AN INVESTIGATION OF SEISMIC RETROFIT OF COLUMNS IN BUILDINGS USING CONCRETE JACKET

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ABSTRACT :

The columns in a typical reinforced concrete multi-storeyed building in India, especially with an open ground storey, are found to be deficient to resist seismic forces. One option of retrofitting the columns is to jacket them with concrete. The conventional analysis of a jacketed column investigates the strength based on interaction diagrams for the composite section or for some equivalent section. The present study investigates the performance of columns jacketed by a certain scheme of reinforcement. First, prism specimens with new concrete cast against the sloping faces of old concrete were tested under compression (slant shear test) to study the interface between old and new concrete. Second, column specimens were tested under pure compression, eccentric compression and pure bending to study the effect of jacketing on the strength. Finally, beam-column sub-assemblages with reference and retrofitted columns, were tested under monotonic and cyclic lateral loads in presence of constant vertical loads. From the tests, it was found that the lateral strength, ductility and energy absorption capacities of the retrofitted specimens were higher than the corresponding reference specimens as per prediction. A lamellar analysis was used for the prediction of the moment versus curvature behavior of a retrofitted column section. An incremental nonlinear approach was used to predict the lateral load versus displacement behavior of the retrofitted sub-assemblage tested under monotonic lateral load. The scheme of strengthening a column is explained with reference to the practical considerations of an existing building.

KEYWORDS: Concrete jacket, column, lamellar analysis, multi-storeyed building, reinforced concrete.

1. INTRODUCTION

The earthquake at Bhuj, Gujarat, in 2001 has been a watershed event in the earthquake engineering practice in India. The Indian code of practice for seismic analysis has been revised to reflect the increased seismic demand in many parts of the country. Many existing reinforced concrete (RC) framed buildings lack the seismic strength and detailing requirements of the current codes of practice, because they were built prior to the implementation of these codes. Failure of the columns can lead to the failure of a storey and the building. The columns in a typical multi-storeyed building in India, especially with an open-ground storey (a ground storey without any infill wall or minimal infill walls, for parking of vehicles or commercial display), are found to be deficient in flexural and shear strengths. Under moderate to severe earthquake, an undesirable column side-sway will lead to a soft-storey collapse mechanism.

To mitigate the disaster in future earthquakes, the existing deficient buildings need to be retrofitted. Selection of an appropriate retrofit scheme is based on seismic evaluation of a building and the available resources. For a building, a combination of retrofit strategies may be selected under a retrofit scheme. Retrofit strategies may be broadly classified as local and global strategies. The global retrofit strategies are applied to improve the overall behavior of the building. In addition to a global retrofit strategy, it may be necessary to retrofit some members. The later can be considered as a local retrofit strategy. An economic way of retrofitting the columns is by concrete jacketing. To enhance the flexural and shear capacities of an existing column, concrete jacketing involves placing additional longitudinal bars and ties and a layer of concrete around the column.

Of course before any intervention, an analysis is required to judge the potential of improvement in the lateral strength and ductility of the retrofitted column. The present paper reports an investigation of the strength and performance of jacketed columns in beam–column sub-assemblages, tested under varying lateral loads and constant vertical loads.

2. PRELIMINARY TESTS

Before the tests of the beam–column sub-assemblages, tests were conducted on prisms and columns. These tests are briefly mentioned here. The details were reported by Gnanasekaran (2008).

2.1 Slant Shear Tests

Slant shear tests were carried out to check the interface bond between old and new concrete. Compression tests were conducted on prisms made of new concrete cast against the sloping faces of old concrete. The specimen size was 150 mm × 75 mm × 75 mm. The procedure as per BS 6319: 1984 (Part 4) was followed. For different specimens, the faces of old concrete were plain without any intentional roughening or roughened by motorized wire brush or hacked by chisel. For each of these types of surfaces there were two varieties: without application of any bonding agent or with the smearing of a bonding agent. From the results, it was found that the specimens with roughened surface of the old concrete and without any bonding agent failed at higher loads compared to the other specimens. Hence, it was decided that the faces of the old concrete for the retrofitted specimens of subsequent tests would be similarly roughened and bonding agent would not be used.

2.2 Tests of Columns

To quantify the increase in strength of a retrofitted column with respect to the pre-retrofit strength, nine column specimens were tested for each of reference and retrofitted cases. In each case, three specimens were tested under each of pure compression, eccentric compression and pure bending. For the specimens tested under eccentric compression, the eccentricity of the compression was about one axis and the values of the eccentricity were selected corresponding to balanced failure.

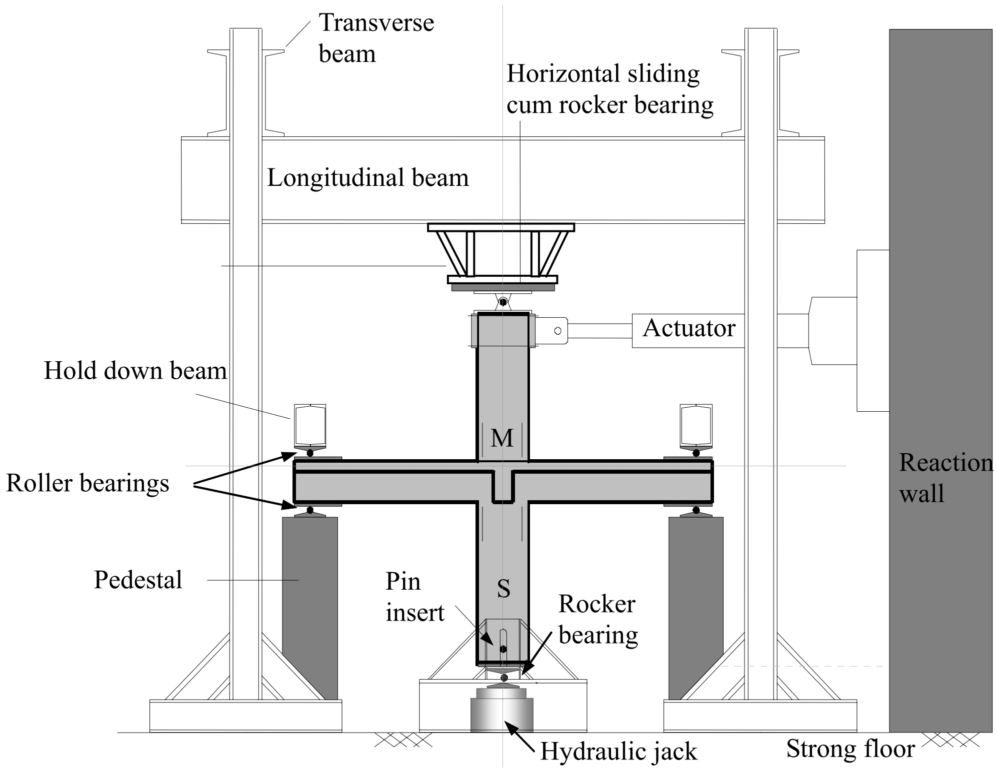
The cross-section and height of the test region of the reference specimens were 150 mm × 150 mm and 1000 mm, respectively. For retrofitted specimens, the size and reinforcement detailing of the inner sections were similar to the reference specimens. After jacketing, the cross-section was 250mm × 250 mm. The cross-section of the columns was same as that of the beam–column sub-assemblage specimens which are explained later (Figure 3.2). It was observed that the increase in strength after retrofitting can be predicted based on the interaction diagram of a retrofitted section developed using a lamellar approach.

3. TESTS OF BEAM–COLUMN SUB–ASSEMBLAGES

Beam–column sub-assemblages were tested to study the effect of retrofitting of the column on the load versus displacement behavior under varying lateral loads and constant vertical loads. The following sub-sections provide specific details of the tests.

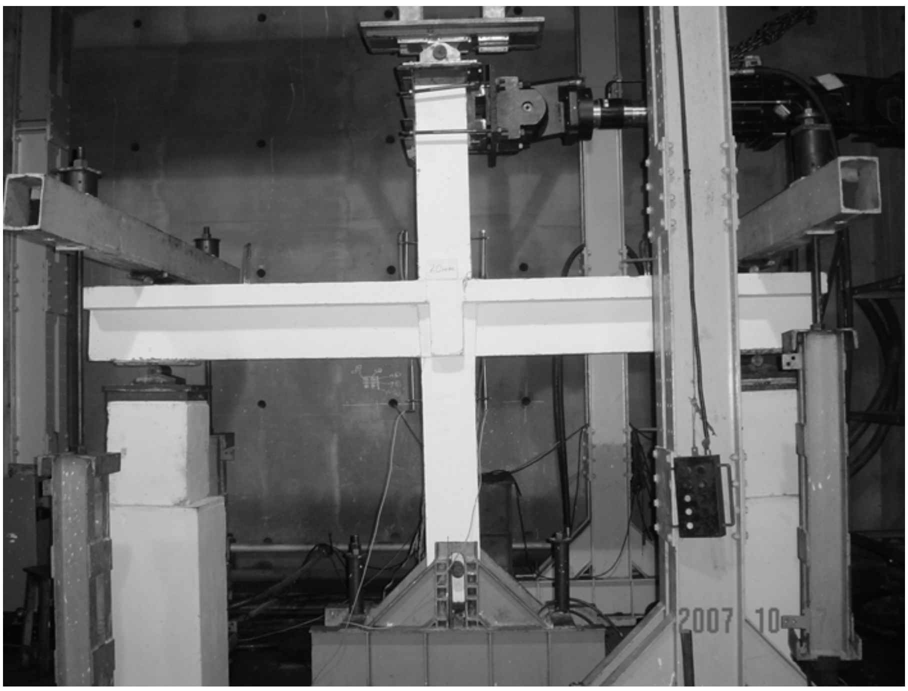
3.1 Test Setup

In a multi-storeyed frame, the points of contra-flexure under lateral loads lie approximately at the centres of the beams and columns. This condition can be simulated by testing a beam–column sub-assemblage as shown in Figure 3.1. A steel frame was installed on a strong floor next to a reaction wall. The top end of the sub-assemblage was attached to the frame through a spacer assembly and horizontal sliding-cum-rocker bearing. The horizontal load was applied at the top end by a displacement-controlled hydraulic actuator.



M = LVDT gage, S = Specimen

(a) Schematic diagram



(b) Photograph with retrofitted specimen

Figure 3.1 Set-up for testing beam–column sub-assemblages

A rocker bearing with the provision of vertical sliding was kept at the bottom end of the sub-assemblage. Vertical load was applied at the bottom end by a load-controlled hydraulic jack. The ends of the beam were supported on pedestals. The ends were allowed to translate horizontally and rotate by providing roller bearings. Hold down beams restricted any uplift of the ends of the beams.

3.2 Specimen Details

Two reference and two retrofitted sub-assemblage specimens were tested. For each type, one specimen was tested under monotonic lateral load and the other under cyclic lateral load. The heights of the columns in a sub-assemblage from the faces of a joint were 1.0 m. The total height of a specimen was 2.5 m. The lengths of the beams from the centre-line of the joint were 1.5 m. Thus, the total length of a specimen was 3.0 m. The beams had top flanges to simulate the obstruction due to the slab in the placement of the additional longitudinal bars in the column jacket. Stub beams in the transverse direction were provided at the joints to simulate a joint in an interior frame.

Table 3.1 provides the material properties and reinforcement details for the columns of the reference and retrofitted specimens. The cross-sectional details of the beams and columns are shown in Figure 3.2. To avoid failure of the beams prior to that of the columns, both the positive and negative yield moments of the beams were at least 10 percent higher than the ultimate flexural capacity of the retrofitted columns. The members had adequate shear reinforcement to avoid any shear failure. A vertical load of 130 kN was selected which is close to the balanced failure load of a reference specimen.

For a retrofitted specimen, to continue the additional longitudinal bars of the column jacket through the slab, holes were drilled in the slab near the corners. To stiffen the additional bars against buckling and to confine the joint region, angles were welded to the bars at the joint. To enhance the integrity of the angles, they were clamped together above the slab and beneath the soffits of the beams with 10 mm diameter threaded bolts. Details of the placement of the additional bars near a joint are shown in Figure 3.3. Placement of additional ties at the joint was purposely avoided. This is because drilling of holes in the beams of an existing building of low grade or poor quality concrete may make the beams vulnerable to cracking. The specimens were cast vertically to simulate the actual method of construction. The jackets were made of self compacting concrete.

Table 3.1 Properties of the columns for the reference and retrofitted specimens

Type of lateral loading	Vertical load	Materials properties				Details of reinforcement in jacket	
		$f_{cm\,E}$	$f_{cm\,J}$	$f_{y\ell}$†	f_{yt}†	Longitudinal bars	Transverse bars
	kN	MPa					
Reference specimens							
Monotonic	130.0	24.0	-	435.0	468.0	4 – 12 Ø	8 Ø @ 110 mm c/c throughout
Cyclic							
Retrofitted specimens							
Monotonic	130.0	22.0	31.0	483.0	504.0	4 – 12 Ø*	8 Ø @ 100 mm c/c*
Cyclic		24.0	32.0				

$f_{cm\,E}$ = mean cube strength of old concrete, $f_{cm\,J}$ = mean cube strength of concrete for jacket, $f_{y\ell}$, f_{yt} = yield strengths of longitudinal and transverse bars, respectively, Ø = diameter of bars in mm.

† The values correspond to proof stress, defined for a plastic strain of 0.002. The modulus of elasticity for steel (E_s) was measured to be 2.05×10^5 N/mm^2.

*These bars are in addition to those in the original cross-sections, which are same as in the reference specimens. Each transverse bar for the jacket was made of two U-bars.

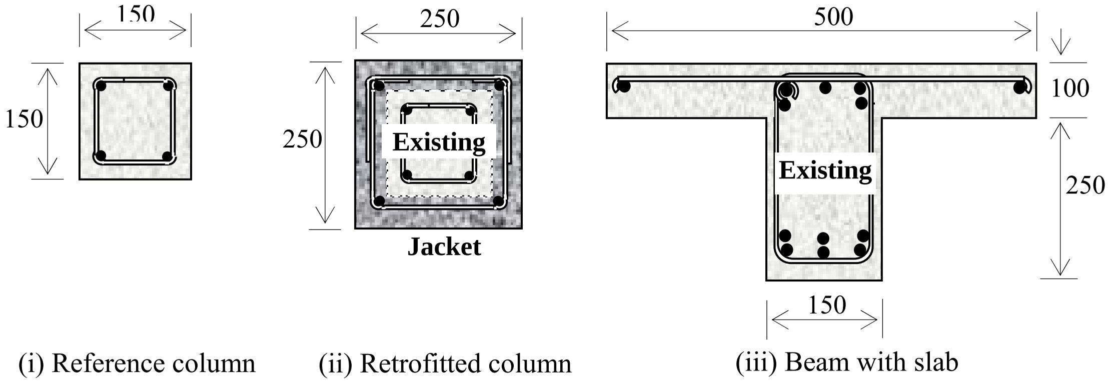


Figure 3.2 Details of the cross-section of the beams and columns (all dimensions in mm)

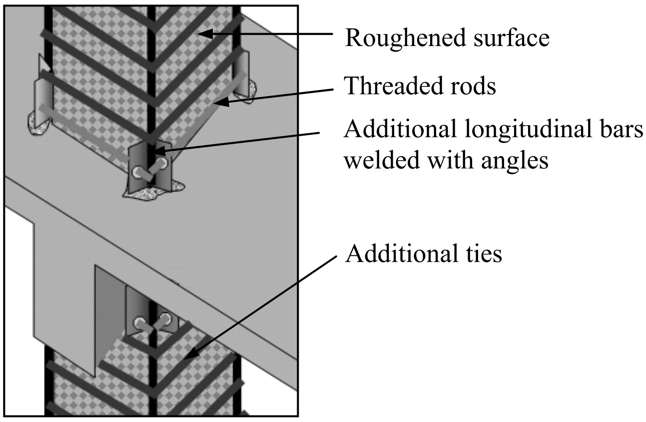


Figure 3.3 Details of placement of additional reinforcement in the retrofitted specimens

3.3 Test Results

3.3.1 Under monotonic loading

The lateral load versus displacement curves for the reference and retrofitted specimens are plotted in Figure 3.4. For the retrofitted specimen, the columns in the retrofitted specimen were found to behave satisfactorily with regards to the strength and ductility, without any premature failure, such as buckling of the additional longitudinal bars at the joint. The top and bottom columns developed plastic hinges near the joint faces.

3.3.2 Under cyclic loading

The lateral load versus displacement curves for the reference and retrofitted specimens are plotted in Figure 3.5. For the retrofitted specimen, the columns were found to behave satisfactorily with regards to the strength and energy dissipation characteristics, without any premature failure. At higher displacements, pinching of the hysteresis loops started due to closure of the wide cracks with yielded longitudinal bars. The values of lateral strength and displacement ductility of the reference and retrofitted specimens are shown in Table 3.2.

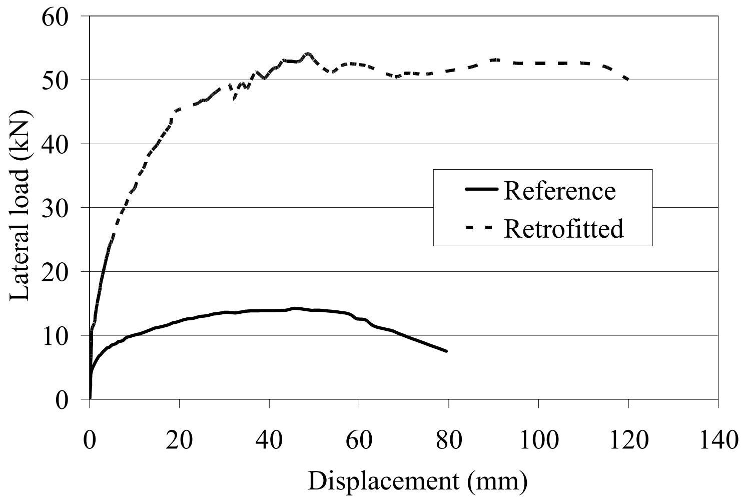


Figure 3.4 Comparison of the lateral load versus displacement curves under monotonic loading

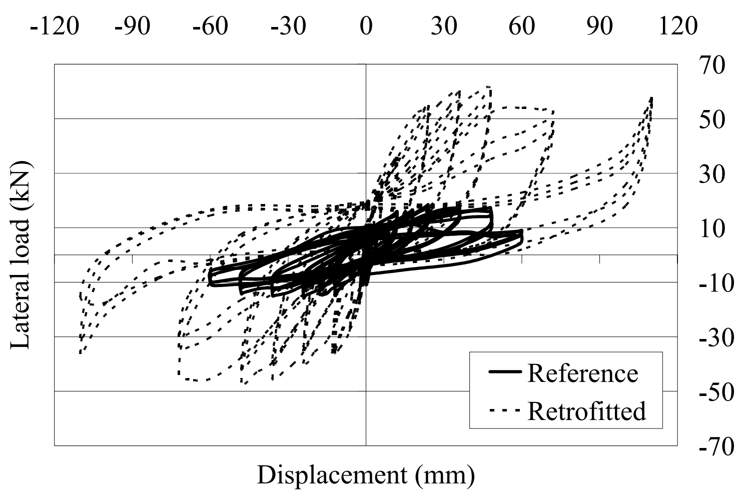


Figure 3.5 Comparison of the lateral load versus displacement curves under cyclic loading

Table 3.2 Values of lateral strength and ductility for reference and retrofitted specimens

Type of loading		Specimen	Lateral strength	Lateral displacement at Yield* (Δ_y)	Lateral displacement at Ultimate† (Δ_u)	Displacement ductility	Cumulative energy absorption till 27th cycle
			kN	mm			kN-mm
Monotonic		Reference	14	18	45	2.5	
		Retrofitted	53	24	110	4.6	
Cyclic	–	Reference	14	30	48	1.6	7617.0
	+		17	24	48	2.0	
	–	Retrofitted	47	22	110	5.0	36944.0
	+		58	20	110	5.5	

* Displacement corresponding to an average strain of ($f_{y\ell}/E_s$) + 0.002 in the extreme longitudinal bars in the plastic hinge regions of the columns. The values of f_y and E_s are given in Table 3.1.
† Displacement corresponding to the onset of the drop in the applied lateral load.

3.4 Analytical Results

To model the effect of retrofitting a column in a building analysis, first the strength and moment versus curvature behavior of a retrofitted column section need to be predicted. Next, in a non-linear static analysis of the building under lateral load, the modeled moment versus rotation behavior needs to be incorporated. These two analyses are illustrated for the retrofitted sub-assemblage tested under monotonic lateral load.

3.4.1Lamellar analysis for predicting moment versus curvature behavior

A retrofitted section is a heterogeneous section with two grades of concrete and several layers of reinforcement bar. To account for the heterogeneity, a lamellar method of analysis was used for the prediction of the moment versus curvature behavior of the column sections of the retrofitted sub-assemblage under consideration. A section was divided into layers to consider the different values of stress for the two grades of concrete and steel for the same strain at a level. The inner portion of the concrete was considered to be confined. The stress versus strain model proposed by Mander et al. (1988) was selected to account for the effect of confinement. A parabolic–plastic stress versus strain model was used for the unconfined concrete of the jacket. Figure 3.6 shows the comparison of the analytical result with the test data. It can be observed that the behavior is well predicted.

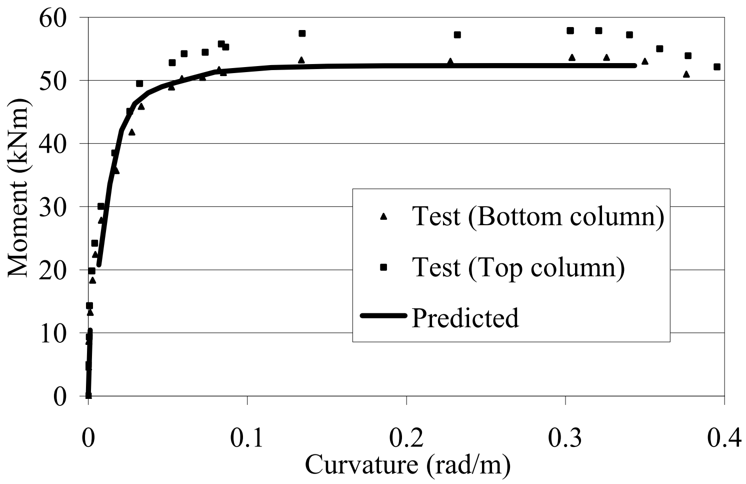


Figure 3.6 Comparison of moment versus curvature curves for the retrofitted column sections

3.4.2 Incremental non-linear analysis for predicting lateral load versus displacement behavior

For the prediction of the lateral load versus displacement behavior of the retrofitted sub-assemblage under consideration, a finite element model was developed. To consider spread plasticity in the columns, the top and bottom columns were sub-divided to isolate the plastic hinge regions of length equal to half of the depth from the faces of the beam-column joint. An incremental nonlinear analysis was adopted to assign the flexural stiffness of each of the plastic hinge member (based on the moment versus curvature property) at each increment of the lateral load. The generation of secondary moment in the columns under vertical load (P-Δ effect) and friction at the bearings were accounted for. The predicted lateral load versus displacement curve for the sub-assemblage is compared with the test result in Figure 3.7. It can be observed that the predicted curve is close to the test result.

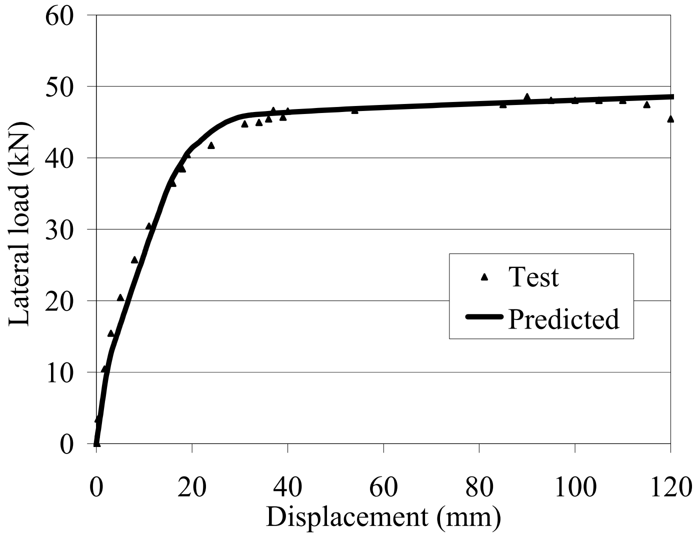


Figure 3.7 Comparison of lateral load versus displacement curves for the retrofitted sub-assemblage

4. CONCLUSIONS

Following are the conclusions from the tests and analyses of the beam–column sub-assemblages.

1. The retrofitted specimens did not show any delamination between the existing concrete and the concrete in the jacket.

2. The lateral strength of the retrofitted specimen tested under monotonic loading was 3.8 times higher than that of the corresponding reference specimen. Similarly, the lateral strength of the retrofitted specimen tested under cyclic loading was 3.3 times higher than that of the corresponding reference specimen.

3. The displacement ductility of the retrofitted specimen tested under monotonic loading was 1.8 times higher than that of the reference specimen. Similar observations were made from the specimens tested under cyclic loading.

4. Under cyclic loading, the cumulative energy absorption (till attaining the strength) for the retrofitted specimen was 4.85 times higher than that of the reference specimen.

5. The lamellar analysis can predict the moment versus curvature behavior of a retrofitted column section reasonably well. Based on this analysis, the incremental non-linear analysis closely predicted the lateral load versus displacement behavior of the retrofitted sub-assemblage.

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