Journal of Engineering and Applied Sciences 3 (7): 591-597, 2008
ISSN: 1816-949X

Performance of Exterior Beam Column Joints with Cross-Inclined Bars under Seismic Type Loading

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Abstract: The main objective of this study is to investigate the effect of cross inclined bars at the joint as confining reinforcement on the behaviour of exterior reinforced concrete beam-to-column connections subjected to earthquake loading. The joint with transverse reinforcement, detailed, as per general RC construction code of practice in India, (non-seismic joints) is unsatisfactory for performance under seismic loading. In this study, an attempt has been made to improve the confinement of core concrete without congestion of reinforcement in joints. Four exterior beam-column joint sub assemblages were tested under reverse cyclic loading applied at beam end. The specimens were sorted into 2 groups based on the joint reinforcement detailing. Group-A comprises of 2 joint assemblages with joint detailing as per ductile detailing code in India (IS 13920:1993) with 2 axial load cases and Group-B comprises of 2 specimens with cross inclined bars as confining reinforcements for the joints detailed as per IS 13920 with 2 axial load cases same as that of in first group. All the test specimens were designed to satisfy the strong column-weak beam concept and with adequate shear strength. The test results indicate that cross-inclined bars as confining reinforcement improve the seismic performance. The performance of the sub assemblages were compared with the analytical model developed using finite element software package ANSYS.

Key words: Beam column joint, confinement, detailing, reinforced concrete, modeling

INTRODUCTION

Damages in reinforced concrete structures are mainly attributed to shear force due to the inadequate detailing of reinforcement and the lack of transverse steel and confinement of concrete in structural elements. Typical failures are brittle in nature, demonstrating inadequate capacity to dissipate and absorb inelastic energy. The beam-column joints that are subjected to reverse cyclic loading require great care in detailing. Diagonal tension cracking is 1 of the main causes of failure of joint. The satisfactory performance of a beam-column joint, particularly under seismic loads, depends strongly on the lateral confinement of joint. The present study deals with the non-conventional reinforcement detailing in the beam-column joint by providing inclined bars on the 2 faces of the joint core, which leads to reduction in compaction and construction difficulties due to congestion of reinforcement in the joint region.

The performance of beam-column joint under seismic conditions has been a research topic for many years. The anchorage length requirements for beam and column bars, the provision of transverse reinforcement, the design and detailing of the joint are the main issues. Number of experiments and analytical studies were carried out on beam-column joints and reported in the literature. Soleimani *et al*. (1979) described that the inelastic deformations are concentrated after the bond of the main beam bars lost. Paulay (1989) used the laws of statics and postulated that joint shear reinforcement is necessary to sustain the diagonal compression field rather than to provide confinement to compressed concrete in a joint core. Tsonos *et al*. (1992) suggested that the use of crossed inclined bars in the joint region is one of the most effective ways to improve the seismic resistance of exterior reinforced concrete beam-column joints. Kumar *et al*. (2002) found that the joint rotation and the axial load in the column increase the ductility and energy dissipation capacity and reduce the joint region damage. Lowes and Altoontash (2003) gave a non-linear model, which requires extensive computational work. Hegger *et al*. (2004) used a nonlinear finite element analysis to investigate the behaviour of exterior and interior beam-column joints. The authors concluded that the most important factors affecting the shear capacity of exterior beam-column connections are the concrete

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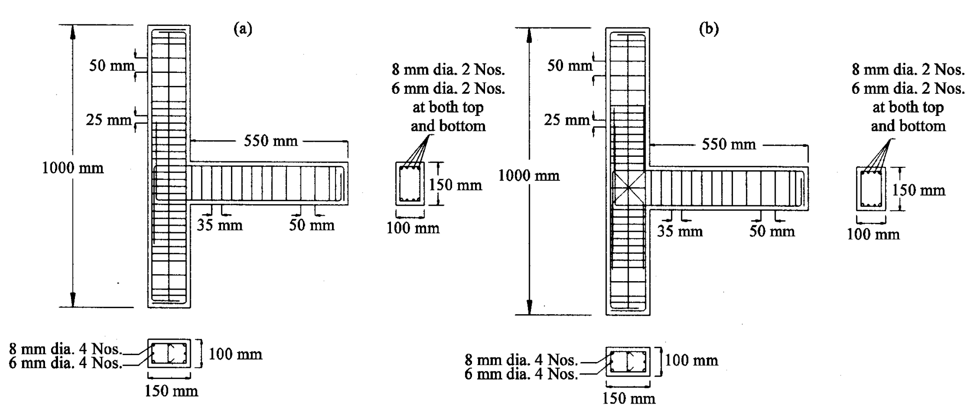
compressive strength, the joint slenderness of the connection, the beam reinforcements (reinforcement ratio, detailing and anchorage) and the amount of stirrups inside the joint. Santhakumar *et al.* (2004) presented a study which simulate the behavior of retrofitted reinforced concrete shear beams. The elements adopted by ANSYS such as Solid 65, Link 8-3D spar, Solid 45 and Solid 46 elements were used to model the concrete, reinforcements, steel plates and CFRP composites, respectively. In order, to incorporate some provisions in Indian code, Sarkar *et al.* (2007) reviewed the design procedures for the RC beam column joints based on international codes.

MATERIALS AND METHODS

Description of specimens: The experimental program included 4 one-third scaled specimens designed for earthquake loads as per IS 1893:2002. The specimens were classified into 2 groups with 2 numbers in each group. The group-A specimens were cast with reinforcement detailing as per IS 13920:1993. The group-B specimens were also detailed as per IS 13920:1993, but by replacing the stirrups at joint region by diagonal cross inclined reinforcement at the 2 faces of the joints for confinement of joint. The specimens were designated as A1-13920, A2-13920, B1-13920 and B2-13920 according to the detailing incorporated such as detailed as per IS: 13920 and IS: 13920 with cross reinforcement at joint region considering 2 axial loads cases. The cross section and reinforcements adopted for the above specimens are shown in the Fig. 1.

Adequate development lengths as per the code requirement were given for the beam longitudinal bars and cross-inclined bars to take care of the pull out force. All the specimens were tested under constant axial load with cyclic load at the end of the beam. One of the specimens from each group was subjected to an axial load of 3% of column axial load capacity and the second specimen was subjected to the axial load of 10% of column axial load capacity. The column and beam were rectangular in shape with dimensions 100×150 mm and an effective cover 15 mm for all specimens. Ordinary Portland cement (53 grade), sand passing through 4.75 mm IS sieve and crushed granite stone of maximum size not exceeding 8 mm were used for the concrete mix. The compressive strength of the cubes at 28 day was 44.22 N mm^{-2}. Steel bars of stress 432 N mm^{-2} were used as main reinforcement and stirrup. The specimens were cast in horizontal position inside a steel mould.

Experimental program: The test set-up is shown schematically in Fig. 2. The joint assemblages were subjected to axial load and reverse cyclic load. A constant column axial load was applied by means of 392.4 kN hydraulic jack mounted vertically to the loading frame to simulate the gravity load on the column. Axial load for the first series specimen was 15.92 kN and for the second series was 53.06 kN. One end of the column was given an external hinge support, which was fastened to the strong reaction floor and the other end was laterally restrained by a roller support to get moment-free rotation at both ends. Cyclic loading was applied by two, 200 kN hydraulic jacks, 1 fixed to the loading frame at the top and another to the strong reaction floor. Reverse cyclic load was applied at 50 mm from the free end of the beam portion of assemblage. The test was load controlled and the specimen was subjected to an increasing cyclic load up to failure. The load increment chosen was 1.962 kN. Figure 3 shows the loading sequence of the test assemblages. To record loads precisely, load cells with least count 0.0981 kN were used.



Fg. 1: Reinforcement details of the specimens, (a) Group-A. (As per IS 13920:1993)), (b) Group-B (As per IS 13920:1993 with non-conventional reinforcement)

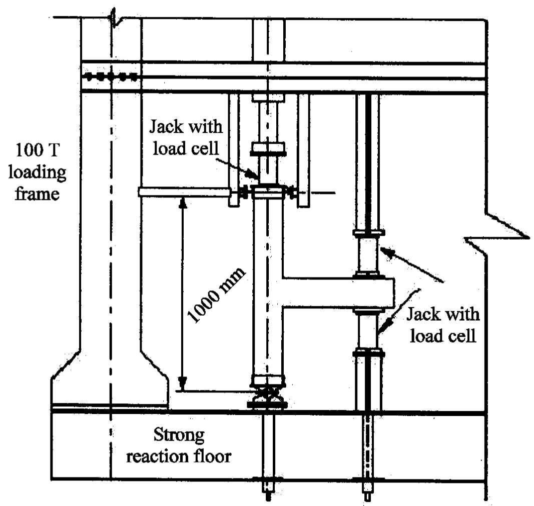


Fig. 2: Schematic diagram of test set-up

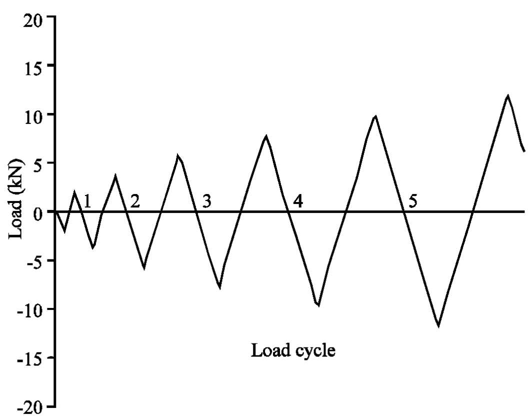


Fig. 3: Sequence of cyclic loading

Analytical modeling: An analytical study was conducted by using the finite element package ANSYS. The elements used in ANSYS to develop the model are Solid 65, Solid 45 and Link 8. The Solid 65 element was used to model the concrete, Solid 45 to model hinge support at base and Link 8 element was used to model the reinforcement. SOLID 65 and SOLID 45 elements are 3-dimensional 8 noded solid isoparametric elements with 3 degree of freedom at each node ie., translations in the nodal x, y and z directions. The 3-dimensional spar element Link 8 is a uniaxial tension-compression element with 3 degree of freedom at each node i.e., translations in the nodal x, y and z directions.

Sectional properties (real constants): The parameters to be considered for Solid 65 element are volume ratio and orientation angles. Since, there is no rebar data (smeared reinforcement), the real constants (volume ratio and

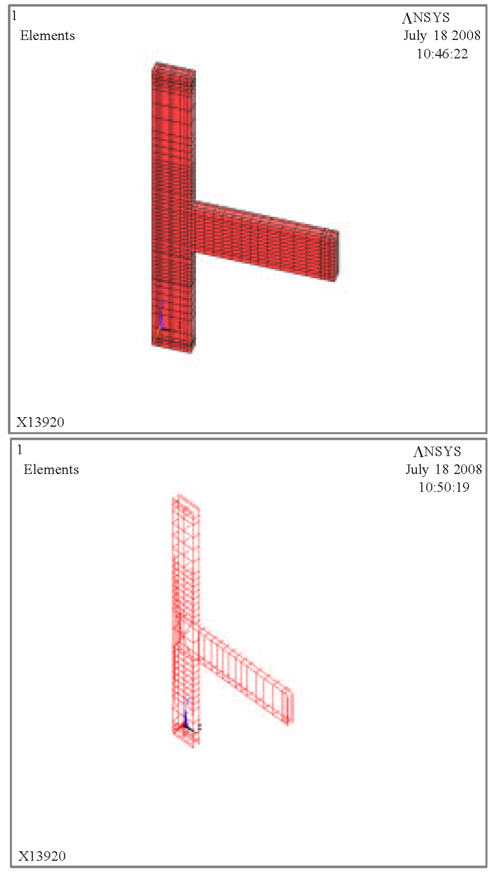


Fig. 4: Modeling details in ANSYS

orientation angle) are set to zero. The parameters to be considered for Link 8 element are cross sectional area and initial strain.

Material properties: For the reinforcing bars, the yield stress was obtained from the experimental test as $f_y = 432$ MPa and the tangent modulus as 847 MPa. The concrete cube compressive strength f_{ck} determined from the experimental result is 44.22 Mpa. Eighty percent of this value is taken as the cylinder strength. The equation developed by Desai and Krishnan (1964) was used for the stress-strain relation for concrete.

Modeling of beam-column joint: The beam-column joint was modeled in ANSYS10 software using the above said element types and the material properties. Only half of the system was modeled through the thickness so that the symmetry conditions were used. Some of the modeling details are shown in the Fig. 4. An axial load of 15.92 kN was applied on the top of column with hinged base and a roller support at 50 mm from the top for the first series. The load on the beam was applied at a distance of 50 mm from the cantilever end. The models were analyzed with monotonic loadings in the upward direction and the performances were compared.

RESULTS AND DISCUSSION

Cracking pattern and failure mode: The yield and ultimate load for the test specimens are shown in Table 1. The cracking patterns of test specimens in the 1st and 2nd series of specimens are shown in Fig. 5 and Fig. 6. In almost all specimens tensile cracks were developed at the interface between the column and beam. The specimens failed due to the advancement of crack width at the interface between beam and column. There was a clear vertical cleavage formed at the junction of all the specimens. For the specimens with diagonal confining bars, no cracks were noticed at the joint and the joint remained intact throughout the test (B1-13920 and B2-13920). The major improvement by developing cracks away from the joint face to the beam region can be noticed for these specimens. For specimen B2-13920 the crack width is also less compared to other specimens.

Hysteretic loops: The force-displacement hysteretic loops for all specimens are as shown in Fig. 7-10. For the specimens in group-B, spindle-shaped hysteresis loops were observed with large energy dissipation capacity. From the Table 1, it can be seen that the ultimate load carrying capacity is higher for specimens in group-B. In this type of non-conventional detailing, the stiffness increases with loading up to seventh cycle. Here, the ductility increased without compromising the stiffness. In general, specimens with diagonal confining bars perform better than conventionally detailed counterparts. It can be

Table 1: Yield and Ultimate load of specimens from experiment

Designation of specimen	Experimental yield load (kN)			Experimental ultimate load (kN)		
	Downward direction	Upward direction	Average (P_y)	Downward direction	Upward direction	Average (P_u)
A1-13920	11.77	11.77	11.77	16.18	15.69	15.93
B1-13920	13.73	13.73	13.73	18.63	17.65	18.14
A2-13920	15.7	15.7	15.7	17.65	19.62	19.62
B2-13920	15.7	15.7	15.7	18.64	18.64	18.64

(a) (b)

Fig. 5: (a) Specimen A1-13920, (b) Specimen A2-13920

(a) (b)

Fig. 6: (a) Specimen B1-13920, (b) Specimen B2-13920

Table 2: Displacement ductility of specimens

	Displacement (mm)						
	Yield		Ultimate		Displacement ductility		Average displacement ductility
Specimen	Downward direction	Upward direction	Downward direction	Upward direction	Downward direction	Upward direction	
A1-13920	4.2	3.8	39.8	18.9	9.480	4.97	7.22
B1-13920	4.0	3.0	43.7	18.0	10.93	6.00	8.46
A2-13920	2.6	1.8	18.2	11.8	7.000	6.56	6.78
B2-13920	5.1	1.9	35.0	14.6	6.860	7.68	7.27

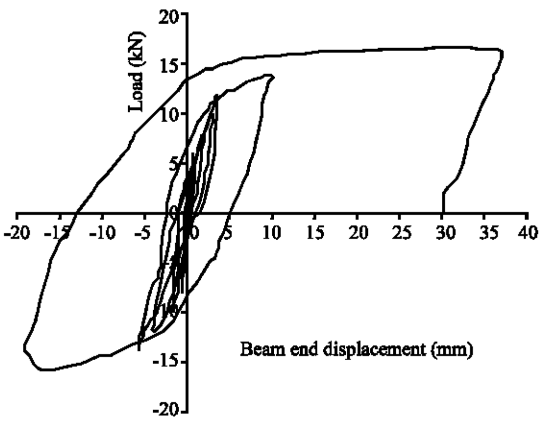


Fig. 7: Load-displacement curve of A1-13920

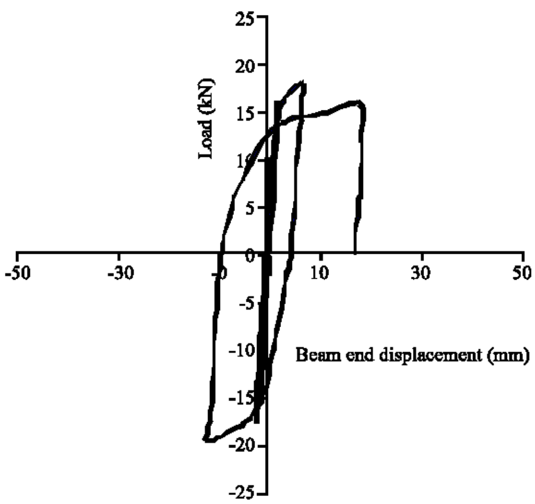


Fig. 8: Load-displacement curve of A2-13920

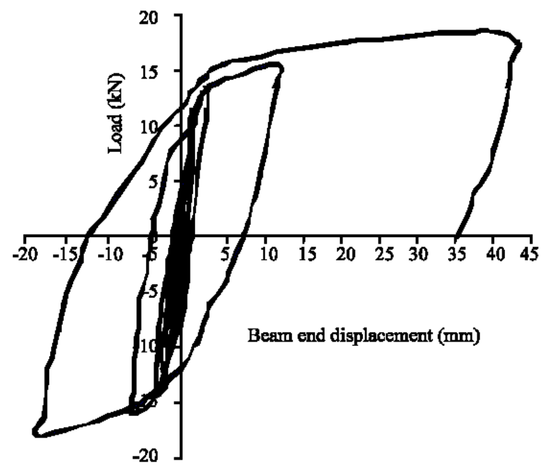


Fig. 9: Load-displacement curve of B1-13920

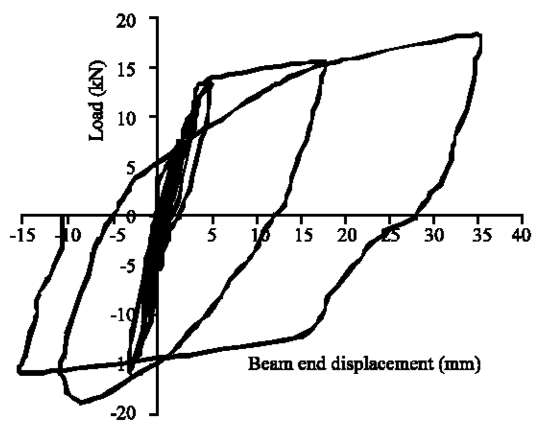


Fig. 10: Load-displacement curve of B2-13920

observed that axial load stiffens the joint and the joints with higher axial loads cover more number of cycles of seismic type loads than the specimens with less axial load.

Energy dissipation: The area enclosed by a hysteretic loop at a given cycle represents the energy dissipated by the specimen during that cycle. Comparison of cumulative energy dissipated among the specimens is shown in Fig. 11. It was found that the energy dissipation capacity is improved by the addition of cross-inclined confining bars. For the non-conventionally detailed joints, the axial load is beneficial to dissipate energy.

Ductility: The ductility is generally measured in terms of displacement ductility, which is the ratio of the maximum deformation that a structure or element can undergo without significant loss of initial yielding resistance to the initial yield deformation. The displacement ductility for all specimens is presented in Table 2. The non-conventional confining reinforcement at joint region improves the ductility of joint.

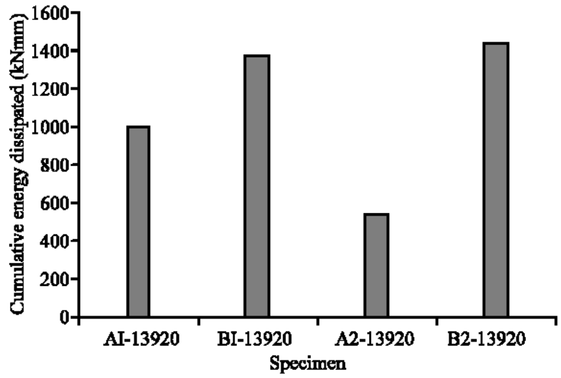


Fig. 11: Comparison of cumulative energy dissipated

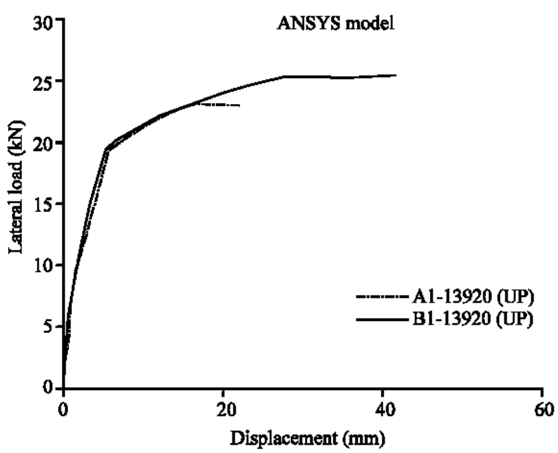


Fig. 12: Comparison of load-displacement relations of monotonic loading in finite element model

The load-deflection relationship obtained for monotonic loading in the finite element models of specimens A1-13920 and B1-13920 is compared and is given in the Fig. 12. It can be seen that the load and deformation capacity is improved in B1-13920 compared to A1-13920. It is also figured out that the provision of cross diagonal reinforcement in the joint region increases the ductility of which B1-13920 performed in a much better manner.

CONCLUSION

The present research aims to study the performance of beam column joint with non-conventional reinforcement detailing. The non-conventional detailing is provided as diagonal cross bracing reinforcement at the faces of the joints along with the longitudinal bars. The joint sub assemblages were tested under reverse cyclic load applied at beam end. In order to compare the performance of the beam column joint, the specimens were also modeled and analyzed using a Finite Element Software ANSYS. Based on test observations and analytical modeling, the following conclusions were drawn:

- All the specimens failed by developing tensile cracks at interface between beam and column. The joint region of specimens of group-B is free from cracks except some hairline cracks, which show the joints had adequate shear resisting capacity.
- The increase in column axial load improves the load carrying capacity and stiffens the joints. Also, this increases the energy absorption capacity of the specimens with cross-inclined bars.
- The specimens detailed as per IS: 13920 with cross-inclined bars had improved ductility and energy absorption capacity than specimens detailed as per IS 13920:1993. The displacement ductility was increased considerably for this non-conventionally detailed specimens.
- The results from the analytical model under monotonic load also show the improved behaviour of the non-conventionally detailed exterior joint sub assemblage.
- Considering the performance enhancements shown above, the detailing of joints with cross inclined bars (Group-B) can be adopted for beam-column joints in low to moderate seismic risk regions.

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