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Study of exterior beam-column joint with different joint core and anchorage details under reversal loading

S. Rajagopal* and S. Prabavathy

Department of Civil Engineering, Mepco Schlenk Engineering College, Sivakasi, Tamil Nadu 626 005, India

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Abstract. In the present study, in reinforced concrete structures, beam-column connections are one of the most critical regions in areas with seismic susceptibility. Proper anchorage of reinforcement is vital to enhance the performance of beam-column joints. Congestion of reinforcement and construction difficulties are reported frequently while using conventional reinforcement detailing in beam-column joints of reinforced concrete structures. An effort has been made to study and evaluate the performance of beam-column joints with joint detailing 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 and without confinement. Apart from finding solutions for these problems, significant improvements in seismic performance, ductility and strength were observed while using mechanical anchorage in combination with X-cross bars for less seismic prone areas and X-cross bar plus hair clip joint reinforcement for 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 having three specimens have been tested under reversal loading and the results are presented in this paper.

Keywords: reinforced concrete structure; beam-column connection; seismic; ductility; mechanical anchorage

1. Introduction

Beam-column connections are critical regions in the reinforced concrete framed structure in higher 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. American Concrete Institute (ACI)-352(2002) recommends additional research on use of T-headed bar in the design of beam-column connections in concrete structure. The investigation of the beam-column connection using longitudinal beam reinforcement bar with 90° standard bent hooks anchorage and mechanical anchor for joint core under reversal loadings has been a research area for many years. Some of the analytical and experimental studies carried out in the area so far are indicated below.

Paulay (1989) suggested that, as in the case of linear element, joint shear reinforcement is necessary to sustain a diagonal compression field rather than to provide confinement to compressed concrete in joint core.

∗Corresponding author, Ph.D. Student, E-mail: srajagopals@gmail.com

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Tsonos *et al*. (1993) 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*. (1998) suggested that use of headed reinforcement had eased specimen fabrication, concrete placement, and improved the behavior equal to that of specimens with standard 90^0 hooks for beam-column corner joint.

Murty *et al*. (2003) reported that the standard hooks for anchorage of the longitudinal beam bar with hair clip-type transverse joint reinforcement as per ACI were more effective and this combination of anchorage with joint reinforcement is easy to construct and can be used in locations demanding ductility moderately.

Chutarat and Aboutaha (2003) reported that the use of straight-headed bars in the exterior beam-column joint for cyclic response is very effective in relocating potential plastic regions.

Uma and Sudhir (2006) in their review of codes of practices considered ACI318, NZS 3101: Part-1 and Eurocode-8 EN1998-1 regarding the design and detailing aspects of interior and exterior beam-column joint.

Bindhu *et al*. (2008) in their experimental investigations validated with analytical studies and concluded that additional cross bracing reinforcement improves the seismic performance of the exterior reinforced concrete beam-column joints.

Lee *et al*. (2009) Proposed extension of ACI design methods to cover the use of mechanical anchorage for eccentric beam-column joints. They also 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.

The use of headed bars has become increasingly popular for relatively large reinforced concrete (RC) structures that are exposed to extreme loads such as strong earthquakes or blasts, often providing an adequate solution to steel congestion (Chun *et al*. 2007, Kang *et al*. 2009, 2010).

Sagbas *et al*. (2011) in their Finite Element Analysis (FEA) computational analysis compared the experimental test results of seismically and non-seismically designed joint detailing for the shear deformations.

Asha and Sundararajan (2012) reported that the use of with square spiral confinement in joint along with different reinforcement detailing for anchorage of beam bars and additional inclined bars from column to beam connection can successfully move the plastic hinge away from the column face.

It is noted that the anchorage requirements for the beam longitudinal reinforcement bar and the joint confinement are the main issues related to problem of congestion of reinforcement in the beam-column connections. An attempt has been made 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 prone zones and mechanical anchorage with X-cross bar for lesser seismic prone zone and the zones are followed as per IS-1893 (2002). It is found that these combinations were effective in reducing the congestion of reinforcement in joint core area and eased pouring of concrete without compromising the strength, ductility and stiffness of beam-column joints under reversal loading.

2. Research significance

The experimental studies have been carried out for different types of anchorages and joint details in the exterior beam-column connection showed that the T-type mechanical anchorage (headed bar) in combination with additional X-cross plus U-bar and T-type mechanical anchorage in combination with additional X-cross bar enhanced load carrying capacity in case of higher seismic prone zones and lower seismic prone zones respectively. Such types of anchorages and joint details improve the seismic performance and ductile behavior of beam-column joint without losing the strength. This arrangement eased the congestion of reinforcement and placements of concrete at joint core. As a result, construction and fabrication become easier and faster at site.

3. Testing program and test setup

Twelve specimens of beam-column joint have been considered in the present studies. The specimens have been divided into four Groups, each Group having three specimens, with different anchorages. The anchorage details are designated as A, B and C and joint details are designated as 1, 2, 3 and 4. Anchorage detail-A represents T-type mechanical anchorage as per ACI-352 (2002). Anchorage detail-B represents conventional 90° standard bent hooks as per ACI-318 (2011) and anchorage detail-C represents full anchorage as per IS-456 (2000). Joint detail-1 contains no confinement reinforcement, Joint detail-2 contains additional X-cross bar, Joint detail-3 contains X-cross bar with U-bars and Joint detail-4 contains conventional shear links arrangement.

4. Experimental research program

The testing of half-scale exterior beam-column joint specimens 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 shown in Fig. 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

Fig. 1 Experimental set up

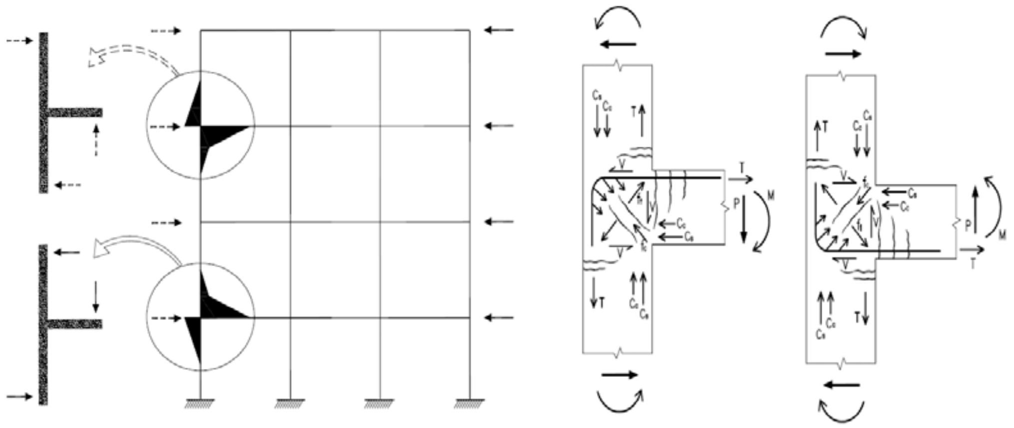

Fig. 2 Typical reinforced concrete frame and joint forces

fasteners. The RCC beam was loaded as shown in Fig. 1. The Linear Variable Differential Transducer (LVDT) was connected on either side of the specimen to monitor the displacements. The testing is a load controlled with a load increment of 1-ton. The specimens have been tested till it reaches its maximum failure capacity.

5. Critical joint behavior and mechanism

A particularly sever ground shake critical situation can arise in certain exterior beam-column joints of plane multistorey frames when they are subjected to higher magnitude of seismic loading. The external action and the corresponding internal forces generated around such a joint are indicated in Fig. 2. It is apparent that diagonal tensile and compressive 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*' stands for beam and '*c*' stands for column.

6. Reinforcement anchorage development length

The ACI-352 (2002) report specifies that the critical section for development length of reinforcement either hooked or headed in case of beams with Type-2 connections should be taken at the outside edge of the column core. The development length measured from the critical section shall be computed as follows.

$$L_{dh} = \frac{\alpha\, f_y d_b}{6.2\sqrt{f'_c}} \tag{1}$$

Where,
L_{dh}-Development length for a hooked bar measured from the critical section to the outside edge of the hook extension, (267.75mm < 272mm), α - Stress multiplier for longitudinal reinforcement at joint-member interface for type 2, ($\alpha \geq 1.25$), f_y- Yield stress of reinforcement, d_b- Nominal diameter of bar, f'_c- Compressive strength of concrete in the connection.

The development length L_{dt} of a headed bar should be taken as 3/4 of the value computed for hooked bars using Eq. (1)

$$\text{For headed bar } L_{dt} = \frac{3}{4} * L_{dh}, \quad [195 \text{ mm} < 270\text{mm}] \tag{2}$$

Where,
L_{dt} - Development length for a headed bar measured from the critical section to the outside end of the head. In headed bar, the bar head should not be located in the confined core within 50 mm from the back of the confined core. The minimum development length L_{dt} should not be less than 8 d_b or 150 mm, in respect of Type-1 and Type-2 connections.

As per IS 456 (2000) the development length (L_d) of the hooked reinforcement bar shall be computed as follows.

$$L_d = \frac{\phi \sigma_s}{4\tau_{bd}} \tag{3}$$

Where,
L_d - Development length, [644.73mm < 710mm], Ø - Nominal diameter of the bar, σ_s - Stress in bar (0.87 f_y) at the section considered at design load, τ_{bd} -Design bond stress of concrete (can be increased by 60% for deformed bars).

7. Transverse reinforcement within the joint

The ACI-352 (2002) committee report recommends adequate lateral confinement of the concrete in the joint core for the shear demand either in the form of spirals or rectangular hoops for both Type-1 and Type-2 joints (Type-1, no inelastic deformations are anticipated whereas joints of Type-2 are designed to sustain strength under deformation reversals into the inelastic range. It should be note that this paper deals only with Type-2 joints, i.e., seismic beam-column joints). For Type-2 joints, the total cross sectional area of transverse reinforcement within the joint in each direction shall be at least equal to but not less than A_{sh}.

$$A_{sh} = 0.3 \frac{s_h b''_c f'_c}{f_{yh}} \left(\frac{A_g}{A_c} - 1 \right) \geq 0.09 \frac{s_h b''_c f'_c}{f_{yh}} \tag{4}$$

The center to center spacing between layers of transverse reinforcement s_h should not exceed the least of 1/4 of the minimum column dimension, six times the diameter of the longitudinal column bars to be restrained, 150mm.
Where,

A_{sh} - Total cross-sectional area of all legs of hoop reinforcement where (301.6mm^2 > 228.82mm^2 ≥ 71.57mm^2) including crossties, crossing a section having core dimension, b''_c. s_h -Center-to-center spacing of hoops or hoops plus crossties, b''_c - Core dimension of tied column outside to outside edge of transverse reinforcement bars perpendicular to the transverse reinforcement area A_{sh} being designed, f'_c -Compressive strength of concrete in the connection, f_{yh} -Yield stress of spiral, hoop and crosstie reinforcement, A_g- Gross area of column section, A_c - Area of column core measured from outside edge to outside edge of spiral or hoop reinforcement.

As per IS-13920 (1993) the area of cross section of the bar A_{sh}, forming rectangular hoop to be used as special confining reinforcement shall not be less than

$$A_{sh} = 0.18sh\frac{f_{ck}}{f_y}\left(\frac{A_g}{A_k} - 1\right) \tag{5}$$

Where

A_{sh} -Area of the bar cross section, (241.30mm^2 < 301.6mm^2), s - Pitch of spiral or spacing of hoop (the spacing of hoops used as special confining reinforcement shall not exceed ¼ of minimum member dimension but not less than 75mm nor more than 100mm), h - Longer dimension of the rectangular confining hoop measured to its outer, f_{ck} - Characteristic compressive strength of concrete cube, f_y -Yield stress of steel, A_g - Gross area of the column cross section, A_k -Area of confined concrete core in the rectangular hoop measured to its outside dimensions.

8. Joint shear strength

The ACI-352(2002) requirements for joint shear strength are based on

$$\Phi\ V_u = \Phi * 0.083\gamma\sqrt{f'_c}\,b_j h_c \geq V_u \tag{6}$$

Where

Φ- 0.85, V_u -Nominal shear strength of the joint, Φ V_u - 253.98kN ≥ 128.60kN, γ- Shear strength factor reflecting confinement of joint by lateral member (referred from Table-1 ACI-352 Type-1 and Type-2 beam column connection), f'_c -Compressive strength of concrete in the connection, b_j - Effective width of the joint transverse to the direction of shear, h_c - Full depth of the column.

The horizontal joint shear demand V_u is calculated based on the amount of beam reinforcement as follows

$$V_u = T - V_{column} = \alpha A_s f_y - V_{column} \tag{7}$$

Where, T - Tension force in the reinforcement, A_s -Area of tension reinforcement, f_y - Nominal yield stress of the tension reinforcement and V_{column} -Shear in the column. Typically, inflection points are assumed at beam mid span and column middle height to compute the column shear. The term α is a stress multiplier to account for over-strength and strain hardening of the reinforcement. Minimum values of α equal to1.00 and 1.25 are recommended for Type-1 and 2 joints respectively.

9. Details of test specimens

All the specimens are in identical size. The beam sizes are 200mm×300mm. The column cross section is 300mm×200mm as shown in Fig. 3. 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 as shown in Figs. 4-6. The joint details used are as shown in Figs. 7-8. 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 respectively. 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.

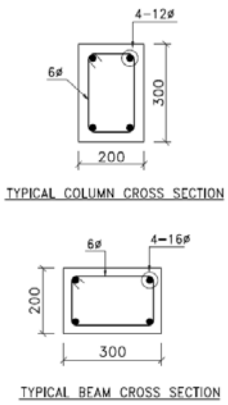

Fig. 3 Specimen size and bar details

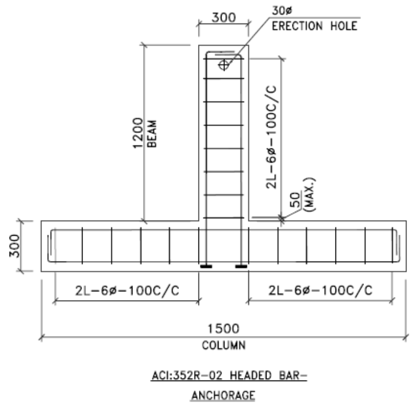

Fig. 4 Specimen type-A

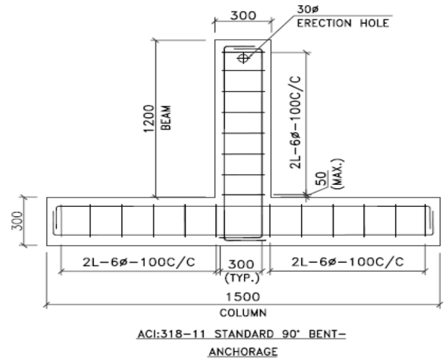

Fig. 5 Specimen type-B

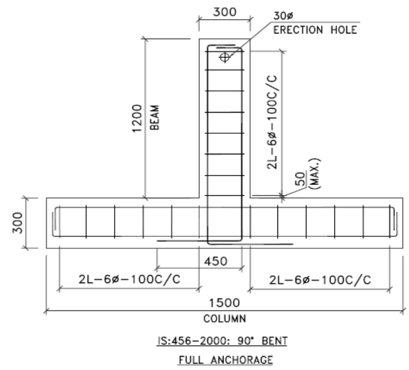

Fig. 6 Specimen type-C

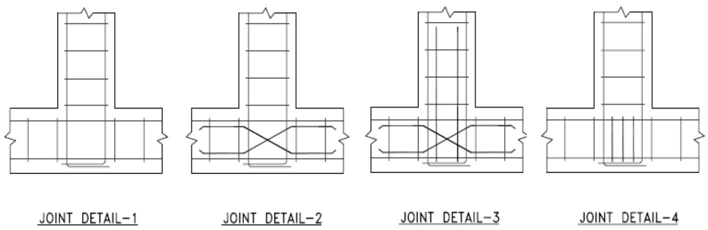

Fig. 7 Joint reinforcement arrangement

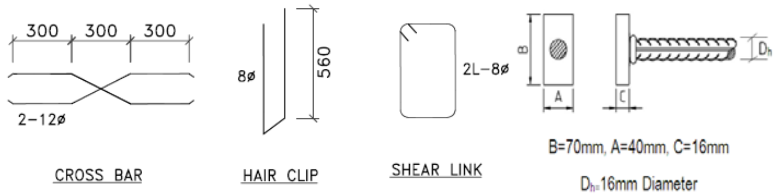

Fig. 8 Joint reinforcement bar and welded T-type headed bar

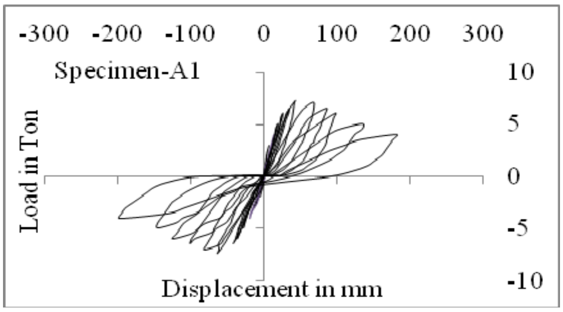

Fig. 9 Load Vs Displacment

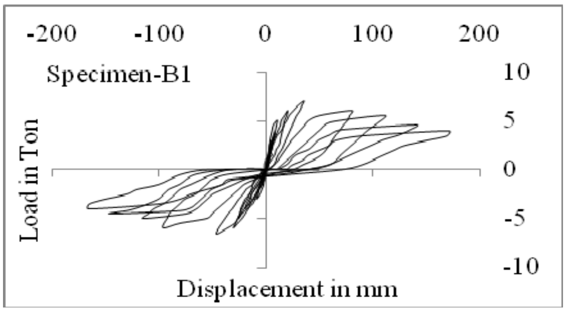

Fig. 10 Load Vs Displacment

10. Materials used

Concrete mix was made with 43 Grade cement with river sand, 20mm and downgrade coarse aggregate. One cubic meter of concrete used for the test specimens contains cement of 435.45 Kg, fine aggregate of 626.673 Kg, coarse aggregate of 1188.22 Kg, water of 191.6 Kg with water cement ratio of 0.45. The 28th day average cube compressive strength was 28.30MPa.The reinforcement bars used were 6,8,12 and 16mm diameter of grade Fe-415 as shown in Figs. 3-8 and the grade of welded T- type headed bar used was E410 (Fe 540) as shown in Fig. 8.

11. Test results and discussion

11.1 Lateral load versus lateral displacement

The hysteresis loops behavior of specimens A1, B1 and C1 in Group-I, A2, B2 and C2 in Group-II subjected to lateral load are indicated in Figs. 9-12 and Figs. 13-16 respectively. The corresponding peak load versus displacement behavior is indicated in Figs. 17 and 27. 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. It is seen from Table 1 and Figs. 17 and 27 that the specimens under Group-II show superior load carrying capacity (A2 by 8.20%, B2 by 13.40% and C2 by 9.50%)

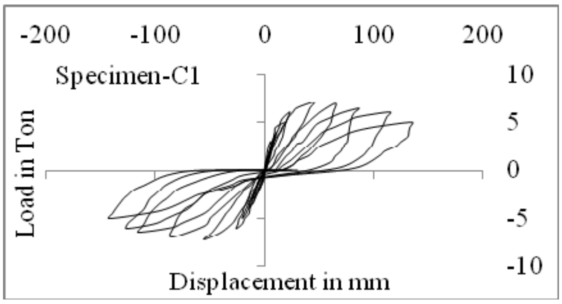

Fig. 11 Load Vs Displacment

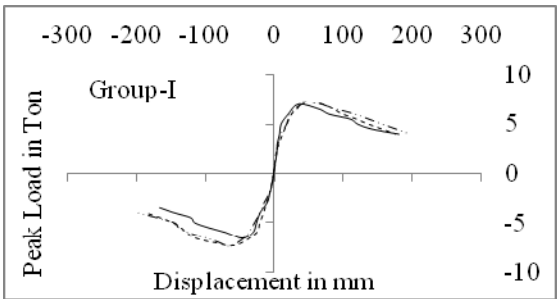

Fig. 12 Peak Load Vs Displacment

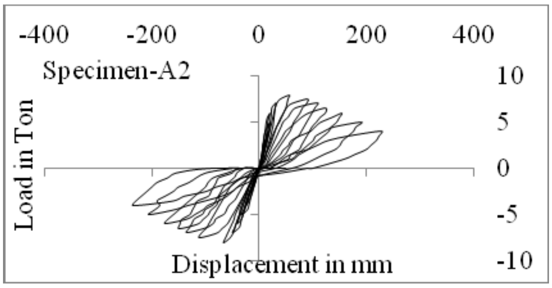

Fig. 13 Load Vs Displacment

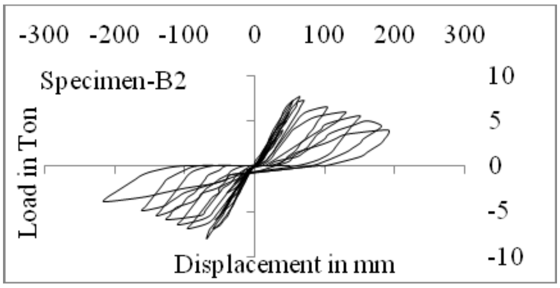

Fig. 14 Load Vs Displacment

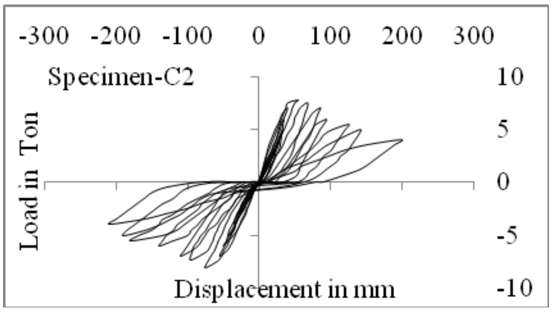

Fig. 15 Load Vs Displacment

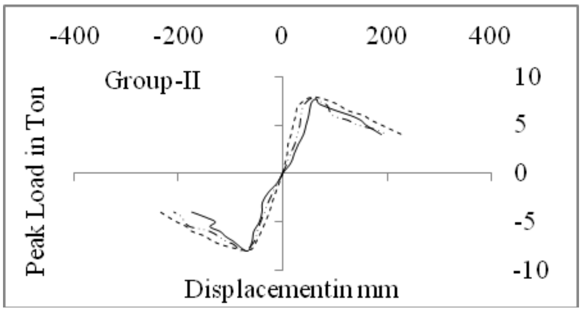

Fig. 16 Peak Load Vs Displacment

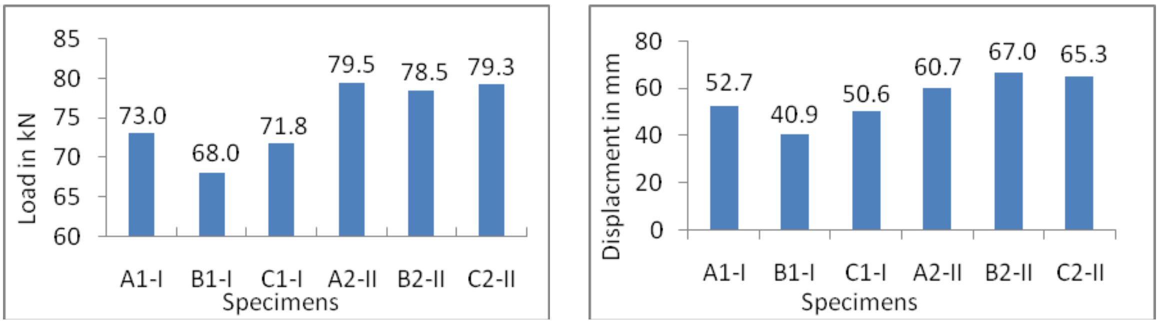

Fig. 17 Load and displacement chart

when compared to specimens under Group-I. From the above test results it can be inferred that the proposed additional X-cross bar has increased the ultimate strength significantly.

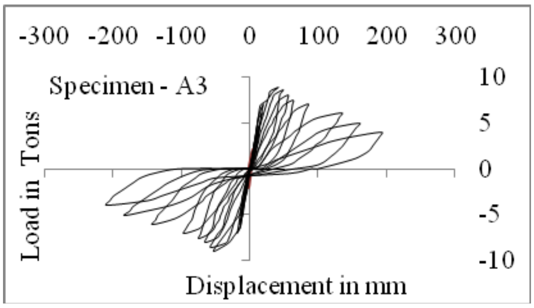

Fig. 18 Load Vs Displacment

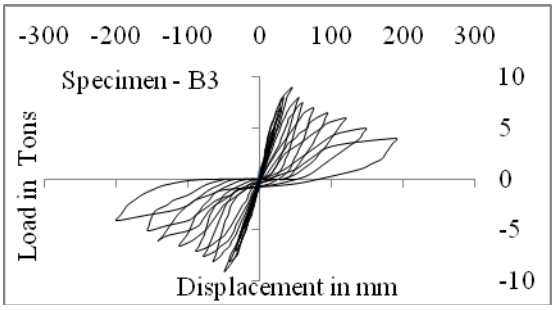

Fig. 19 Load Vs Displacment

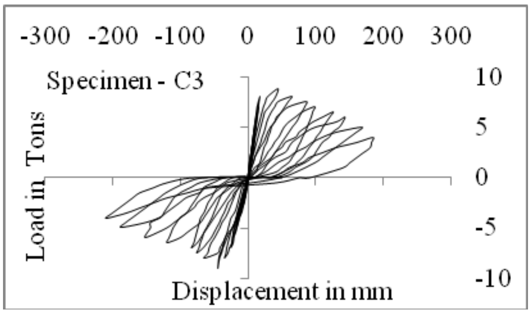

Fig. 20 Load Vs Displacment

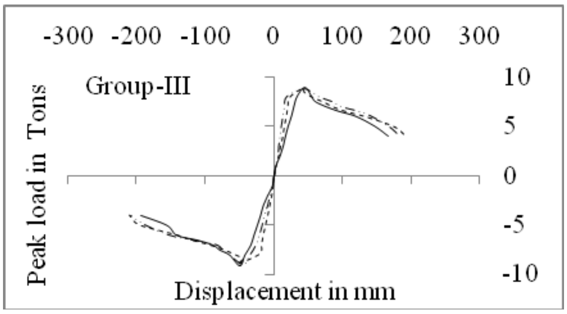

Fig. 21 Peak Load Vs Displacment

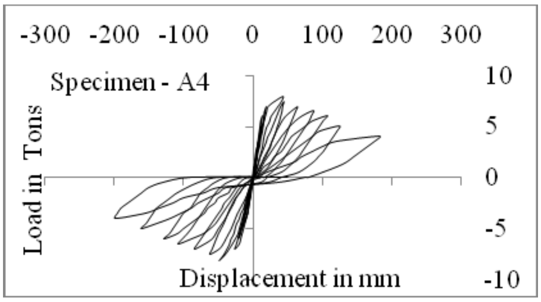

Fig. 22 Load Vs Displacment

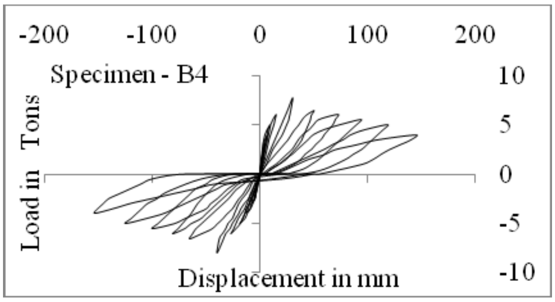

Fig. 23 Load Vs Displacment

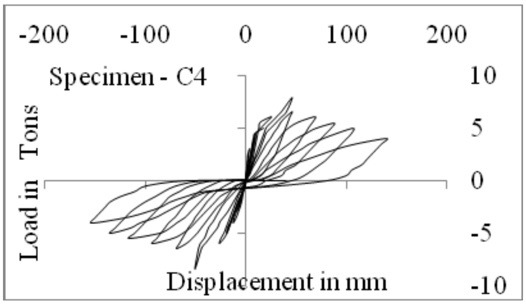

Fig. 24 Load Vs Displacment

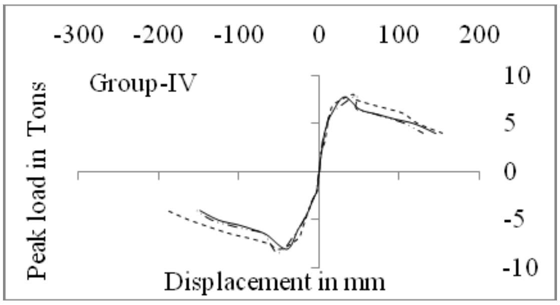

Fig. 25 Peak Load Vs Displacment

The hysteresis loops of specimens A3, B3 and C3 in Group-III, A4, B4 and C4 in Group-IV subjected to lateral load are indicated in Figs. 18-21 and Figs. 22-25 respectively, the corresponding peak load versus displacement are indicated in Figs. 28-29. It is observed that in Group-III, the average ultimate load carrying capacity of the specimens A3, B3 and C3 are

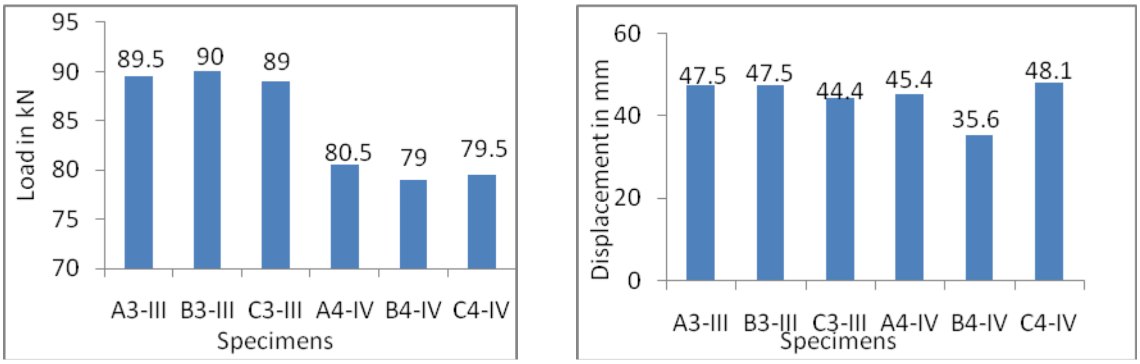

Fig. 26 Load and displacement chart

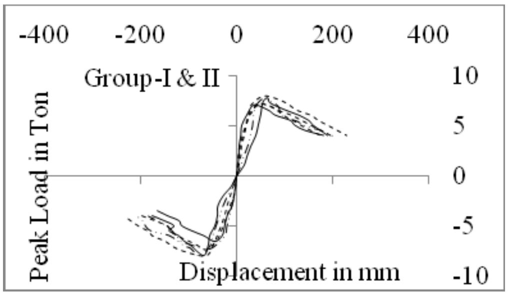

Fig. 27 Peak Load Vs Displacment

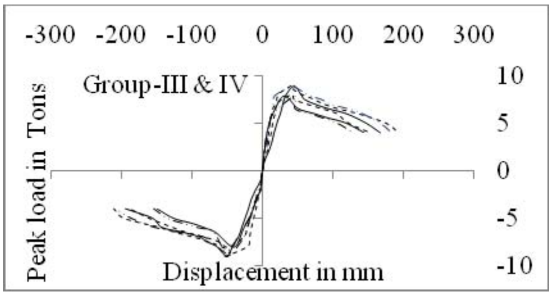

Fig. 28 Peak Load Vs Displacment

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. It is seen from Table 1, Figs. 26 and 28 that specimens in Group-III show superior load carrying capacity (A3 by 10.05%, B3 by 12.22% and C3 by 10.67%) when compared to specimens in Group-IV. From the above test results it can be inferred that the additional X-cross bar with U-bar increases the ultimate strength of beam-column joint significantly.

11.2 Ductility behavior

It is essential that the beam-column joint in an earthquake resistant structure will behave in a ductile manner while 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 (μ) can be defined as the ratio of ultimate deflections (δ_u) to initial yielding deflection (δ_y). $\mu = (\delta_u/\delta_y)$.

From Table 1 and Fig. 29, 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, three 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. From Table 1and

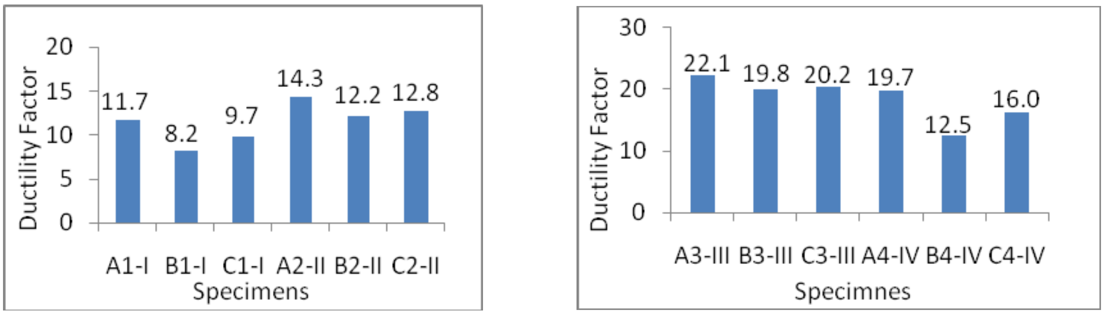

Fig. 29 Ductility factor chart of the test specimens

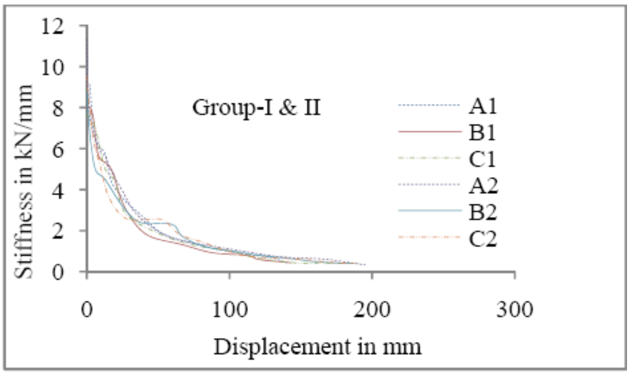

Fig. 30 Stiffness Vs Displacment

Fig. 29, it is observed that Group-III specimens namely A3 (ACI-352, mechanical anchorage), B3 (ACI-318, 90° 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.

11.3 Stiffness behavior

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. Formation of micro cracks initially inside the joint lead to the lowering of energy limit of the materials, which results in the increase of 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 behaviors of specimens are indicated in the Figs. 30 and 31. The stiffness (K) is calculated K- (P/δ), where 'P'is the peak average shear forces and 'δ' is the peak average displacement values, which are the peak values of each hysteresis loops. Among specimens in Group-I and II, specimens A1 and A2 have higher stiffness values than specimens B1, C1, B2 and

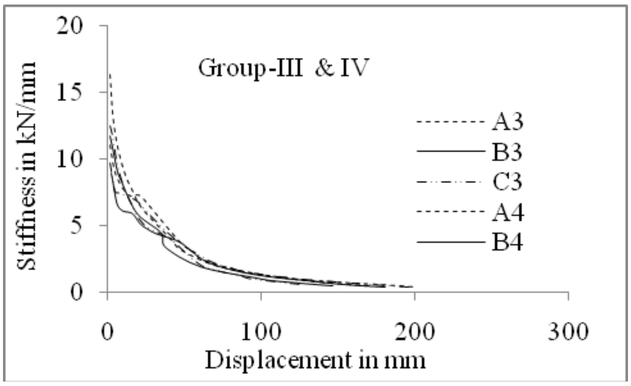

Fig. 31 Stiffness Vs Displacment

Table 1 Observed yield displacement, ultimate load, ductility and stiffness of test specimens

Specimen name and Groups	Yielding displacement in mm (δ_y)	Average ultimate Load in kN (P_u)	Average dis. for ultimate load in mm (δ_u)	Average Stiffness in kN/mm k=(P_u/δ_y)
A1-I	4.50	73.00	52.715	16.222
B1-I	5.00	68.00	40.905	13.600
C1-I	5.20	71.75	50.615	13.798
A2-II	4.23	79.50	60.660	18.794
B2-II	5.50	78.50	67.000	14.273
C2-II	5.12	79.25	65.295	15.479
A3-III	2.15	89.50	47.500	41.628
B3-III	2.40	90.00	47.500	37.500
C3-III	2.20	89.00	44.430	40.455
A4-IV	2.30	80.50	45.375	35.000
B4-IV	2.85	79.00	35.550	27.719
C4-IV	3.00	79.50	48.115	26.500

C2. Among specimens in Group-III and IV, specimens A3 and A4 have higher stiffness values than specimens B3, C3, B4 and C4.

Table1 indicates only the average initial stiffness (Stiffness $K= P_u/ \delta_y$, where 'P_u'-is the ultimate load and 'δ_y' is the yielding displacement). It has been observed from the experimental results that among specimens in Group-I, specimen A1 has higher stiffness than specimens B1 and C1. In Group-II, specimen A2 has higher stiffness than specimens B2 and C2. Between these two Groups, Group-II has higher stiffness. The specimen A2 which had in additional X-cross bar, exhibited better performance among six specimens in Group-I and II against stiffness degradation. The stiffness of specimen A2 is higher than A1 by 13.68%.

In Group-III, the stiffness of specimen A3 is higher than that of specimens B3 and C3. 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.

Fig. 32 Crack pattern of Group-I (A1, B1, and C1)

Fig. 33 Crack pattern of Group-II (A2, B2, C2)

11.4 Crack pattern

On visual examination of crack pattern of Figs. 32 and 33, flexural cracks on the beam-column junction and no shear cracks are found in A1 and A2. Further to these cracks, the specimens B1, C1, B2 and C2 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 it will forming the diagonal cracks in the beam-column joint. Besides, 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 and considerable improvement in seismic performance.

Fig. 34 Crack pattern of Group-IV (A3, B3, and C3)

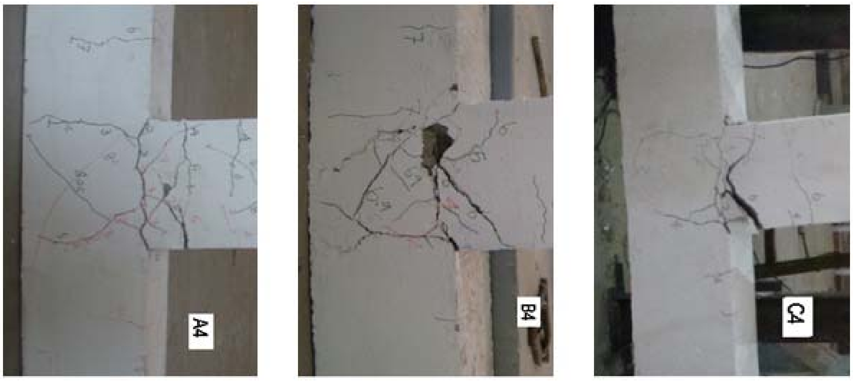

Fig. 35 Crack pattern of Group-IV (A4, B4, and C4)

On visual examination of crack pattern shown in Figs. 34 and 35, flexural cracks on the beam-column junction and no shear cracks are found in A3 and A4. 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 it will 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, B4, C3 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-I and II 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 with improvement in seismic performance than other specimens.

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 of standard 90° hooks in exterior beam-column joints in moderate and severe seismic prone area. In addition easy to repair using FRP composite wraps techniques to restore the flexural strength, ductility of earthquake damaged concrete beam-column joints.

12. Conclusions

The following suggestions for the detailing of reinforced concrete T-type exterior beam-column joint are made from the knowledge obtained through the experimental test results.

・Among specimens Group-I and II, specimens reinforced with T-type mechanical anchorage systems as per ACI-352 have better performance than the specimens reinforced with conventional 90° standard bent hooks anchorage as per ACI-318 and full anchorage specimen as per IS-456.

・Specimens in Group-II (A2, B2 and C2) reinforced with X-Cross bar joint detailing exhibit significant improvement in strength, ductility and stiffness than that of specimens in Group-I. Specimen A2 has superior performance. This combination of anchorage and joint detailing may be used in location demanding low ductility.

・In Group-III, Specimen A3 has better performance than specimens B3, C3. In Group-IV, specimen A4 has better performance than that of specimens B4 and C4. Significant improvements in strength, stiffness and ductility have been noticed in case of specimens in Group-III reinforced with X-cross bars and hair clip when compared to specimens in Group-IV.

・The T-type mechanical anchorage in combination with X-cross bar and hair clip improve load carrying capacity of beam-column joint. This arrangement improves the seismic performance without compromising the strength, ductility and stiffness. This arrangement of detailing of reinforcements in the beam-column connection not only reduces the congestion of reinforcement in the joint core area, but also eases placement of concrete and helps in faster construction at site. This combination of anchorage and joint detailing may be used in locations demanding higher ductility.

・The use of conventional 90° standard bent hook anchorage arrangements in the beam- column connection regions in case of severe seismic prone zone leads to increase in the size of column to accommodate required amount of beam reinforcements in the joint core whereas, the usage of mechanical anchorage results in reduction in quantum of reinforcement as well as congestion in the beam-column joint core.

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

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