CHAPTER 5

DISCUSSION OF TEST RESULTS AND STRUCTURAL BEHAVIOUR

5.1 GENERAL

The aim of this investigation is to assess the load-displacement behavior, ductility, stiffness, crack pattern behavior for the reinforced concrete structures beam-column joint. An effort has been made to study and evaluate the performance of beam-column joints.

The joints are detailed as per ACI-352 (mechanical anchorage), ACI -318 (conventional hooks bent) and IS-456 (full anchorage conventional hooks bent) along with confinement as per IS-13920, X-cross bars for less seismic prone areas and X-cross bar plus hair clip joint reinforcement for higher seismic prone areas. To assess the performances of anchorages and joint details, the specimens were assembled into four groups, each group having three specimens. The specimens were tested under reversal loading, test results are discussed and presented in this chapter.

5.1.1 Grouping of Specimens

The four groups of twelve test specimens are detailed below.
• Group-I for the low seismic prone area.
  1. Specimen-A1 (ACI-352 mechanical anchorage without confinement reinforcement)
  2. Specimen-B1 (ACI-318 conventional 90° hooks bent anchorage without confinement reinforcement)
  3. Specimen-C1 (IS-456 full anchorage without confinement reinforcement)

• Group-II for the low seismic prone area.
  1. Specimen-A2 (ACI-352 mechanical anchorage with X-cross bar)
  2. Specimen-B2 (ACI-318 conventional 90° hooks bent with X-cross bar)
  3. Specimen-C2 (IS-456 full anchorage with X-cross bar)

• Group-III for the moderate and high seismic prone area.
  1. Specimen-A3 (ACI-352 mechanical anchorage with X-cross plus U-bar)
  2. Specimen-B3 (ACI-318 conventional 90° hooks bent with X-cross plus U-bar)
  3. Specimen-C3 (IS-456 full anchorage with X-cross plus U-bar)

• Group-IV for the moderate and high seismic prone area.
  1. Specimen-A4 (ACI-352 mechanical anchorage with confinement reinforcement)
  2. Specimen-B4 (ACI-318 conventional 90° hooks bent with confinement reinforcement)
  3. Specimen-C4 (IS-456 full anchorage with confinement reinforcement)
5.1.2 Behavior in Load-Displacement

The beam-column joint test assemblage load and displacement value were measured using LVDT during the loading, un-loading and reloading course of action and this process is called reversal loading. The hysteresis curves of all the test specimens were developed and displacement values were plotted in the ±X axis and load in the ±Y axis. The yielding load and ultimate failure load and the corresponding displacement were also observed.

5.1.3 Behavior in Stiffness

In case of reinforced concrete beam-column joints, stiffness of the joint gets degraded while 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. Due to this, micro cracks were formed initially inside the joint which lead to the lowering of energy limit of the materials and also increases the deformation inside the joints. This may consequently results in reduction of joint stiffness. Therefore, it becomes essential to assess the degradation of stiffness in the beam-column joints subjected to reversal loading.

The stiffness ($K$) is calculated $K = (P/\delta)$, where ‘$P$’ is the peak average load and ‘$\delta$’ is the peak average displacement values. The stiffness
subjected 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 ($\delta_y$). $\mu = \frac{\delta_u}{\delta_y}$. The ductility behaviors of all the specimens are discussed in detail at Section 5.10.

5.1.5 Behavior in Yielding and Ultimate Failure Crack Pattern

Yielding of steel reinforcement reached prior to or at maximum load and displacement of the beam begins to increase at a higher rate beyond this point. The capacity of the beam-column joint regained to distribute the load throughout the cross-section but soon diminishes significantly due to the cracking of the concrete elements and yielding of steel reinforcing bars. This results in nonlinearity of concrete materials and reduced flexural rigidity of the members. Eventually, the greater deflection occurs at the beam edge due to these effects. The crack behavior is discussed in detail at Section 5.11.

5.2 LOADING SEQUENCE

The reversal lateral load was applied at top of the beam and the load sequence is followed for the beam-column joint assemblage as shown in Figure 5.1. The testing is load controlled with a load increment of 1-ton (10kN). The specimens have been tested till it reaches its maximum failure capacity.
5.3 LOAD-DISPLACEMENT BEHAVIOR OF SPECIMENS A1, B1, C1 FOR GROUP-I

5.3.1 Load -Displacement Behavior of Specimen A1 for Group-I

Figure 5.1 Loading sequence for specimen groups I -IV

Figure 5.2 Hysteresis curve of load-displacement relationship for specimen A1
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.2 for group-I of A1 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 4.50mm. Again the specimen are loaded, unloaded and reloaded till the 8th cycle where it reaches the ultimate load with the corresponding average ultimate load as 73.00 kN and displacement 52.715mm as indicated in Table 5.1 & Figure 5.2. After reaching the ultimate load, there were no signs of diagonal cracks on the shear panel area of the joint core. These specimens were detailed as per ACI-352 mechanical anchorages without confinement reinforcement for the low seismic prone area.

5.3.2 Load –Displacement Behavior of Specimen B1 for Group-I

![Hysteresis curve of load-displacement relationship for specimen B1](image)

**Figure 5.3 Hysteresis curve of load-displacement relationship for specimen B1**
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.3 for group-I of B1 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 5.00mm. Again the specimen are loaded, unloaded and reloaded till the 7th cycle where it reaches the ultimate load with the corresponding average ultimate load as 68.00 kN and displacement 40.90mm as indicated in Table 5.1 & Figure 5.3. After reaching the ultimate load, there are many diagonal cracks on the shear panel area of the joint core, concrete had also crushed and spalled out due to compression failure. These specimens were detailed as per ACI-318 conventional 90° hook bent anchorages without confinement reinforcement for the low seismic prone area.

5.3.3 Load -Displacement Behavior of Specimen C1 for Group-I

![Hysteresis curve of load-displacement relationship for specimen C1](image)

**Figure 5.4** Hysteresis curve of load-displacement relationship for specimen C1
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.4 for group-I of C1 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 5.20mm. Again the specimen are loaded, unloaded and reloaded till the 8\textsuperscript{th} cycle where it reaches the ultimate load with the corresponding average ultimate load as 71.75 kN and displacement 50.60 mm as indicated in Table 5.1 & Figure 5.4. After reaching the ultimate load, there are many diagonal cracks on the shear panel area of the joint core, concrete had also crushed due to compression failure. These specimens were detailed as per IS-456 full anchorage without confinement reinforcement for the low seismic prone area.

### 5.4 LOAD-DISPLACEMENT BEHAVIOR OF SPECIMENS A2, B2, C2 FOR GROUP-II

#### 5.4.1 Load–Displacement Behavior of Specimen A2 for Group-II

![Hysteresis curve of load-displacement relationship for specimen A2](image)

**Figure 5.5** Hysteresis curve of load-displacement relationship for specimen A2
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.5 for group-II of A2 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 4.23mm. Again the specimen are loaded, unloaded and reloaded till the 8th cycle where it reaches the ultimate load with the corresponding average ultimate load as 79.50 kN and displacement 60.70mm as indicated in Table 5.1 & Figure 5.5. After reaching the ultimate load, there were no signs of diagonal cracks on the shear panel area of the joint core, but wide open cracks were formed on column face. These specimens were detailed as per ACI-352 mechanical anchorage in combination with X-cross bar for the low seismic prone area.

5.4.2 Load –Displacement Behavior of Specimen B2 for Group-I1

![Figure 5.6 Hysteresis curve of load-displacement relationship for specimen B2](image-url)
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.6 for group-II of B2 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 5.50mm. Again the specimen are loaded, unloaded and reloaded till the 8\textsuperscript{th} cycle where it reaches the ultimate load with the corresponding average ultimate load as 78.50kN and displacement 67.00mm as indicated in Table 5.1 & Figure 5.6. After reaching the ultimate load, there are many diagonal cracks on the shear panel area of the joint core, concrete had also crushed due to compression failure on the joint location. These specimens were detailed as per ACI-318 conventional 90\textdegree hooks bent in combination with X-cross bar for the low seismic prone area.

5.4.3 Load –Displacement Behavior of Specimen C2 for Group-I1

![Specimen-C2 Hysteresis Curve](image_url)

**Figure 5.7** Hysteresis curve of load-displacement relationship for specimen C2
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.7 for group-II of C2 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 5.12mm. Again the specimen are loaded, unloaded and reloaded till the $8^{th}$ cycle where it reaches the ultimate load with the corresponding average ultimate load as 79.25 kN and displacement 65.30mm as indicated in Table 5.1 & Figure 5.7. After reaching the ultimate load, there are many diagonal cracks on the shear panel area of the joint core. In addition, concrete had also crushed and spalled out due to compression failure on the joint. These specimens were detailed as per IS-456 full length anchorage in combination with X-cross bar for the low seismic prone area.

5.5 COMPARISON OF LOAD-DISPLACEMENT BEHAVIOR FOR GROUP-I AND GROUP-II SPECIMENS

![Figure 5.8 Load-displacement chart for group-I & II](image-url)

<table>
<thead>
<tr>
<th>Specimens and Groups</th>
<th>Group-I (A1,B1,C1)</th>
<th>Group-II (A2,B2,C2)</th>
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</thead>
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<tr>
<td>A</td>
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<tr>
<td>B</td>
<td>68</td>
<td>78.5</td>
</tr>
<tr>
<td>C</td>
<td>71.75</td>
<td>79.25</td>
</tr>
</tbody>
</table>

Figure 5.8 Load-displacement chart for group-I & II
Figure 5.9 Backbone curve of load-displacement for group-I

Figure 5.10 Backbone curve of load-displacement for group-II
Table 5.1 Load - displacement value of test specimens for group-I and II

<table>
<thead>
<tr>
<th>Specimen /Groups</th>
<th>Yielding displacement in mm- $\delta_y$</th>
<th>Ultimate load in kN - $P_u$</th>
<th>Average ultimate load in kN-$P_u$</th>
<th>Ultimate displacement in mm-$\delta_u$</th>
<th>Average displacement for ultimate load in mm-$\delta_u$</th>
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<td>Right Side</td>
<td>Left Side</td>
<td>Right Side</td>
<td>Left Side</td>
</tr>
<tr>
<td>A1-I</td>
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<td>74.00</td>
<td>73.00</td>
<td>42.13</td>
</tr>
<tr>
<td>B1-I</td>
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<td>66.00</td>
<td>68.00</td>
<td>35.96</td>
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<td>71.75</td>
<td>45.63</td>
</tr>
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<td>C2-II</td>
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<td>81.00</td>
<td>79.25</td>
<td>54.63</td>
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The hysteresis curves obtained from the experimental test results of lateral load versus displacement are shown in Figures 5.2-5.4 and the corresponding peak load-displacement chart and backbone curve of load-displacement for group-I are shown in Figure 5.8 and Figure 5.9. It is observed that in group-I, the average ultimate load carrying capacity of the specimens A1, B1 and C1 are 73.00, 68.00 and 71.75 kN with the corresponding lateral displacement as 52.72, 40.91 and 50.62 mm respectively. Among these, A1 exhibits the maximum load carrying capacity which is marginally higher than B1 by 7.35% and C1 by 1.75%. The hysteresis curves (of group-II) obtained from the experimental test results of lateral load-displacement chart and backbone curve of load-displacement for group-II are shown in Figure 5.8 and Figure 5.10. It is observed that in group-II, the average ultimate load carrying capacity of the specimens A2, B2 and C2 is 79.50, 78.50 and 79.25 kN with the corresponding lateral displacement as 60.66, 67.00 and 65.23 mm respectively. Among these, A2 exhibits the maximum load carrying capacity than B2 by 1.30% and C2 by 0.4%. The ultimate load carrying capacity of the test specimens was assessed from Table 5.1 and Figure 5.8, it was observed that the ultimate load carrying capacity of
group-I specimens namely A1, B1 and C1 exhibits higher load carrying capacity than group-II specimens namely A2, B2 and C2 by 9.00%, 15.50% and 10.50% respectively. From the above test results, it can be inferred that the additional X-cross bar joint details significantly increases the ultimate strength in addition to moment carrying capacity of the beam.

5.6 LOAD-DISPLACEMENT BEHAVIOR OF SPECIMENS A3, B3, C3 FOR GROUP-III

5.6.1 Load –Displacement Behavior of Specimen A3 for Group-III

![Hysteresis curve of load-displacement relationship for specimen A3](image)

Figure 5.11 Hysteresis curve of load-displacement relationship for specimen A3

The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.11 for group-III of A3 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to
the column junction with yielding displacement of 2.15 mm. Again the specimen are loaded, unloaded and reloaded till the 9th cycle where it reaches the ultimate load with the corresponding average ultimate load as 89.50 kN and displacement 47.50mm as indicated in Table 5.2 & Figure 5.11. After reaching the ultimate load, there were no signs of diagonal cracks on the shear panel area of the joint core and no wide open crack on the beam-column joint. These specimens were detailed as per with ACI-352 mechanical anchorage in combination with X-cross plus U-bar (hair-clip bar) for the moderate and high seismic prone area.

5.6.2 Load -Displacement Behavior of Specimen B3 for Group-III

![Hysteresis curve of load-displacement relationship for specimen B3](image)

**Figure 5.12 Hysteresis curve of load-displacement relationship for specimen B3**

The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.12 for group-III of
B3 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 2.40mm. Again the specimen are loaded, unloaded and reloaded till the 9th cycle where it reaches the ultimate load with the corresponding average ultimate load as 90.00 kN and displacement 47.50mm as indicated in Table 5.2 & Figure 5.12. After reaching the ultimate load, there are several diagonal cracks on the shear panel area of the joint core and in addition concrete had also spalled out due to compression failure on the beam-column joint. These specimens were detailed as per ACI-318 conventional 90° hooks bent anchorage in combination with X-cross plus U-bar (hair-clip bar) for the moderate and high seismic prone area.

5.6.3 Load –Displacement Behavior of Specimen C3 for Group-III

Figure 5.13 Hysteresis curve of load-displacement relationship for specimen C3
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.13 for group-III of C3 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 2.20mm. Again the specimen are loaded, unloaded and reloaded till the 9th cycle where it reaches the ultimate load with the corresponding average ultimate load 89.00 kN and displacement 44.43mm as indicated in Table 5.2 & Figure 5.13. After reaching the ultimate load, there are a number of diagonal cracks on the shear panel area of the joint core and in addition concrete had also spalled out due to compression failure on the beam-column joint. These specimens were detailed as per IS-456 full anchorage in combination with X-cross bar plus U-bar (hair-clip bar) for the moderate and high seismic prone area.

5.7 LOAD-DISPLACEMENT BEHAVIOR OF SPECIMENS A4, B4, C4 FOR GROUP-IV

5.7.1 Load –Displacement Behavior of Specimen A4 for Group-IV

![Hysteresis curve of load-displacement relationship for specimen A4](image-url)
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.14 for group-IV of A4 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 2.30mm. Again the specimen are loaded, unloaded and reloaded till the 9th cycle where it reaches the ultimate load with the corresponding average ultimate load as 80.50 kN and displacement 45.37mm as indicated in Table 5.2 & Figure 5.14. After reaching the ultimate load, there are few diagonal cracks on the shear panel area of the joint core. In addition, deep cracks were formed on the beam-column joint. These specimens were detailed as per ACI-352 mechanical anchorage with confinement reinforcement on the joint core for the moderate and high seismic prone area.

5.7.2 Load –Displacement Behavior of Specimen B4 for Group-IV

![Figure 5.15 Hysteresis curve of load-displacement relationship for specimen B4](image_url)
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.15 for group-IV of B4 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 2.85mm. Again the specimen are loaded, unloaded and reloaded till the 8th cycle where it reaches the ultimate load with the corresponding average ultimate load 79.00 kN and displacement 35.55mm as indicated in Table 5.2 & Figure 5.15. After reaching the ultimate load, there are quite a lot of diagonal cracks on the shear panel area of the joint core. In addition, concrete had also spalled out due to compression failure on the beam-column joint. These specimens were detailed as per ACI-318 conventional 90° hooks bent with confinement reinforcement on the joint core for the moderate and high seismic prone area.

5.7.3 Load -Displacement Behavior of C4 Specimen for Group-IV

![Hysteresis curve of load-displacement relationship for specimen C4](image)

**Figure 5.16** Hysteresis curve of load-displacement relationship for specimen C4
The load was applied as discussed in the Section 5.2 and the loading sequences are followed as shown in Figure 5.1. The hysteresis curve of the load-displacement is plotted as shown in Figure 5.16 for group-IV of C4 specimen. In the second cycle, initial flexural cracks were noticed in the beam-column assemblage in the column joint where the beam is connected to the column junction with yielding displacement of 3.00mm. Again the specimen are loaded, unloaded and reloaded till the 8th cycle where it reaches the ultimate load with the corresponding average ultimate load 79.50 kN and displacement 48.12mm as indicated in Table 5.2 & Figure 5.16. After reaching the ultimate load, there are quite a lot of diagonal cracks on the shear panel area of the joint core and concrete had also spalled due to compression failure. In addition, wide deep crack were formed on the beam-column joint. These specimens were detailed as per IS-456 full anchorage with confinement reinforcement on the joint core for the moderate and high seismic prone area.

5.8 COMPARISON OF LOAD-DISPLACEMENT BEHAVIOR FOR GROUP-III AND GROUP-IV SPECIMENS

![Figure 5.17 Load-displacement chart for group-III & IV](image-url)
Figure 5.18 Backbone curve of load-displacement for group -III

Figure 5.19 Backbone curve of load-displacement for group -IV
Table 5.2 load-displacement value of test specimens for group-III and IV

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<tr>
<th>Specimen /Groups</th>
<th>Yielding displacement in mm-$\delta_y$</th>
<th>Ultimate load in kN-$P_u$ Left Side</th>
<th>Right Side</th>
<th>Average ultimate load in kN-$\delta_u$ Left Side</th>
<th>Right Side</th>
<th>Ultimate displacement in mm-$\delta_u$ Left Side</th>
<th>Right Side</th>
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<td>89.00</td>
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The hysteresis loops obtained from the experimental test results of lateral load versus displacement are shown in Figures 5.11-5.13 and the corresponding peak load versus displacement are shown in Figure 5.18. It is observed that in group-III, the average ultimate load carrying capacity of the specimens A3, B3 and C3 are 89.50, 90.00 and 89.00 kN with the corresponding lateral displacement as 47.50, 47.50 and 44.43 mm respectively. Among these, B3 exhibits the maximum load carrying capacity which is marginally higher than A3 by 0.5% and C3 by 1.1%. The hysteresis loops (of group-III) obtained from the experimental test results of lateral load versus displacement are shown in Figures 5.14-5.16, and the corresponding peak loads versus displacement are shown in Figure 5.19. It is observed that in group-IV, the average ultimate load carrying capacity of the specimens A4, B4 and C4 is 80.50, 79.00 and 79.50 kN with the corresponding lateral displacement as 45.38, 35.55 and 48.12 mm respectively. Among these, A4 exhibits the maximum load carrying capacity which is higher than B4 by 1.86% and C4 by 1.24%. The ultimate load carrying capacity of the test specimens were assessed from Table 5.2 and Figure 5.17, it was observed that
the ultimate load carrying capacity of group-III specimens namely A3, B3 and C3 exhibits higher load carrying capacity than group-IV specimens namely A4, B4 and C4 by 10%, 12.2% and 10.67% respectively. From the above test results, it can be inferred that the proposed additional X-cross bar joint details significantly increases the ultimate strength in addition to moment carrying capacity of the beam.

5.9 STIFFNESS BEHAVIOR STUDY

5.9.1 Stiffness Behavior of Group-I Specimens

![Bar chart showing stiffness behavior of group-I specimens](image)

Table 5.3 shows the average stiffness (stiffness \( K = \frac{P_u}{\dot{\gamma}} \), wherein \( P_u \) is the ultimate load and \( \dot{\gamma} \) is the yielding displacement). It has been observed from the experimental results that in group-I, specimen A1 is having higher stiffness than specimens B1 and C1 as shown in Figure 5.20.
5.9.2 Stiffness Behavior of Group-II Specimens

![Figure 5.21 Stiffness behavior chart for group-II specimens](image)

In group-II, specimen A2 has higher stiffness than specimens B2 and C2 as shown in Figure 5.21. Between these two groups, group-II has higher stiffness. The specimen A2 which had additional X-cross bar exhibited better performance. Among six specimens in group-III and IV against
stiffness degradation, the stiffness of specimen A2 is higher than A1 by 13.68%.

5.9.3 Stiffness Behavior of Group-III Specimens

![Graph showing stiffness behavior of group-III specimens]

Table 5.4 shows the average stiffness \( K = \frac{P_u}{\delta y} \) wherein \( P_u \) is the ultimate load and \( \delta y \) is the yielding displacement. It has been observed from the experimental results that in group-III, specimen A3 is having higher stiffness than specimens B3 and C3 as shown in Figure 5.22.

5.9.4 Stiffness Behavior of Group-IV Specimens

![Graph showing stiffness behavior of group-IV specimens]
Table 5. 4 Yielding displacement and stiffness value of group-III and IV

<table>
<thead>
<tr>
<th>Specimens names and groups</th>
<th>Yielding displacement in mm - $\delta_y$</th>
<th>Ultimate load in kN</th>
<th>Average ultimate load in kN - $P_u$</th>
<th>Stiffness of the test specimens $K= P_u/\delta_y$</th>
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</thead>
<tbody>
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<td>Right hand side (RHS)</td>
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<td>80.00</td>
<td>81.00</td>
<td>80.50</td>
</tr>
<tr>
<td>B4-IV</td>
<td>2.85</td>
<td>78.00</td>
<td>80.00</td>
<td>79.00</td>
</tr>
<tr>
<td>C4-IV</td>
<td>3.00</td>
<td>78.50</td>
<td>80.50</td>
<td>79.50</td>
</tr>
</tbody>
</table>

In group-IV, specimen A4 is having higher stiffness than specimens B4 and C4. The specimen A3 which had additional X-cross bar with hair clip exhibited better performance among six specimens in group-III and IV against stiffness degradation. The stiffness of specimen A3 is higher than A4 by 15.92%. Between these two groups, the specimens in group-III are having higher stiffness as shown in Figure 5.23.

5.10 DUCTILITY BEHAVIOR STUDY

5.10.1 Ductility Behavior of Group-I Specimens

![Figure 5.24 Ductility behavior chart for group-I specimens](image)
5.10.2 Ductility Behavior of Group-II Specimens

![Figure 5.25 Ductility behavior chart for group-II specimens](image)

![Table 5.5 Yielding displacement and ductility value of group-I and II](table)

<table>
<thead>
<tr>
<th>Specimens names and groups</th>
<th>Yielding displacement in mm - $\delta_y$</th>
<th>Ultimate displacement in mm</th>
<th>Average displacement for ultimate load in mm - $\delta_u$</th>
<th>Displacement ductility factor $\mu = \delta_u/\delta_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1-I</td>
<td>4.50</td>
<td>42.13</td>
<td>63.30</td>
<td>52.72</td>
</tr>
<tr>
<td>B1-I</td>
<td>5.00</td>
<td>35.96</td>
<td>45.85</td>
<td>40.91</td>
</tr>
<tr>
<td>C1-I</td>
<td>5.20</td>
<td>45.63</td>
<td>55.60</td>
<td>50.62</td>
</tr>
<tr>
<td>A2-II</td>
<td>4.23</td>
<td>56.00</td>
<td>65.32</td>
<td>60.66</td>
</tr>
<tr>
<td>B2-II</td>
<td>5.50</td>
<td>65.00</td>
<td>69.00</td>
<td>67.00</td>
</tr>
<tr>
<td>C2-II</td>
<td>5.12</td>
<td>54.63</td>
<td>75.96</td>
<td>65.30</td>
</tr>
</tbody>
</table>

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 5.5 and Figures 5.24 - 5.25, 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 additional X-cross bar joint core details was used in group-II. Among these six specimens in group-I and II, A2 exhibits better performance. Such combination of anchorage and joint details may be used in seismic prone zones demanding lesser ductility.

5.10.3 Ductility Behavior of Group-III Specimens

![Figure 5.26 Ductility behavior chart for group-III specimens]

5.10.4 Ductility Behavior of Group-IV Specimens

![Figure 5.27 Ductility behavior chart for group-IV specimens]
Table 5.6 Yielding displacement and ductility value of group-III and IV

<table>
<thead>
<tr>
<th>Specimens names and groups</th>
<th>Yielding displacement in mm - $\delta_y$</th>
<th>Ultimate displacement in mm</th>
<th>Average displacement for ultimate load in mm - $\delta_u$</th>
<th>Displacement ductility factor $\mu = \frac{\delta_u}{\delta_y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left hand side (LHS)</td>
<td>Right hand side (RHS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3-III</td>
<td>2.15</td>
<td>42.00</td>
<td>53.00</td>
<td>47.50</td>
</tr>
<tr>
<td>B3-III</td>
<td>2.40</td>
<td>45.00</td>
<td>50.00</td>
<td>47.50</td>
</tr>
<tr>
<td>C3-III</td>
<td>2.20</td>
<td>43.50</td>
<td>45.36</td>
<td>44.43</td>
</tr>
<tr>
<td>A4-IV</td>
<td>2.30</td>
<td>42.15</td>
<td>48.60</td>
<td>45.38</td>
</tr>
<tr>
<td>B4-IV</td>
<td>2.85</td>
<td>30.85</td>
<td>40.25</td>
<td>35.55</td>
</tr>
<tr>
<td>C4-IV</td>
<td>3.00</td>
<td>45.63</td>
<td>50.60</td>
<td>48.12</td>
</tr>
</tbody>
</table>

From Table 5.6 and Figures 5.26-5.27, it is observed that group-III specimens namely A3 (ACI-352, mechanical anchorage), B3 (ACI-318,90\(^0\) 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 locations demanding moderate and severe ductility.

5.11 YIELDING AND ULTIMATE FAILURE CRACK PATTERN STUDY

The testing is load controlled with a load increment of 1-ton (10kN). The specimens have been tested till it reaches its maximum failure capacity on visual examination of crack pattern behavior as shown in Figures 5.28-5.39. During the first cycle with 1 ton load, no cracks were noticed. When the 2\(^{nd}\) cycle started with a load of 2 ton, initial flexural cracks were observed on the beam-column junction. The crack got closed on the applied load direction when the load was released. Again when reloaded on
the other face of the beam, initial flexural cracks were again noticed on the beam-column junction. These same cycles of loading procedure were followed till maximum ultimate loading capacity was reached. At some point the beam-column assemblages were found with wide open cracks and diagonal cracks due to tensile force. Few numbers of test assemblage joint core concrete were spalled out due to compressive force and also found some of them with shear cracks on the column. The usage of mechanical anchorage assemblages are having the good control on the overall crack failure behavior.

5.11.1 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen A1 for Group-I

Figure 5.28 Crack pattern behavior of A1 specimen
In group-I A1 specimen, initial flexural cracks were noticed in beam-column joint. When the load is increased initial crack length got increased and many of the secondary cracks and other cracks were observed. In addition shear crack is also formed in the column (due to bearing stress using of mechanical anchorage) as shown in Figure 5.28. There were no signs of diagonal cracks on the shear panel area of the joint core, since there is no $90^0$ bent anchorage bars to develop the compression strut and tension tie action on the beam-column joint. The specimens reached its average ultimate failure load of 73.00 kN with the corresponding displacement of 52.70mm.

5.11.2 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen B1 for Group-I

![Figure 5.29 Crack pattern behavior of B1 specimen](image)
In group-I B1 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with yielding displacement of 5.00\text{mm} and the average ultimate failure load is 68\text{ kN} with the corresponding displacement of 40.91\text{mm}. In this specimen there is 90\textdegree bent anchorage bars to develop the compression strut and tension tie action since there are diagonal cracks on the beam-column joint, shear cracks on the column, flexural cracks on face of the column as shown in Figure 5.29 and in addition concrete had also spalled out from the assemblage due to reversal loading.

5.11.3 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen C1 for Group-I

![Figure 5.30 Crack pattern behavior of C1 specimen](image)
In group-I C1 specimen, initial flexural cracks were noticed in the column joint where the beam gets connected to the column junction at the second cycle with yielding displacement of 5.20mm. The average ultimate failure load is 71.75 kN with the corresponding displacement of 50.62mm. In this specimen, there is $90^0$ bent anchorage bars to develop the compression strut and tension tie action since there are diagonal cracks on the beam-column joint, shear cracks on the column and wide open flexural cracks on face of the column due to reversal loading as shown in Figure 5.30.

5.11.4 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen A2 for Group-II

![Crack pattern behavior of A2 specimen](image.png)

Figure 5.31 Crack pattern behavior of A2 specimen
In group-II A2 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with yielding displacement of 4.23mm and the average ultimate failure load is 79.50 kN with the corresponding displacement 60.66mm. In this specimen there are no diagonal cracks, only the shear cracks on the column due to the T-type headed anchorage for the bearing stress action and wide open flexural cracks on face of the column as shown Figure 5.31.

5.11.5 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen B2 for Group-II

![Crack pattern behavior of B2 specimen](image)

Figure 5.32 Crack pattern behavior of B2 specimen
In group-II B2 specimen, initial flexural cracks were noticed in the column joint where the beam gets connected to the column junction at the second cycle with yielding displacement of 5.50mm. The average ultimate failure load is 78.50 kN with corresponding displacement of 67.00mm. In this specimen there is $90^\circ$ bent anchorage bars to develop the compression strut and tension tie action since there are diagonal cracks on the beam-column joint, shear cracks on the column, very wide open flexural cracks on face of the column and in addition concrete had also spalled out from the assemblage due to reversal loading (as shown in Figure 5.32).

5.11.6 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen C2 for Group-II

Figure 5.33 Crack pattern behavior of C2 specimen
In group-II C2 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with the yielding displacement of 5.12mm and the average ultimate failure load is 79.25kN with corresponding displacement of 65.30mm. In this specimen there are diagonal cracks, shear cracks on the column, very wide open flexural cracks on face of the column as shown in Figure 5.33 and in addition concrete had also spalled out from the assemblage due to reversal loading.

5.11.7 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen A3 for Group-III

Figure 5.34 Crack pattern behavior of A3 specimen
In group-III A3 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with the yielding displacement of 2.15mm and the average ultimate failure load is 89.50 kN with corresponding displacement of 47.50mm. In this specimen, there are no diagonal cracks only the shear cracks on the column due to the T-type headed anchorage for the bearing stress action, wide open flexural cracks on face of the column. This specimen is having a good crack controlled capacity as shown in Figure 5.34.

5.11.8 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen B3 for Group-III

Figure 5.35 Crack pattern behavior of B3 specimen
In group-III B3 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with the yielding displacement of 2.40mm and the average ultimate failure load is 90.00 kN with corresponding displacement of 47.50mm. In this specimen there is 90° bent anchorage bars to develop the compression strut and tension tie action since there are diagonal cracks on the beam-column joint, shear cracks on the column, very wide open flexural cracks on face of the column and in addition concrete had also spalled out from the assemblage due to reversal loading as shown in Figure 5.35.

5.11.9 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen C3 for Group-III

Figure 5.36 Crack pattern behavior of C3 Specimen
In group-III C3 specimen, initial flexural cracks were noticed in the column joint where the beam gets connected to the column junction at the second cycle with the yielding displacement of 2.20mm. The average ultimate failure load is 89.00 kN with corresponding displacement of 44.43mm. In this specimen there are diagonal cracks, shear cracks on the column, very wide open flexural cracks on face of the column and in addition concrete had also spalled out from the assemblage as shown in Figure 5.36.

5.11.10 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen A4 for Group-IV

Figure 5.37 Crack pattern behavior of A4 specimen
In group-IV A4 specimen, initial flexural cracks were noticed in the column joint where the beam gets connected to the column junction at the second cycle with the yielding displacement of 2.30mm. The average ultimate failure load is 80.50kN with corresponding displacement of 45.38mm. In this specimen there are no diagonal cracks, only shear cracks on the column due to the T-type headed anchorage for the bearing stress action and wide open flexural cracks on face of the column as the beam getting connected due to reversal loading. The crack details are as shown in Figure 5.37.

5.11.11 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen B4 for Group-IV

Figure 5.38 Crack pattern behavior of B4 specimen
In group-IV B4 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with the yielding displacement of 2.85mm and the average ultimate failure load is 79.00kN with corresponding displacement of 35.55mm. In this specimen there are diagonal cracks, shear cracks on the column, very wide open flexural cracks on face of the column, as shown in Figure 5.38, in addition concrete had also spalled out from the assemblage due to reversal loading.

5.11.12 Yielding and Ultimate Failure Crack Pattern Behavior of Specimen C4 for Group-IV

Figure 5.39 Crack pattern behavior of C4 specimen
In group-IV C4 specimen, initial flexural cracks were noticed in the column joint where the beam getting connected to the column junction at the second cycle with the yielding displacement of 3.00mm and the average ultimate failure load is 79.50kN with corresponding displacement of 48.12mm. In this specimen there are diagonal cracks, shear cracks on the column, very wide open flexural cracks on face of the column and in addition concrete had also spalled out from the assemblage due to reversal loading. The crack details are as shown in Figure 5.39.

5.11.13 Ultimate Failure Behavior Comparison for Group-I and II

On visual examination of crack pattern of Figures 5.28-5.33, flexural cracks on the beam-column junction and shear cracks have developed on the column in all the specimens. Further to these cracks, the specimens B1, C1, B2 and C2 have $90^\circ$ bent tensile anchorage bars which induce a compressive stress in the joint diagonally forming a compression strut due to contact pressure under the bent. Tension tie developed in the joint perpendicular to the direction of the diagonal tension tie in the shear panel area it will be forming the diagonal cracks in the beam-column joint. Besides the formation of wide open cracks in the junction, the concrete had also crushed and spalled out from the specimens B1, B2, C1 and C2 due to compressive force, the specimens A1 and A2 with mechanical anchorage shows the lesser crack pattern than other specimens using conventional joint details in group-I and II without losing the strength. However specimen A2 with mechanical anchorage (ACI-352, mechanical anchorage) plus X-cross bar shows lesser cracks and much better control of crack capacity with higher load carrying capacity than other specimens with considerable improvement in seismic performance for lower seismic prone areas.
5.11.14 Ultimate Failure Behavior Comparison for Group-III and IV

On visual examination of crack pattern shown in Figures 5.34-5.39, flexural cracks on the beam-column junction and shear cracks have developed on the column in all the specimens. Further to these cracks, the specimens B3, C3, B4 and C4 have 90° bent tensile anchorage bars, which induce a compressive stress in the joint diagonally forming a compression strut due to contact pressure under the bent. Tension tie developed in the joint perpendicular to the direction of the diagonal tension tie in the shear panel area will be forming the diagonal cracks on the beam-column joint. Besides, formation of wide open cracks in the junction, the concrete had also crushed and spalled out from the specimens B3, B3, C4 and C4 due to compressive force. The specimens A3 and A4 with mechanical anchorage shows the lesser crack pattern than other specimens using conventional joint details in group-III and IV without losing the strength, however specimen A3 with mechanical anchorage (ACI-352, mechanical anchorage) in combination X-cross bar plus U-bar, shows lesser cracks and much better control of crack capacity than the other specimens with improvement in seismic performance for moderate and high seismic prone areas.

It can therefore be concluded that these types of anchorage with proposed joint core details are much more effective in controlling beam-column joint than conventional details. It is apparent that the use of mechanical anchored bars is a viable alternative to use standard 90° hooks in exterior beam-column joints in moderate and severe seismic prone area. In addition, it is easy to repair using FRP composite wraps techniques to restore the flexural strength, ductility of earthquake damaged concrete beam-column joints.
5.12 SUMMARY

Reinforced concrete structures beam-column joints are one of the most critical regions in seismic prone areas. Proper reinforcement anchorage is essential to enhance the performance of the joints. An attempt has been made to study and evaluate the performance of beam-column joints anchorages and joint detailing. The anchorages are followed as per ACI-352 (mechanical anchorage/or headed bar), ACI -318 (conventional hooks bent) and IS-456 (full anchorage conventional hooks bent) along with confinement as per IS-13920 and without confinement. Apart from finding solutions for congestion of reinforcement and construction difficulty problems, significant improvements in seismic performance, ductility, strength, stiffness and controlled crack pattern were observed while using mechanical anchorage in combination with X-cross bars for less seismic prone areas and X-cross bar plus hair clip (U-bar) joint reinforcement for moderate / higher seismic prone areas. To evaluate the performances of these types of anchorages and joint details, the specimens were assembled into four groups, each group of three specimens have been tested under reversal loading.