SEISMIC REHABILITATION OF DAMAGED SHEAR-CRITICAL COLUMNS OF RC FRAME USING CFRP JACKETING

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ABSTRACT

Open ground story reinforced concrete (RC) buildings designed only for gravity loads are more vulnerable to severe damage or complete collapse under seismic loading. The inadequate shear and flexural strengths of ground story columns to resist the seismically-induced demand is considered as the main cause of failure of these structures. Very often, carbon fiber reinforced polymer (CFRP) jacketing is used to improve the axial and lateral load-resisting capacity of RC members. An experimental investigation was conducted in this study to explore the effectiveness of CFRP jacketing in improving the overall seismic performance of a damaged RC frame. A two-story half-scale RC frame with severely damaged columns in open ground story and masonry infill walls in the top story was considered as the test specimen. These damaged columns were rehabilitated using micro-concreting followed by CFRP jacketing process. Slow-cyclic testing of the rehabilitee test frame was carried out by applying gradually-increasing lateral cyclic displacements at both story levels. The main parameters investigated were lateral strength, hysteretic response and ductility response. Test results showed that the proposed rehabilitation technique significantly improved the lateral strength and drift capacity of the test frame.

Keywords: Drift; Fiber reinforced polymer; Lateral strength; Seismic strengthening; Soft-story RC frame

1. INTRODUCTION

Non-ductile reinforced concrete (RC) frame buildings exhibit poor seismic performance, in terms of lateral load resistance, displacement ductility, energy dissipation and mode of failure. The reasons for structural deficiencies in these buildings are: (i) the inadequate confinement of concrete in the potential plastic hinge regions, (ii) the insufficient amount of transverse reinforcement in the joint regions, (iii) the insufficient amount of longitudinal and transverse steel in main members, (iv) the inadequate anchorage detailing of reinforcement bars, and (e) the improper lap splicing of longitudinal reinforcement (Oinam et al. 2014). Significant lack of ductility, rather than the inadequate lateral strength, has been recognized as the primary source of deficiency in the seismic performance of the gravity-load designed RC buildings (Priestley 1997). The presence of open ground story (also known as soft-story) makes these non-ductile RC frame structures more vulnerable to severe damages or complete collapse under seismic loading as compared to those with the regular configurations (Jain et al. 2002; Oinam and Sahoo 2017a). In spite of the poor seismic performance, RC buildings with soft-story are still preferred in many developing countries. The use of open ground story offer some added functional and architectural advantages, such as, provision of parking, garages, storage and other commercial activities (Haran Pragalath et al. 2016; Oinam and Sahoo 2017a). Several building codes (e.g., ASCE 41-13 2013; ATC-58 2007; IS:1893-I 2016) recommend an amplified lateral force at the soft-story level for the design of new structures. However, suitable strengthening techniques should be adopted for such highly-deficient existing buildings in order to achieve the desired seismic performance objectives.
Many local and global retrofitting techniques are used in the practice to improve the seismic performance of a RC structure. These techniques include steel jacketing, concrete jacketing, steel caging, external pre-stressing and polymer wrapping (Belal et al. 2015; Saatcioglu and Yalcin 2003; Sakino et al. 2004; Teng et al. 2016; Vandoros and Dritsos 2008). Fiber reinforced polymer (FRP) has many advantages, such as, high tensile strength (nearly five-times stronger than steel), high initial stiffness (nearly twice of steel), high chemical resistance, high temperature tolerance, light weight and low thermal expansion. Therefore, FRP wrapping technique is being adopted in various retrofitting projects to improve the strength and deformation capacity of components, such as, beams, columns, beam-column joints and slabs. Extensive studies have been conducted to investigate the efficiency of FRP jackets in upgrading the seismic behavior of damaged or light-reinforced concrete members previously damaged under a combination of axial compression and a reversed cyclic lateral displacement history (Tastani and Pantazopoulou 2008; Thermou and Pantazopoulou 2009; Bour纳斯 and Triantafillou 2011; De Luca et al. 2011). FRP retrofitted RC columns have exhibited the higher lateral strength and lateral stiffness as compared to the unstrengthened columns (Niroomandi et al. 2010). Fiber orientation and number of FRP layers to be used depend on the type of retrofitting required to enhance the shear/flexure capacity of RC members (Guo et al. 2017).

However, very limited studies have been conducted on the damaged RC frames to investigate their effectiveness under seismic loading conditions. Hence, in this study, an experimental investigation was carried out on a damaged two-story RC frame specimen with open ground story. The ground story columns were strengthened using carbon fiber reinforced polymer (CFRP) jacketing. Slow-cyclic test was conducted to investigate the lateral load resisting capacity, mode of failure and ductility capacity of the CFRP strengthened RC frame.

2. EXPERIMENTAL INVESTIGATION

A two-story and single-bay RC frame representing an interior bay of a prototype structure was considered as the test frame. Figure 1(a) shows the details of test specimen representing an open ground story frame. The test frame was a half-scale model of a non-ductile (gravity-load designed) five-story RC frame (Oinam and Sahoo 2017a). The dimensions of frame members and the amount of reinforcement bars in the test frame were finalized based on similitude relationships for the respective parameters of the prototype frame. Half-scale bricks arranged in English bond with cement mortar was used in the masonry infill. Thus, number of units, mortar joints, and type of bond used in the test frame were exactly same in the test specimen and the prototype frame. Overall width and height of test specimen were 4000 mm and 3800 mm, respectively. The size of footing and columns were 1500 mm ×400 mm and 200 mm ×200 mm (square), respectively. All beams were of 200 mm ×280 mm in size including a monolithic RC slab of 60 mm thickness. Figure 1(b) shows the dimensions and reinforcement detailing in various components of test specimen. Columns at both story levels were provided with eight numbers of 12 mm diameter bars as main longitudinal bars and 8 mm diameter shear stirrups at a constant spacing of 200 mm on centers. The spacing of stirrups in the beam was varied from 125 mm near the support to 150 mm near the mid-span regions. A monolithic RC slab of 1000 mm width was constructed over the beam of the specimen to support the superimposed dead load.

2.1 Rehabilitation Procedure

Previously, the test frame was subjected to a peak displacement excursion of 2% drift ratio in which the peak lateral load resisted by it was measured as 62.0 kN. At the end of the testing, the ground story columns were heavily damaged in shear as shown in Figure 2(a). In this study, the same damaged frame was rehabilitated using CFRP wrapping. It was intended to rehabilitate the damaged columns so as to enhance their lateral strength and stiffness. The original dimension of these columns were 200 mm× 200 mm, which was later increased to 280 mm × 280 mm by adding a micro-concreting layer during the rehabilitation process. The percentage of longitudinal reinforcement (12 mm diameter bars) in the rehabilitated ground story column was computed as 1.15 %, whereas the percentage of steel in the upper column was 2.31% computed based on the original dimension. High compressive strength of micro-concreting would improve the load-resisting capacity and lateral stiffness of the rehabilitated columns.
Figure 1. Details of test specimen: (a) dimensions of frame members and (b) reinforcement detailing

Figure 2. Preparation of specimen for micro-concreting: (a) damaged column, (b) chiseling of damaged concrete, (c) epoxy primer before micro concrete, and (d) finished surface after micro concreting

Figures 2(b-d) show the different stages of rehabilitation procedure adopted in this study. First step involved in the rehabilitation process was the removal of the fragments of concrete from the damage regions of the severely-damaged column by chiseling. Some portion of undamaged concrete was also removed so as to facilitate the proper bonding between the old and fresh concrete during the retrofitting process. The frame was supported on a hydraulic jack during the removal of concrete as shown in Figure 2 (b). After removing the damage concrete, surface of the concrete was cleaned with the help of wire brush followed by air blower to remove dust particles. Epoxy primer was applied on the concrete surface.
prior to putting the micro-concrete of M50 grade in place as shown in Figure 2(c). For the preparation of the micro-concrete, the powder and water was mixed with help of a slow-speed electric drill fitted with a spiral paddle. Water was added intermittently to get the desired consistency of the mix. The mixture was poured into the formwork within 20 minutes to avoid loss of workability. Due to the self-compacting characteristics of micro-concrete, no additional vibration process was adopted for compaction. The formwork was removed after 24 hrs of casting. The finished surface was water cured as per the standard practice for a period of at least 28 days (Figure 2(d)). Epoxy injection technique was used to fill up the small existing cracks in the damaged beam. Same treatment was carried out on columns to ensure proper bonding between the fresh micro-concrete and old hardened concrete.

Next step involved in the rehabilitation process was the FRP jacketing of these columns. The sharp edges of square columns were made rounded by providing a 30 mm curvature. Epoxy primer was applied on the column surface. The primer substrate was made by two components of epoxy saturate. The coated surface was wrapped with single layered unidirectional CFRP sheets. The sequence of CFRP wrapping of the ground story columns is shown in Figure 3. At the time of wrapping, CFRP sheets were stretched in the longitudinal direction of the fibers using a deforming roller and rubber spatula in order to impregnate the resin into the fibers and to deform the resin coat. At the joints of fiber sheets, a 20 mm overlap was provided to maintain the continuity. It is worth mentioning that ACI 440.2R-08 (2008) recommends a minimum overlapping gap of 15 mm on the horizontal member (beam) and 20 mm on vertical member (column) at the beam-column joint region. Additional resin was applied at the overlap locations on the top of outer layer of fiber sheets. After wrapping and fixing of CFRP at proper places, primed substrate was applied on the surface of fiber sheet. The coated surface was strongly stretched in the fiber longitudinal direction two or three times with the roller and spatula in order to impregnate the fiber sheet in the same manner as discussed above.

2.2 Material Properties

Thermo-mechanically-treated (TMT) steel was used as both longitudinal and transverse reinforcement bars in the frame members. Tensile coupon testing showed that the yield and ultimate tensile strengths of TMT bars were 405 MPa and 597 MPa, respectively. Similarly, the 28-days compressive strength of concrete cubes and cylinder were found to be 40.2 MPa and 29.2 MPa respectively. The design target mean cube compressive strength of concrete was 31.6 MPa for the characteristic value of 25 MPa. Micro-concreting of M50 grade (i.e., characteristic compressive strength of 50 MPa) was prepared for a water-powder ratio of 0.14 to get the flow-able concrete of the desired strength. Standard cubes of
70.6 mm in size were prepared to measure the compressive strength of hardened micro-concrete. The mean value of compressive strength of micro-concrete cubes at 28-days of curing was found to be 51.3 MPa. The average 28-days compressive strength of mortar and half-scale masonry prism were found to be 11.82 MPa and 15.19 MPa, respectively. CF240 (weight of 230 gsm) grade of CFRP was used for fiber wrapping on the damaged columns. CFRP sheet had a unidirectional tensile strength of 3800 MPa, which was 9.15 times the yield strength of reinforcing steel. Table 1 shows the detailed mechanical properties of CFRP sheets used in this experimental study.

Table 1. Material properties CFRP sheet

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>1</td>
<td>Modulus of elasticity</td>
<td>240 kN/mm²</td>
</tr>
<tr>
<td>2</td>
<td>Tensile strength</td>
<td>3800 N/mm²</td>
</tr>
<tr>
<td>3</td>
<td>Weight of fiber</td>
<td>200 g/m²</td>
</tr>
<tr>
<td>4</td>
<td>Total weight of sheet</td>
<td>230 g/m²</td>
</tr>
<tr>
<td>5</td>
<td>Density</td>
<td>1.7 g/cm³</td>
</tr>
<tr>
<td>6</td>
<td>Ultimate strain</td>
<td>1.55 %</td>
</tr>
<tr>
<td>7</td>
<td>Thickness</td>
<td>0.117 mm</td>
</tr>
</tbody>
</table>

2.3 Test Set-up

Two servo-hydraulic actuators of rated force capacity of 250 kN and stroke length of ±125 mm were used to apply the cyclic lateral displacements to the test specimen. The in-built load-cells and displacement transducers of these hydraulic actuators were used to monitor the resisting forces and the applied displacements. A digital servo-controller unit mounted on the actuator manifolds controlled the movement of actuator pistons depending on the input signal. The actuators were supported by a reaction frame firmly held to the laboratory strong floor with the help of high strength bolts. Actuators were placed at the center-lines of beam-slabs at each floor level of the test frame. Two linearly varying differential transformers (LVDTs) were installed at the beam levels in the rear side. Several uniaxial electrical-resistance (120Ω) strain gauges were installed to the main reinforcement bars of various members to monitor the state of strain at different locations. The locations of strain gauges were finalized based on the expected plastic hinges in the specimen. Figure 4 shows the test set-up used in this study.

3. TEST RESULTS

Two tests, namely, force-vibration test and slow-cyclic test, were carried out on the test specimen. Forced-vibration test was conducted to determine the initial dynamic properties of the specimen, whereas the slow-cyclic test was carried out to study the overall behavior of specimen under the action of cyclic lateral loading.

3.1 Forced-vibration Test

An electro-dynamic shaker was placed on top slab of the test frame to provide the input excitations of varying frequencies. Two accelerometers were attached at the beam ends to monitor the amplitude response of the test specimen under the input excitations applied through the shaker. Sinusoidal input excitation was applied in the frequency range of 1-10 Hz at an increment of 1.0 Hz. The input frequency corresponding to the maximum acceleration response was considered as the damped natural frequency of test specimen. Figure 5 shows the mass distribution in the test frame and the amplitude-frequency response. The natural frequency of test specimen was noticed as 7.0 Hz and the corresponding natural period was computed as 0.14 sec. The value of natural period computed theoretically was 0.18 sec. Natural frequency and period of undamaged frame were 1.34 Hz and 0.75 sec., respectively. Due to CFRP wrapping on the damaged columns, natural frequency of this frame was improved by 5.2 times.
3.2 Slow-cyclic Test

The test frame was subjected to the gradually-increasing reversed cyclic lateral displacements in addition to the constant gravity loads in the slow-cyclic test. Displacement history as specified in ACI 374.1-05 (2006) was used for the slow-cyclic testing of specimen in this study (Figure 6). This loading history consisted of predefined story drift cycles of 0.125%, 0.25%, 0.35%, 0.50%, 0.75%, 1.0%, 1.40%, 1.75%, 2.0% and 2.5% at the roof level. Story drift (or drift ratio) may be defined as the ratio of the roof displacement to height of the story measured from the top of footing to the centerline of beam. Each displacement cycle was repeated for three times at any drift ratio level followed by a single drift cycle of the smaller magnitude. The displacements applied on first floor beam level was considered as the 0.9 times of the roof displacement at any instance. For the study frame with open ground story and the masonry infill at the upper story, the drift distribution would be uniform over the height instead of a linear variation. Hence, a value of 90% of roof displacement was considered at the first floor level. Eigenvalue analysis result showed that this displacement ratio was very close to that obtained...
corresponding to the fundamental mode of vibration. Superimposed loads were imposed on both slabs by means of concrete cubes and heavy beams. It was estimated that the axial stress in columns due to the applied gravity loads (i.e., dead load + superimposed load) was nearly 10% of their axial capacity. Considering the axial stress in columns is much higher than this value in practice, the applied gravity loads in this study did not truly reflect the field condition. However, this load would simulate the P- Delta effect to some extent during the testing. It is worth-mentioning that the slow-cyclic testing did not consider the inertia force effects as expected during the dynamic loadings.

![Figure 6. Imposed displacement history on test specimen](image)

### 3.2.1 Overall Behavior

Figure 7 shows the state of ground-story columns, masonry infill panel, and first floor beam of the test frame at different drift levels. No visible damages were noticed at 0.125% drift level indicating the elastic behavior of the test specimen. Cracking of CFRP in both columns was noted at a drift level of 0.25%. Few micro-cracks were observed in the beam-column joint region at 0.35% drift level. A horizontal crack was also noted at the masonry bed joint at this drift level. At a drift level of 0.5%, the tearing of CFRP was initiated near the beam-column joints and the existing micro-cracks was found to be extended towards the center of beam-column joint. Major horizontal cracks were noted in the column near the beam-column joint at 0.75% drift level. Simultaneously, major horizontal cracks were appeared at the junction of column and foundation. It is worth-mentioning that FRP wrapping was only carried out on columns with no connection with the footing. The maximum width of horizontal cracks in masonry bed joints was measured to be 1.0 mm.

At 1.0% drift level, the width of existing horizontal cracks in columns near the beam–column joints was increased to 2.5 mm along with the complete tearing of CFRP sheets at this location. At 1.4% drift level, a major crack was noted at the bottom of the right column at a distance of about 150 mm away from the foundation surface along with some additional minor cracks in the beam near the beam-column joint. The width of crack at the foundation and column interface was measured to be 3.0 mm. At 1.75%, drift level, the width of cracks at the interface of column and foundation and in the column were measured as 3.5 mm and 2.5 mm, respectively. At 2.0% drift level, cracks in the masonry bed joints were opened up to 2.0 mm. New diagonal crack was noted in the masonry infill near the beam-column joint. Figure 8 shows the hinge (or yield) mechanism of the test frame along with the crack propagation in various elements. Both the ground story columns developed the plastic hinges at both ends (total four hinges) and full frame mechanism was visible at this drift level (Figure 8). In addition, the width of cracks in the column and at the column-foundation interface were increased to 9.0 mm and 8.0 mm, respectively. At 2.5% drift level, diagonal cracks were observed in the right upper beam-column joint. Simultaneously, multiple minor cracks were noted in the masonry infill. The maximum width of crack in column was measured as 11.0 mm.
3.2.2 Hysteretic response

Figure 9(a) shows the lateral load vs. displacement (hysteretic) response of test frame under the imposed displacement history. Yield drift of the test frame was noted as 0.35% (10.25 mm) and corresponding value of lateral strength was noted as 116.6 kN. The frame showed the ultimate lateral load resistance at 2.5% and 1.4% drift levels in the push and pulls directions, respectively. The corresponding values of lateral loads were noted as 171.8 kN and 142.0 kN. The test frame sustained a roof drift demand of 2.5% without collapse. The corresponding value of interstory drift ratio at the ground story level was found to be 4.1%. Usually, the collapse of non-ductile RC frame with open ground story occurs is noted at very small drift levels under the seismic loading. The results clearly showed that CFRP wrapping of damaged ground story columns significantly improved the drift capacity of the soft-story RC frame.
The test frame exhibited the higher lateral stiffness in the first cycles of each drift level. However, no further degradation in the lateral strength was noticed in the subsequent repetitive cycles of the same displacement excursion level. Very minor pinching was observed in the hysteresis loops indicating the less severity of bond-slip behavior of reinforcing bars in the frame members. This behavior was more evident in the larger displacement excursions where the major cracks were developed at the beam-column joints and the column bases of test specimen. Figure 9(b) shows the backbone curves of hysteretic response of test frame. The test frame exhibited nearly symmetric backbone curves under the cyclic loadings. A gradual increase in the lateral resistance of the frame was noted with the increase in drift levels till the end of testing. As compared to the lateral strength of 62 kN for the test frame at the undamaged condition noted in the previous tests, the proposed rehabilitation technique improved the lateral strength of the test frame by nearly 200%.
3.2.3 Stiffness degradation under cyclic load

Effective lateral stiffness (\(K_{eq}\)) in each drift cycle was computed as the ratio of lateral load resisted by the specimen to the corresponding displacements observed in both pull and push directions.

Mathematically, the value of \(K_{eq}\) can be determined as follows (FEMA-356, 2000):

\[
K_{eq} = \frac{F^+ - F^-}{\Delta^+ - \Delta^-}
\]  

(1)

Where, \(F^+\) and \(F^-\) are the peak positive and negative forces; \(\Delta^+\) and \(\Delta^-\) are the peak positive and negative displacements in the hysteresis loops. Figure 10 shows the variation in lateral stiffness of the test frame with the drift cycles. Initially, test frame exhibited an effective lateral stiffness of 15.19 kN/mm at 0.125% drift level. This value was marginally smaller than the initial stiffness measured in the forced-vibration test. At each drift cycle, the effective lateral stiffness was gradually reduced till the end of the experiment. At the last cycle (i.e., 2.5% drift level), the value of effective lateral stiffness was computed as 2.01 kN/mm. Table 2 summarizes the effective stiffness of the test frame for each drift level.

![Figure 10. Lateral stiffness degradation under cyclic loading](image)

Table 2. Computation of stiffness degradation with drift cycles

<table>
<thead>
<tr>
<th>Drift level (%)</th>
<th>Peak pos. displacement, (\Delta^+) (mm)</th>
<th>Peak neg. displacement, (\Delta^-) (mm)</th>
<th>Peak positive force, (F^+) (kN)</th>
<th>Peak negative force, (F^-) (kN)</th>
<th>Effective stiffness, (K_{eq}) (kN/mm)</th>
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<tr>
<td>0.13</td>
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<td>64.61</td>
<td>-46.50</td>
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<td>-73.26</td>
<td>171.85</td>
<td>-109.55</td>
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</table>
4. SUMMARY AND CONCLUSIONS

This study is focused on the rehabilitation of a damaged soft-story RC frame in which the shear-damaged ground story columns were retrofitted using CFRP wrapping. Slow-cyclic test was conducted on a two-story single-bay test frame. A predefined displacement history was imposed on the test frame till a roof drift of 2.5%, which is equivalent to the interstory drift ratio of 4.1% at the ground story level.

The following conclusions can be drawn from this experimental study:

- The proposed rehabilitation technique using the micro-concrete in the cracks followed by CFRP wrapping of columns enhanced the lateral strength, stiffness, and drift capacity of the soft-story RC frame. The retrofitted frame can sustain an interstory drift demand of 4.0% at the ground story level without collapse.

- The expected shear failure of columns due to inadequate shear stirrups can be effectively controlled using CFRP wrapping resulting the flexural mode of failure of the RC frame. Further, the hysteretic response of the CFRP retrofitted RC frame showed very minor strength and stiffness degradation.

- CFRP wrapping technique can be adopted for rehabilitation of the damaged open ground story RC building to avoid the soft-story collapse under the seismic loading. In addition to the improvement in the structural performance, this technique can provide the maximum useable floor area as compared to the other available retrofitting solutions.

5. REFERENCES


