STUDY ON SEISMIC PERFORMANCE OF EXTERIOR BEAM-COLUMN CONNECTION WITH DIFFERENT JOINT CORE DETAILS

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ABSTRACT

Generally reinforced concrete exterior beam-column connections joint core are detailed with conventional standard 90° bent hooks for longitudinal beam reinforcement anchorages as per ACI 318, IS 456. Joint are detailed without confinement in seismic zone-II, with confinement in seismic zones-III to V as per IS 13920. This results in congestion of reinforcement in the joint core, concrete placement difficult at site. A potential solution for these problems with significant improvement in the seismic performance, strength, ductility, stiffness and lesser cracks were observed by using mechanical anchorage as per ACI 352 in combination with additional X-cross bars plus hair clip joint reinforcement for zone-III to V and in combination with X-cross bars for zone-II. To evaluate the performances of these types of anchorages and joint details, the specimens assembled into four groups, each group having three specimens were tested under reversal loading.

Keywords: Beam-column connection; ductility; stiffness; crack; mechanical anchorage; reversal loading

1. INTRODUCTION

Beam-Column connections are critical regions for the reinforced concrete framed structure in seismic prone area. Proper anchorage of reinforcement is essential to enhance the performance. Innovative joint designs that can reduce congestion of reinforcement without compromising strength, stability, stiffness is desirable, ACI 352 [1] recommends additional research on use of T-headed bar in design of beam-column connections in concrete structure. The investigation of the beam-column connection longitudinal beam reinforcement bar with 90° standard bent hooks anchorage and mechanical anchor for joint core under reversal loading.

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loadings has been a research area for many years. Some of the analytical studies and experimental studies carried out so far and indicated below.

Lee et al. [2] proposed extension of ACI design methods to cover the use of mechanical anchorage for eccentric beam-column joints. They reported that cyclic behavior of exterior beam-column joints can be significantly improved by attaching double mechanical device on each beam bar within the joint. 

Murty et al. [3] reported that the ACI standard hooks for anchorage of the longitudinal beam bar with hairclip-type transverse joint reinforcement were more effective and this combination of anchorage with joint reinforcement is easy to construct and can be used in moderate ductility demand situations.

Bindhu and Jeya [4] in their experimental investigations validated with analytical studies carried out by finite element model using ANSYS indicate that additional cross bracing reinforcement improves the seismic performance of the exterior reinforced concrete beam-column joints.

Tsonos et al. [5] suggested that the use of crossed inclined bars in the joint region was one of the most effective ways to improve the seismic resistance of exterior beam-column joints.

Wallance et al. [6] suggested use of headed reinforcement had eased specimen fabrication, concrete placement and the behavior was as good as than similarly constructed specimens with standard 90° hooks for beam-column corner joint.

Chutarat et al. [7] reported that the use of straight-headed bars in the exterior beam-column joint for cyclic response very effective in relocating potential plastic regions.

Asha and Sundararajan [8] reported that the use of square spiral confinement in joint with different anchorage detailing of beam bars and additional inclined bars from column to beam connection successfully move the plastic hinge away from the column face.

Park and Paulay [9] recommendations for the detailing of joints for the earthquake resistance structure were made of bent-up bars, stub beam with bent-up bars and mechanical anchorage for anchorage and effective ties for confinement in the joint core of the exterior beam-column joints.

The anchorage requirements for the beam longitudinal reinforcement bar and joint confining are the main issues found from the literature reviewed for the reinforcement congestion in the beam-column connection joint core region. 

The main aim of present study is to evaluate the performance of the exterior beam-column joint by replacing the 90° standard bent bar anchorages by T-type mechanical anchorage and additional X-cross bar with U-bar in the beam-column joint core for the moderate and severe seismic zones-III and IV. Mechanical anchorage with X-cross bar lower seismic zone-II, these zones are followed as per IS 1893 [10], IS 13920 [11] and it is found that these combinations aid in, reducing the reinforcement congestion in joint core and pouring concrete without compromising the strength, ductility and stiffness with lesser cracks of beam-column joints under the reversal loading.

2. RESEARCH SIGNIFICANCE

The experimental study has been carried out for different types of anchorages and joint...
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details in the exterior beam-column connection, The T-type mechanical anchorage in combination with additional X-cross plus U-bar for higher seismic zone and T-type headed bar anchorage in combination with additional X-cross bar for lower seismic zone as joint detail offers a better load carrying capacity. This anchorages and joint details improve the seismic performance and ductile behavior without losing the strength. This arrangement reduces the congestion of reinforcement at joint core and placements on concrete, construction and fabrication easier at site.

3. TESTING PROGRAM AND SCHEMATIC TEST SETUP

Towel numbers of beam-column joint specimens have been considered in the present study. The specimens have been divided into four groups, each group having three specimens, with different anchorages. This anchorage details are designated as A, B and C and joint details designated as 1, 2, 3 and 4. Anchorage detail-A is T-type mechanical anchorage as per ACI 352R [1]. Anchorage detail-B is conventional $90^\circ$ standard bent hooks as per ACI 318 [12] and anchorage detail-C is full anchorage as per IS 456 [13]. Joint detail-1 confinement reinforcement not been use, Joint detail-2 has proposed additional X-cross bar, Joint detail-3 has proposed additional X-cross bar with U-bars and Joint detail-4 has standard conventional shear links arrangement are shown in Figure 6.a to 6.g.

4. EXPERIMENTAL RESEARCH PROGRAM

The testing of half-scale exterior beam-column joint specimen was carried out at MEPCO
Engineering College, Sivakasi, INDIA. The Joint assemblage was subjected to reversal loading using Hydraulic jack of 25 Ton capacity. The specimen column is kept in horizontal direction and beam is kept vertical as illustrated in Figure 1. Both ends of the RCC columns are restrained in vertical and also in both horizontal directions by using strong built up steel boxes which in turn are connected to the reaction floor using holding down anchor bolts. To facilitate application of reversal load (Left Hand Side-LHS and Right Hand Side-RHS) on either side of the RCC beam, the hydraulic jacks are used which are connected to the strong steel frame with mechanical fasteners. The RCC beam was loaded as shown in Figure 2. The Linear Variable Differential Transducer (LVDT) was connected on either side of the specimen to monitor the displacements. Loading cycle of the test assemblage to record the loads accurately is shown in Figure 3, the testing is a load controlled with a load increment of 1-ton. The specimens have been tested up to reach its maximum failure capacity.
5. CRITICAL JOINT MECHANISM DETAILS

Critical situation can arise in certain exterior beam-column joints of plane multistory frames when they are subjected to high seismic loading. The external action and the corresponding internal forces generated around such a joint are indicated in Figures 4 and 5. It is apparent that diagonal tension and compression stress ($f_c$ and $f_t$) are induced in the shear panel zone of the joint.

The following notations refer to the stress resultants. T-Tension force in the reinforcement, Cc-compression force in the concrete, Cs-compression force in reinforcement and V- shear force, subscript ‘b’ for beam and ‘c’ for column.
6. DETAILS OF TEST SPECIMENS

All the specimens are identical size. The beam sizes are 200mm x 300mm. The column cross section is 300mm x 200mm as shown in Figure 6.d. The length of the beam is 1200mm from the column face and the height of the column is 1500mm. The various types of anchorages used are shown in Figure 6.a, 6.b and 6.c, the Joint details used are shown in Figure 6.e and 6.f. In group-I, the anchorages A, B and C are combined with joint detail-1 and these specimens are named as A1, B1 and C1. Similarly the anchorages A, B and C are combined with joint detail-2, 3 and 4. In group-II these specimens are named as A2, B2 and C2, in group-III these specimens are named as A3, B3 and C3 and in group-IV these specimens are named as A4, B4 and C4.
7. MATERIALS USED

Concrete was made with 43 Grade cement with river sand and 20mm and down coarse aggregate. The quantities of material per cubic meter of concrete used were; Cement = 435.45 kg/m³, fine aggregate = 626.673 kg/m³, coarse aggregate = 1188.22 kg/m³, Water = 191.6 kg/m³, water/cement ratio = 0.45 and the 28th day average cube compressive strength was 28.30MPa. The reinforcement bars used were 6, 8, 12 and 16mm diameter, all of HYSD steel of grade Fe-415 (fy = 415N/mm²) as shown in Figure 6.a to 6.f and the grade of headed bar used was E410 (Fe 540) with yield strength of 410MPa as shown in Figure 6.g.

8. TEST RESULTS AND DISCUSSION

8.1. Lateral Load Versus Lateral Displacement

The hysteresis loops behavior of specimens A1, B1 and C1 for group-I, A2, B2 and C2 for group-II subjected to lateral load are indicated in Figure 7.a to 7.c and Figure 8.a to 8.c respectively, the corresponding peak load versus displacement are indicated in Figure 7.d and 8.d. It is observed that in group-I, the average ultimate load carrying capacity of the specimens A1, B1 and C1 are 73.00kN, 68.00kN and 71.75kN with the corresponding lateral displacement of 52.72mm, 40.90mm and 50.62mm respectively. Among these A1 exhibits the maximum load carrying capacity. In group-II, the average ultimate load carrying capacity of the specimens A2, B2 and C2 are 79.50kN, 78.50kN and 79.25kN with the
corresponding lateral displacement of 60.66mm, 67.00mm and 65.29mm respectively. Among these A2 exhibits the maximum load carrying capacity than B2 and C2. As well it can be observed from Table 1 and Figure-11 comparing group-I and II, Group-II has superior load carrying capacity A2 by 8.20%, B2 by 13.40% and C2 by 9.50%. From the above test results it can be inferred that the proposed additional X-cross bar significantly increases the ultimate strength.

Figure 7. (a) Load Vs Displacement (A1); (b) Load Vs Displacement (B1); (c) Load Vs Displacement (C1); (d) Peak load Vs Displacement (Group-I)
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Figure 8. (a) Load Vs Displacement (A2); (b) Load Vs Displacement (B2); (c) Load Vs Displacement (C2); (d) Peak Load Vs Displacement (Group-II)

The hysteresis loops behavior of specimens A3, B3 and C3 for group-III, A4, B4 and C4 for group-IV subjected to lateral load are indicated in Figures 9.a to 9.c and Figures 10.a to 10.c respectively, the corresponding peak load versus displacement are indicated in Figures 9.d and 10.d.

Figure 9. (a) Load vs Displacement (A3); (b) Load vs Displacement (B3); (c) Load vs Displacement (C3); (d) Peak load vs Displacement (Group-III)
It is observed that in group-III, the average ultimate load carrying capacity of the specimens A3, B3 and C3 are 89.50kN, 90.00kN and 89.00kN with the corresponding lateral displacement of 47.50mm, 47.50mm and 44.43mm respectively. Among these B3 exhibits the maximum load carrying capacity it’s slightly higher than A3 by 0.5% and C3 by 1.1%. In group-IV, the average ultimate load carrying capacity of the specimens A4, B4 and C4 are 80.50kN, 79.00kN and 79.50kN with the corresponding lateral displacement of 45.37mm, 35.55mm and 48.12mm respectively. Among these A4 exhibits the maximum load carrying capacity than B4 and C4. As well it can be observed from Table 1 and Fingure-12 comparing group-III and IV, group-III has superior load carrying capacity A3 by 10.05%, B3 by 12.22% and C3 by 10.67%. From the above test results it can be inferred that the proposed additional X-cross bar with U-bar significantly increases the ultimate strength.
8.2. Ductility Behavior

It is essential that an earthquake resistant structure should be capable of deforming in a ductile manner when subject to several cycles of lateral loads in the inelastic range. Ductility is the property which allows the structure to undergo large deformation beyond the initial yield deformation without losing its strength abruptly. Ductility ($\mu$) can be defined as the ratio of ultimate deflections ($\delta_u$) to initial yielding deflection ($\delta_y$). $\mu = (\delta_u/\delta_y)$.

From Table 1, it is observed that group-II specimens namely A2, B2 and C2 exhibit higher ductility than group-I specimens namely A1, B1 and C1 by 18.31%, 32.84% and 23.67% respectively, wherein proposed additional X-cross bar joint core details was used in group-II. Among these six specimens (group-I and II), A2 exhibits better performance. This combination of anchorage and joint details may be used in seismic zone-II area were lower ductility demanding situations. As well from Table 1, it is observed that group-III specimens namely A3 (ACI 352- mechanical anchorage), B3 (ACI 318 -90\degree bent hook anchorage) and C3 (IS 456- full anchorage) exhibit higher ductility than group-IV specimens namely A4, B4 and C4 by 10.70%, 36. 97% and 20.58% respectively, wherein additional X-cross bar with hair clip joint details are used in group-III and standard conventional shear ties are used as joint confinement in Group-IV specimens. Among these six specimens (group-III and IV), A3 exhibits better performance. This combination of anchorage and joint details may be used in moderate and severe ductility demanding situations.

<table>
<thead>
<tr>
<th>Spec. groups</th>
<th>Yielding dispt in mm ($\delta_y$)</th>
<th>Ultimate load in kN ($P_u$)</th>
<th>Average ultimate load in kN ($P_u$)</th>
<th>Ultimate dispt in mm ($\delta_u$)</th>
<th>Average dispt for ultimate load in mm ($\delta_u$)</th>
<th>Average dispt ductility factor $\mu=(\delta_u/\delta_y)$</th>
<th>Average initial stiffness in kN/mm $k=(P_u/\delta_u)$</th>
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<tr>
<td>A1-I</td>
<td>4.50</td>
<td>72.00</td>
<td>74.00</td>
<td>73.00</td>
<td>42.13</td>
<td>63.30</td>
<td>52.715</td>
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<tr>
<td>B1-I</td>
<td>5.00</td>
<td>70.00</td>
<td>66.00</td>
<td>68.00</td>
<td>35.96</td>
<td>45.85</td>
<td>40.905</td>
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<tr>
<td>C1-I</td>
<td>5.20</td>
<td>71.00</td>
<td>72.50</td>
<td>71.75</td>
<td>45.63</td>
<td>55.60</td>
<td>50.615</td>
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<tr>
<td>A2-II</td>
<td>4.23</td>
<td>79.00</td>
<td>80.00</td>
<td>79.50</td>
<td>56.00</td>
<td>65.32</td>
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<td>5.50</td>
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<td>78.50</td>
<td>65.00</td>
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<td>75.96</td>
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<td>90.00</td>
<td>45.00</td>
<td>50.00</td>
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<td>90.00</td>
<td>89.00</td>
<td>43.50</td>
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<td>81.00</td>
<td>80.50</td>
<td>42.15</td>
<td>48.60</td>
<td>45.375</td>
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<tr>
<td>B4-IV</td>
<td>2.85</td>
<td>78.00</td>
<td>80.00</td>
<td>79.00</td>
<td>30.85</td>
<td>40.25</td>
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<tr>
<td>C4-IV</td>
<td>3.00</td>
<td>78.50</td>
<td>80.50</td>
<td>79.50</td>
<td>45.63</td>
<td>50.60</td>
<td>48.115</td>
</tr>
</tbody>
</table>

8.3. Stiffness Behavior

In the case of reinforced concrete beam-column joints, stiffness of the joint gets degraded when the joint is subjected to reversal loading. During the reversal loading concrete and reinforcement steel bars are subjected to several loading, unloading and reloading cycles. The joints initially develop micro cracks inside and it leads to the lowering of energy limit of the materials, and thereby results in the increase of deformation inside the joints. This may consequently cause the reduction in the stiffness. Therefore it becomes essential to assess the
degradation of stiffness in the beam column joints subjected to reversal loading.

The stiffness behavior of specimens are indicated in the Figures 13 and 14. The stiffness (K) is calculated $K = (P/\delta)$, P-is the peak average shear forces and $\delta$-is the peak average displacement values ($\delta$), which are the peak values of each hysteresis loops. Between group-I and II, specimens A1 and A2 have higher values, than specimens B1, C1, B2 and C2. Among group-III and IV, specimens A3 and A4 have higher values, than specimens B3, C3, B4 and C4.

Table 1 indicated only the average initial stiffness (Initial stiffness $K = P_u/\delta_y$, where $P_u$ is the ultimate load and $\delta_y$ is the yielding displacement). It has been observed from the experimental results in group-I, specimen A1 having the higher stiffness than specimens B1 and C1. In group-II, specimen A2 having the higher stiffness than specimens B2 and C2. Between these two groups, group-II having the higher stiffness. The specimen A2 which had the proposed additional X-cross bar joint detail exhibited better performance among these six specimens (group-I and II) against stiffness degradation as well stiffness of specimen A2.
is higher than A1 by 13.68%.

In group-III, specimen A3 is having the higher stiffness than specimens B3 and C3. In group-IV, specimen A4 is having the higher stiffness than specimens B4 and C4. The specimen A3 which had the proposed additional X-cross bar with hair clip joint detail exhibited better performance among these six specimens (group-III and IV) against stiffness degradation, stiffness of specimen A3 is higher than A4 by 15.92%. Between these two groups, group-III having the higher stiffness.

8.4. Crack pattern
On examination of crack pattern of Figure 15 and 16, shear cracks have developed on the beam-column junction in all the specimens. Further to these cracks, diagonal cracks have also developed in the column shear panel area of the specimens B1 C1, B2 and C2. Besides the wide open cracks in the junction, the concrete had also spalled out from the specimens B1, B2 and C2, the specimens A1 and A2 shows the lesser crack pattern than other specimens in group-I and II without losing the strength, however A2 has significantly improved the seismic performance and increasing the load carrying capacity.

Figure 15. Crack pattern of group-I (A1, B1 and C1)

Figure 16. Crack pattern of group-II (A2, B2 and C2)

On examination of crack pattern of Figure 17 and 18, shear cracks have developed on the beam-column junction in all the specimens. Further to these cracks, diagonal cracks have also developed in the column shear panel area of the specimens B3 C3, A4, B4 and C4.
Besides the wide open cracks in the junction, the concrete had also spalled out from the specimens B3, C3 in group-III, B4 and C4 in group-IV, specimen A3 and A4 shows the lesser crack pattern than other specimens in group-III and IV without losing the strength however A3 has significantly improved the seismic performance with higher ductility, stiffness.

![Figure 17. Crack pattern of group-IV (A3, B3 and C3)](image)

![Figure 18. Crack pattern of group-IV (A4, B4 and C4)](image)

9. CONCLUSION

The following conclusions were derived based on the experimental investigation carried out. Between group-I and II specimens, A1 and A2 reinforced with T-type mechanical anchorage systems as per ACI 352 has better performance than specimens reinforced with conventional 90° standard bent hooks anchorage specimen B1 and B2 as per ACI 318 and full anchorage specimen C1 and C2 as per IS 456.
Group-II specimens A2, B2 and C2 in combination with X-Cross bar joint detail significantly improve the strength, ductility and stiffness than group-I specimens. Specimen A2 has superior performance. This combination of anchorage and joint details may be used in lower ductility demanding situations, seismic zone-II.

In group-III, Specimen A3 has better performance than specimens B3, C3. In group-IV, specimen A4 has better performance than specimens B4, C4. Between these two groups, group-III specimens’ combination with X-Cross bar plus hair clip joint detail significantly improves the strength, ductility and stiffness than group-IV specimens.

The T-type mechanical anchorage in A3 specimen in combination with proposed X-cross bar and hair clip joint detail offers a better load carrying capacity. These details improve the seismic performance without compromising the strength, ductility and stiffness. This arrangement of reinforcement detail in the beam-column connection reduces the congestion of reinforcement in the joint core area, aids in easier placement of concrete and faster construction at site than specimens B3, C3, A4, B4 and C4. This combination of anchorage and joint details may be used in higher ductility demanding situations, seismic zone-III to V.

The use of conventional $90^\circ$ standard bent hook anchorage arrangements in the beam-column connection region for severe seismic zone leads to increase in size of column to accommodate required amount of beam reinforcement in the joint core whereas, the usage of mechanical anchorage results in the reduction of the amount of reinforcement and congestion in the beam-column joint core.

In Indian design practice, beam-column connection is given less attention. The above finding, recent research and suggestions by various national and international codes for using the mechanical anchorage systems may be accounted for in the upcoming revisions.

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