) tested beams of rectangular cross-section, which were jacketed all around the periphery. Shehata et al. (2009) attached the additional longitudinal reinforcement along with expansion bolts as shear connectors. The analysis of the test results was limited to the prediction of the ultimate flexural strength. The above investigations targeted strengthening of beams for the mid-span positive flexural capacity under gravity loads. The authors did not consider the beam as a component of a frame and hence, did not address the strengthening for positive flexural capacity near the joint that is required under seismic forces.

For resisting seismic forces, the experiments conducted by Alcocer and Jirsa (1993) on beam–column–slab sub-assemblages showed that concrete jacketing is effective in strengthening frame members, including the joint region. However, the adopted jacketing scheme involved substantial drilling of the existing concrete. The discontinuity of the bottom longitudinal bars of the existing beams at the joint region was not addressed.

3. TESTS OF BEAMS

3.1 Test Setup

Simply supported beam specimens were tested under two-point loading to study the effectiveness of concrete jacketing in increasing the mid-span positive flexural capacity. The tests were also helpful in assessing the constructability of the jacketing scheme. The test setup is shown in Figure 1. An actuator was used to apply displacement controlled loading. The longitudinal deformations near the top and bottom faces of a specimen were measured in the central region of the span. A deformation was measured over a gauge length equal to the plastic hinge length that was adopted for the beams in the subsequent sub-assemblage specimens. The rotation of the member over the selected gauge length was calculated from the deformation readings near the top and bottom faces.

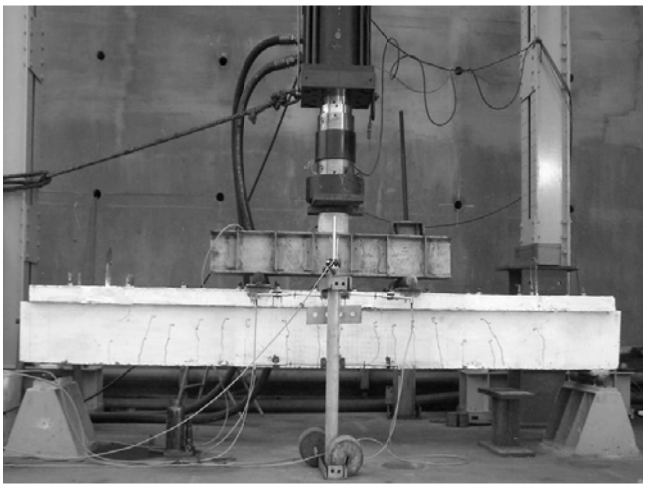


Figure 1. Setup for testing the beam specimens

3.2 Specimen Details

3.2.1 Reference Specimens

A reference specimen without jacketing, was tested under monotonic loading. The presence of the slab in cast-in-place beam–and–slab construction hinders the use of conventional closed stirrups. A flanged beam section was selected to simulate the obstruction due to the slab. The material properties and reinforcement details for the specimen are given in Table 1.

3.2.2 Retrofitted Specimens

Two retrofitted specimens were tested, one under each of monotonic and repeated cyclic loadings. For a retrofitted specimen, the cross-section, reinforcement detailing and the concrete mix of the inner (existing) portion were similar to the reference specimen. The additional longitudinal bars in the jacket were limited so as to retain the ductile behaviour of an under-reinforced section.

Table 1 Material properties and reinforcement details for the beam specimens

(a) Reference specimen

<table>
<tr><th rowspan="2">Specimen</th><th>Concrete</th><th colspan="3">Reinforcement</th><th rowspan="2">Loading</th></tr>
<tr><th>$f_{cm,E}$ (MPa)</th><th>Longitudinal bars</th><th>f_y (MPa)</th><th>Transverse bars</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">24</td><td rowspan="2">Top: 2-16 Ø
Bottom:
2-16 Ø + 2-20 Ø</td><td>416 for 16 Ø</td><td rowspan="2">2 legged, 10 Ø
@ 150 c/c in middle third of the span,
@ 175 c/c at the ends</td><td rowspan="2">Monotonic</td></tr>
<tr><td>420 for 20 Ø</td></tr>
</table>

(b) Retrofitted specimens

<table>
<tr><th rowspan="2">Specimen</th><th colspan="2">Concrete</th><th colspan="2">Additional reinforcement*</th><th rowspan="2">Loading</th></tr>
<tr><th>$f_{cm,E}$</th><th>$f_{cm,J}$</th><th>Longitudinal bottom bars</th><th>Transverse bars</th></tr>
<tr><td>1</td><td>20</td><td>25</td><td rowspan="2">2-16 Ø</td><td rowspan="2">2 legged, 8 Ø
@ 100 c/c in middle third of the span,
@ 150 c/c at the ends</td><td>Monotonic</td></tr>
<tr><td>2</td><td>17</td><td>33</td><td>Cyclic</td></tr>
</table>

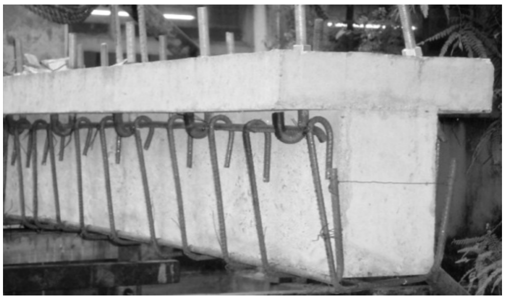
$f_{cm,E}$ = mean cube strength of existing concrete, $f_{cm,J}$ = mean cube strength of jacket concrete, f_y = yield strength of steel, Ø = diameter of bars in mm.

* These bars in the jacket are in addition to those in the existing section. The existing section had the same reinforcement as the reference specimen.

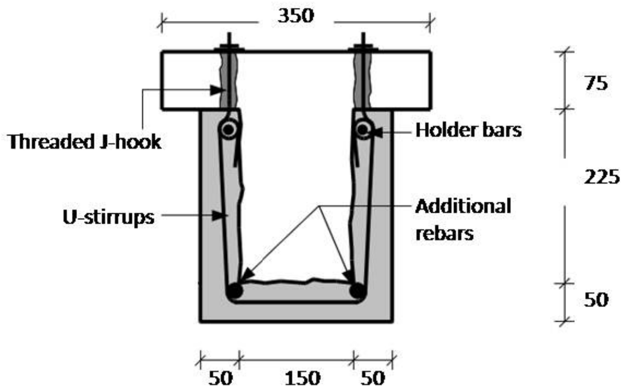
For ensuring the composite action of the jacketed beams, the interface was selected based on the slant shear tests. First, the surface of the existing concrete was roughened with a motorised wire brush to expose the aggregates. The surface was cleaned with a jet of water to remove the dust. The use of bonding agents was not necessary. Next, the additional reinforcement cage for the jacket was anchored to the existing beam. Finally, the additional concrete was made of self compacting concrete.

Seismic retrofit requires closely spaced stirrups for confinement of concrete. Drilling the slab or beam for closed stirrups at frequent interval can lead to considerable damage due to cracking and pop-outs. Hence, the reinforcement cage was made of open stirrups and attached to the slab by J-hooks with larger interval of the drilled holes – in this case, double the spacing of stirrups. The zone of compression in the beam spreads in to the slab, which acts as a flange. This reduces the deficiency due to lack of closed stirrups by delaying the crushing of concrete. The size of the J-hooks was selected such that the strength of the hooks placed per unit length was larger than the yield strength of the stirrups per unit length.

The sequence of fabrication and installation of the rebar cage was such that the cage could be fabricated separately and then attached to the underside of an existing beam. This is convenient when applied to an existing building with high ceiling. Moreover, the technique is applicable without damaging any wall above the beam. Of course, if there is a wall beneath the beam, a few courses of masonry units have to be removed to accommodate the cage. A photograph of the installed cage and the details of a retrofitted section are shown in Figure 2. The self compacting concrete was poured through a drilled hole in the slab.



a) View of cage after installation



b) Sectional details

Figure 2. Reinforcement cage for the concrete jacket (All dimensions are in mm)

3.3 Test Results

Under monotonic loading, the behaviour of each of the reference and retrofitted specimens was typical that for an under-reinforced beam. For the retrofitted specimen, there was no apparent delamination of the jacket up to the peak load. Figure 3 shows the moment versus rotation curves for the reference and retrofitted specimens. The retrofitted specimen had higher moment capacity with comparable ductility with respect to the reference specimen.

For the retrofitted specimen tested under cyclic loading, the variation of peak moment for each cycle of loading showed that the degradation of the strength was gradual even beyond reaching the capacity.

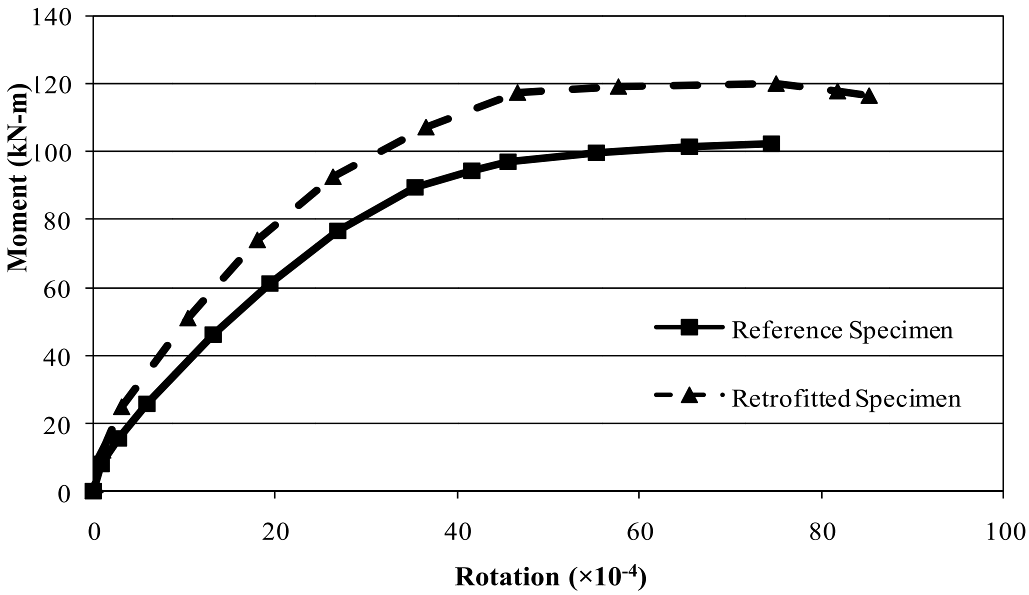


Figure 3. Comparison of moment vs. rotation curves for the beam specimens tested under monotonic loading

4. TESTS OF BEAM−COLUMN−JOINT SUB-ASSEMBLAGES

4.1 Test Setup

Beam–column–slab sub-assemblage specimens were tested using a facility that consisted of a reaction wall, a strong floor and a test frame (Figure 4). The frame was designed and fabricated under the present study. A specimen was erected in a steel assembly at the bottom, which had the provision of placing a hydraulic jack (for applying an upward vertical load at the bottom end of the lower column) and a vertical sliding-cum-rocking pin support. The top end of the upper column was attached to the frame through a spacer assembly and a horizontal sliding-cum-rocking bearing assembly. The lateral load was applied at the top end by an actuator fitted to the adjacent reaction wall. The ends of the beams were supported on horizontal sliding-cum-rocking roller bearings placed on pedestals. Hold down steel members restricted any uplift of the ends of the beams. The longitudinal deformations at the top and bottom faces of the beams were measured near the joint, over gauge lengths equal to the considered plastic hinge length. The later was equated to the effective depth of the beams of the reference specimens and rounded off.

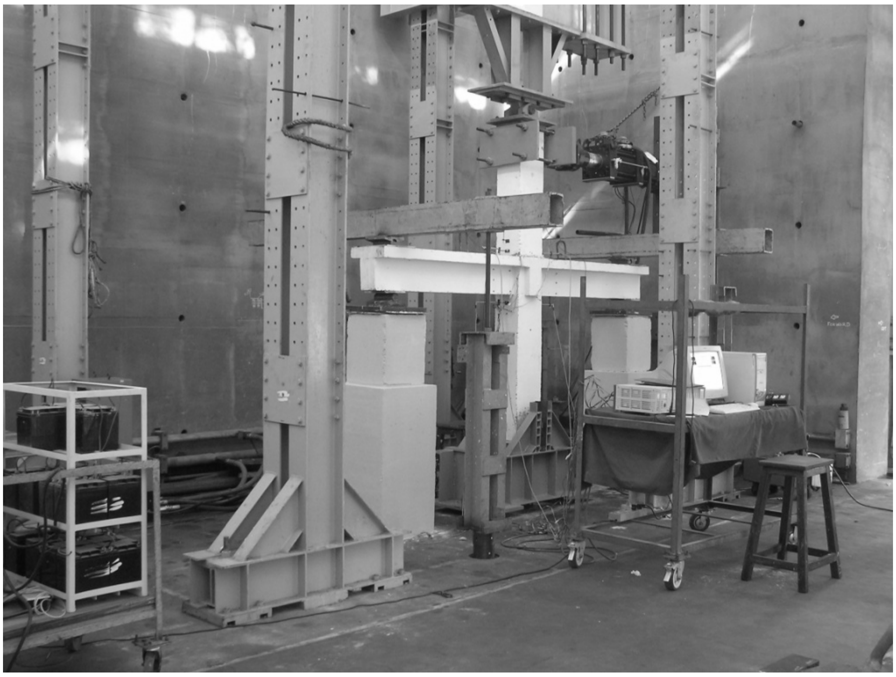


Figure 4. Setup for testing the sub-assemblage specimens

Two reference and two retrofitted sub-assemblage specimens were tested. For each specimen, to simulate the gravity load, first a constant vertical compression approximately equal to the balanced failure load of the column in a reference specimen, was applied on the column. Next, for each type of specimen, one specimen was tested under monotonic lateral load and the other under reversed cyclic lateral load, applied at the top end of the upper column. For the cyclic loading, the increment of displacement was equal to the displacement at the first yield of the longitudinal bars in the beam. At each displacement level, three cycles of loading were applied.

4.2 Specimen Details

The objective of the present study was to investigate the effect of jacketing on the positive flexural capacity of beams at the face of an interior joint. Hence, failure of the columns, shear failures of the beams or the joints were deliberately avoided. Stub beams in the transverse direction and slab over the beams were provided to create obstruction in placing the additional longitudinal and transverse bars in the jacket, like in an interior joint of an existing building.

4.2.1 Reference Specimens

Table 2 provides the material properties and reinforcement details for the specimens. The bottom reinforcing bars of the beam were deliberately discontinued at the joint, to simulate the conventional condition as per gravity load design.

4.2.2 Retrofitted Specimens

The details of the specimens are shown in Figure 5. The construction procedure for jacketing the beams of the sub-assemblage specimens was similar to that for the beam specimens. In the joint region, the additional bottom longitudinal bars were made continuous around the joint by cranking with a splay of 1 in 10. This avoided drilling through the joint. The amount of additional reinforcement was limited to ensure that the column was still stronger than the beam. The stirrups provided along the length of each splay, with spacing as per the ductile detailing requirement for a potential plastic hinge, reduced the straightening of the splay.

In an existing building, a column should also be jacketed to satisfy the design force requirements, and to keep it stronger than the jacketed beams. Hence, the columns in the specimens were also jacketed with additional longitudinal bars and ties. The slab was drilled near the four corners of the columns and the additional bars were continued through the holes. The additional longitudinal bars of the beams were secured with binding wires to the longitudinal bars of the columns for the transfer of moment between the beams and columns, as expected in a rigid joint. Since the joints were provided with adequate amount of ties, additional confining of the joint during jacketing was not adopted. However, in an existing building additional confining of the joints may be required.

The specimens were cast vertically to simulate the actual method of construction. The self compacting concrete for the jacket of a retrofitted specimen was poured from the top for the column, and through a drilled hole in the slab for the beam.

Table 2 Material properties and reinforcement details for the beams in the sub-assemblage specimens

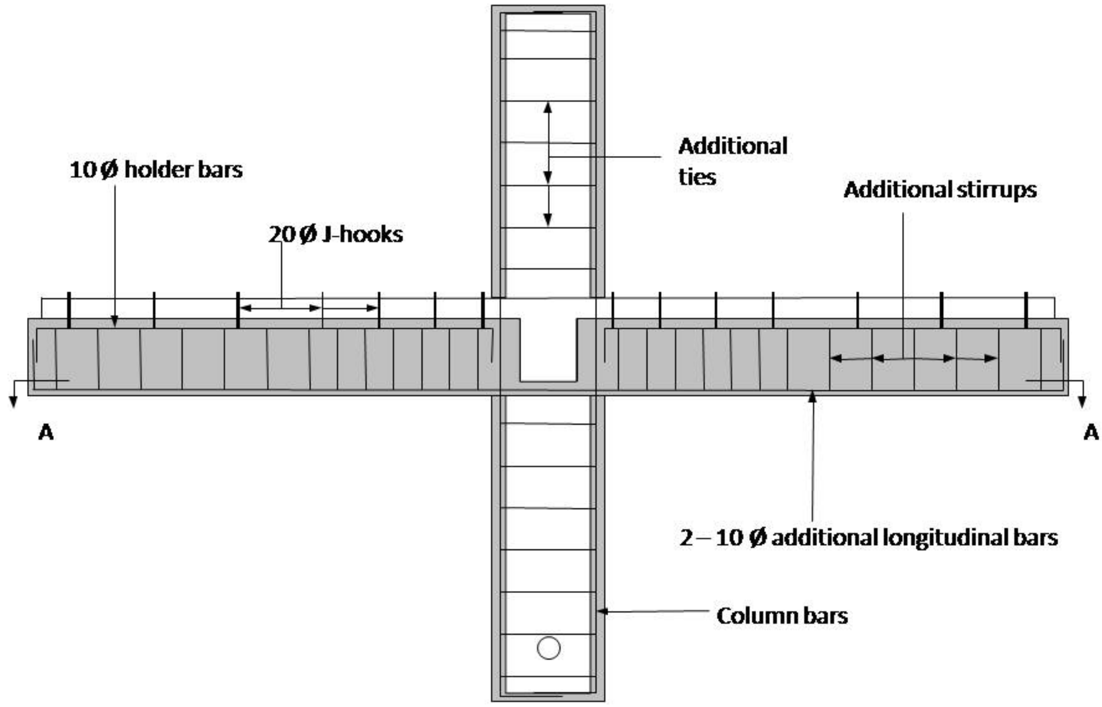
a) Reference specimens

Speci-men	Concrete	Reinforcement			Loading
	$f_{cm,E}$	Longitudinal bars	f_y	Transverse bars	
1	39	Top: 6-10 Ø	450	2 legged, 8 Ø @ 150 c/c in middle third of the span, @ 200 c/c at the ends	Monotonic
2	15	Bottom: 2-8 Ø	420		Cyclic

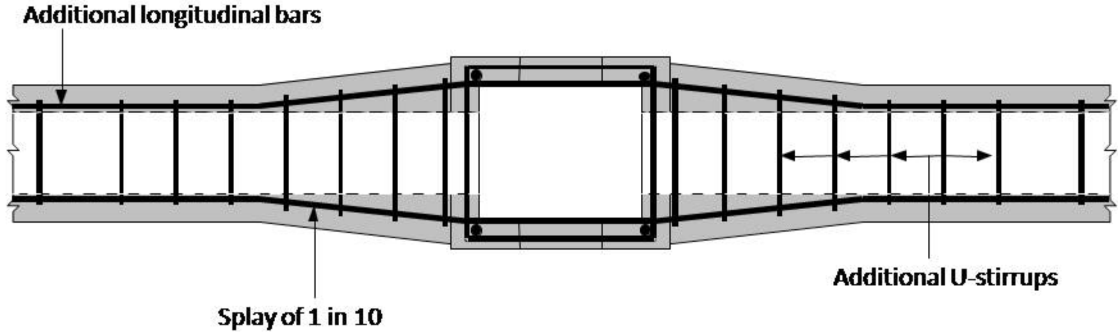
b) Retrofitted specimens

Speci-men	Concrete		Additional reinforcement*			Loading
	$f_{cm,E}$	$f_{cm,J}$	Longitudinal bottom bars	f_y	Transverse bars	
1	20	27	2-10 Ø	450	2 legged, 8 Ø @ 100 c/c in middle third of the span, @ 150 c/c at the ends	Monotonic
2	19	38				Cyclic

* These bars in the jacket are in addition to those in the existing section. The existing section had the same reinforcement as the reference specimen.



a) Sectional elevation



b) Section A-A

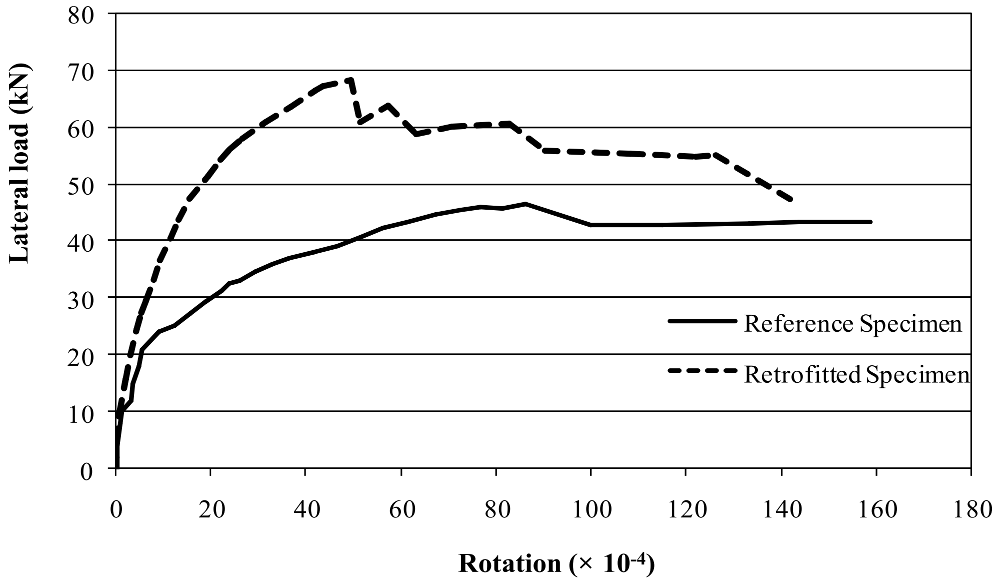
Figure 5. Sectional details for the retrofitted sub-assemblage specimens

4.3 Test Results

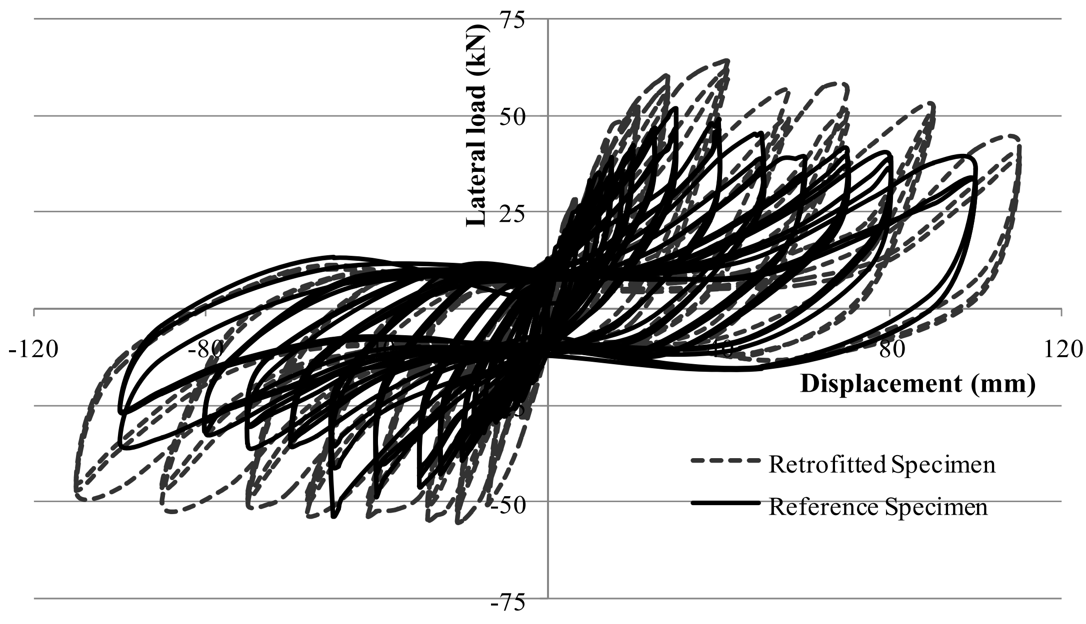
For the reference specimen tested under monotonic lateral loading, the lateral displacement was nearly zero till about 10 kN was reached. Thereafter, a sudden jump in the displacement was noticed at this load. It was inferred that this was due to the effect of friction generated at the sliding bearing in presence of the vertical load. For the specimen tested under cyclic lateral loading, the degradations of the strength and stiffness were observed. Due to the friction generated from the vertical load, the bond of the discontinuous (cut) beam bars at the joint enhanced, and their pull-out was not evident.

For the retrofitted specimen tested under monotonic loading, no spalling of concrete or buckling of the additional longitudinal bars was observed throughout the experiment. Beyond the increased peak load, there was gradual pull out of the discontinuous bars in the inner section of a beam. The retrofitted specimen tested under cyclic loading was found to behave satisfactorily with regard to the strength and energy dissipation, without any drastic effect due to pull out of the cut bars.

The lateral load versus rotation curves for the beam members under sagging, for the reference and retrofitted specimens tested under monotonic loading, are compared in Figure 6a. The lateral load versus top end displacement curves for the reference and retrofitted specimens tested under cyclic loading are compared in Figure 6b. It can be observed that for both the types of loadings, there was increase in lateral strength after retrofitting. The introduction of the continuity bars in the beams and transferring the moment from the beams to the columns were satisfactory. For the retrofitted specimen tested under monotonic loading, although there was pull out of the cut bars beyond the peak load, the deformation was ductile with sufficient residual load capacity. For the retrofitted specimen tested under cyclic loading, there was increase in the energy dissipation. However, the pinching of the hysteresis loops could not be improved. Along with pull-out of the cut bars, the yielding of the continuity bars led to wide cracks, which retained the effect of pinching.



a) Under monotonic loading



b) Under cyclic loading

Figure 6. Comparison of the lateral load versus displacement curves for the sub-assemblage specimens

5. ANALYSIS FOR RETROFITTED SPECIMENS

5.1 Analysis of Beams

The moment versus rotation curves for the plastic hinges formed in the retrofitted beams were predicted by a layered analysis. A retrofitted section is a heterogeneous section with two grades of concrete and several layers of reinforcement bar. To account for the heterogeneity, the layered analysis was used, wherein the section was divided into layers through the depth. Considering limited interfacial shear stress in the flexure dominated behaviour, a perfect bond for strain compatibility between the existing concrete and the jacket was assumed. First, the behaviour of the retrofitted beam specimen tested under monotonic loading, was predicted. Next, the predicted behaviours of the beams near the joint of the retrofitted sub-assemblage specimen tested under monotonic loading, were used to estimate the lateral load versus displacement behaviour of the sub-assemblage specimen.

5.2 Analysis of Sub-assemblage Specimen

The behaviour of the retrofitted specimen was predicted by a computational model of the sub-assemblage. The model consisted of frame elements with appropriate boundary conditions. To consider spread plasticity, the beam members were sub-divided to isolate the plastic hinge regions of length approximately equal to their effective depths. An incremental non-linear analysis was conducted with varying flexural stiffness for the plastic hinge elements. The variation of the flexural stiffness with increasing lateral load was assigned based on the moment versus rotation curves computed by the layered analysis. The capacity of a discontinuous bar was reduced based on the provided embedment length. However, any slip of the bar beyond the peak load was not modelled.

During the tests of the specimens, horizontal frictional forces were induced at the bearings at the ends of the beams and the top end of the upper column, due to reactions from the applied vertical load. For a precise prediction of the behaviour, based on the measured coefficients of friction for the bearings, the frictional forces were included in the computational model. The predicted lateral load versus displacement curve for the retrofitted specimen is plotted in Figure 7. It can be observed that the predicted curve is close to the experimental results up to the peak. Beyond the peak, the experimental results deviated from the predicted curve due to the pull out of the discontinuous bars.

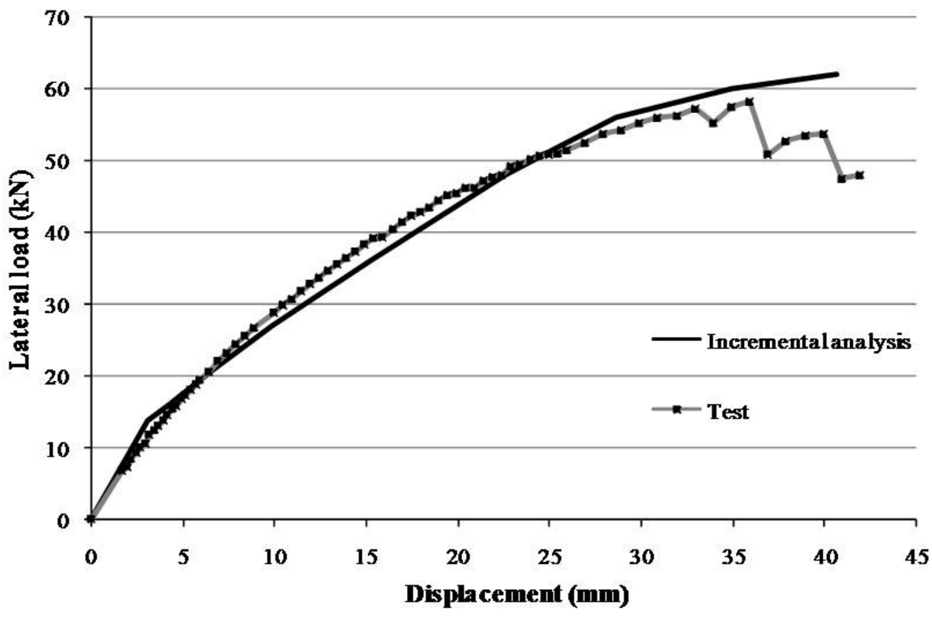


Figure 7. Lateral load versus displacement curves for the retrofitted sub-assemblage specimen tested under monotonic loading

6. SUMMARY AND CONCLUSIONS

The beams in existing reinforced concrete buildings with moment resisting frames, tend to be deficient in sagging (positive) flexural capacity near the joints due to inadequate amount and anchorage of the bottom longitudinal bars. The present study investigated the effect of concrete jacketing on the positive flexural capacity and performance of beams near an interior joint. First, slant shear tests were carried out to check the interface bond between the existing (old) and new concrete. Second, reference and retrofitted simply supported beam specimens were tested under two-point bending to investigate the constructability and effectiveness of the selected jacketing scheme in enhancing the positive flexural capacity in the span region. Finally, beam−column−slab sub-assemblage specimens were tested to study the effect of introducing bottom bars continuous at the joints, and subsequent jacketing of the beams on their positive bending near the joints. The retrofitted specimens tested under monotonic loading were analysed based on the layered method for the beams and a non-linear incremental method for the sub-assemblage. Instead of discretising a member using solid elements, a macro approach was adopted for the analysis of a sub-assemblage specimen, so that a similar approach can be used for the analysis of a building with retrofitted members.

Following are the conclusions from the present study.

1. From the beam tests, it was observed that the increase in strength and retention of ductility after concrete jacketing was as predicted by the analysis. The retrofitted specimens did not show visible delamination between the existing concrete and the concrete in the jacket.

2. For the selected scheme of jacketing, the retrofitted sub-assemblage tested under monotonic loading showed expected increase in the lateral strength. Even after the initiation of pull out of the discontinuous bars of the beam under sagging, the ductility in the deformation was adequate along with residual capacity.

3. The degradations of strength and stiffness of the retrofitted sub-assemblage under cyclic loading were gradual. The energy dissipation increased after retrofitting. However, the pinching in the hysteresis loops could not be reduced.

4. A layered analysis provides good prediction of the strength and the moment versus rotation behaviour of the plastic hinge region of a retrofitted beam. The incremental non-linear analysis with varying flexural stiffness for the plastic hinge elements and incorporation of friction in the bearings, showed adequate prediction of the lateral load versus top end displacement behaviour of the retrofitted sub-assemblage specimen tested under monotonic lateral loading.

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