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Performance of RC Beam Column Connections Subjected to Cyclic Loading

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Abstract : *Structures and lifelines designed for typical loading are often badly damaged or can collapse during earthquakes. The observations from recent earthquakes show that many RC structures have failed in the brittle behaviour of beam-column connections due to the deficiency of seismic details in the joint regions. Joint shear failures have been observed recently in many existing RC structures subjected to severe earthquake loadings. In this study, RC beam column specimen was casted and tested for excitation of cyclic loading. Attempts are made to study the performance of the test specimen by studying loop hysteresis, maximum push and pull load and load at the propagation of first crack.*
Keywords: *Non-linear analysis; Crack propagation, cyclic loading*

I. Introduction

Designing beam–column joints is considered to be a complex and challenging task for structural engineers, and careful design of joints in RC frame structures is crucial to the safety of the structure. Although the size of the joint is controlled by the size of the frame members, joints are subjected to a different set of loads from those used in designing beams and columns. It has been identified that the deficiencies of joints are mainly caused due to inadequate design to resist shear forces (horizontal and vertical) and consequently by inadequate transverse and vertical shear reinforcement and of course due to insufficient anchorage capacity in the joint [1].

In this study, a conventional four-storey RC school building (**Fig.1**) is considered for analysis, design and detailing of exterior joint. Different failure modes are expected in beam-column joints depending on the type of joint (exterior or interior) and the adopted structural details. Hence, in the present study, exterior beam-column joint has been chosen for investigating the performance under seismic type loading.

II. Design Of Test Specimen

Characteristic compressive strength of concrete and tensile strength of steel used in the specimen have been taken as 30 MPa and 415 MPa, respectively. The specimen has the following general and cross-sectional dimensions: height of column is 3200 mm having cross-sections of (425 x 425) mm and length of beam is 2500 mm with beam size (300 x 525) mm. For casting the specimen, weight ratio of cement: sand: coarse aggregate was adopted as 1 (cement): 2.25 (fine aggregate): 2.35 (coarse aggregate-60% 10 mm size, 40% 20 mm size): 0.5 (w/c). Ordinary Portland Cement (OPC) with 28 days minimum compressive strength of 53 MPa is used.

Analysis of a conventional four storey RC building frame is carried out using STAAD.Pro. Based on analysis data, critical region such as exterior joint is selected for the study. Gravity load design (GLD) specimen was designed and the reinforcement is provided as per details given in IS: 456 – 2000. The geometry of the specimen is finalised in order to match the bending moment distribution at the joint for which it is designed. Seismic analysis (Response Spectrum Analysis) of the framed structure (**Fig. 1**) has been performed using STAAD.Pro to obtain the design forces. The results obtained from the analysis of a 3 - bay four-storey RC building under the load combinations are used to design the specimen. Finally, as shown in **Fig. 2**, the geometry of the components (top and bottom portion of column and beam length from joint face) is chosen to match the bending moment distribution at the joint for which it was designed.

III. Preparation Of Test Specimen

For the construction of beam column specimen, foldable wooden moulds are prepared so set specimen can be easily removed from the mould. These moulds can be reused. As per details given in **Fig. 2** reinforcement bars are provided. **Fig. 3** shows the wooden mould with reinforcement bars placed inside it. Strain gauges were fixed with reinforcement bars in order to study the strain developed in the bars when the specimen is loaded. After the assemblage of the beam and column reinforcement, the assembly was put into the formwork and was made ready for casting as shown in **Fig. 3 (a)**. The plain concrete used in all groups was prepared by proportion 1: 1.57: 3.20. The concrete was poured in the formwork horizontally. The compaction of the concrete was performed using a vibrator to produce uniformity throughout the specimen. A needle vibrator with a head of

25 mm diameter was used for compaction. The trowels were used to finish the concrete allowing a smooth surface for crack mapping as shown in **Fig.3 (b)**.

After 24 hours of casting, formwork was removed and specimen was kept for the curing under the wet gunny bags. Specimen was given curing continuously for 28 days. Before testing, the specimen was white washed for proper marking of crack.

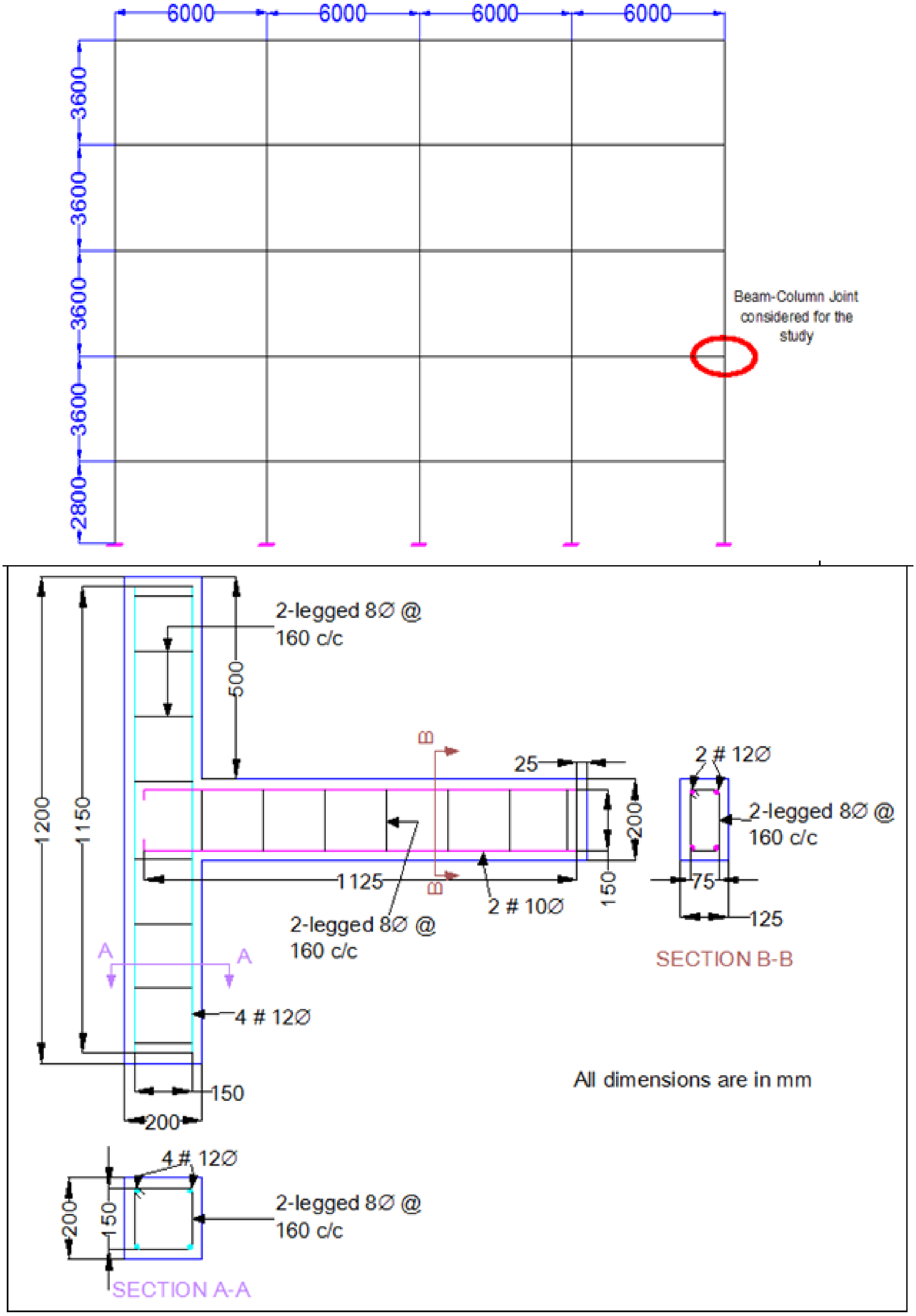


Fig. 1 General Arrangement of the Building Frame Considered for the Study

(a) Reinforcement cage in mould

(b) Concreting in mould

Fig. 3 Preparation of Test Specimen

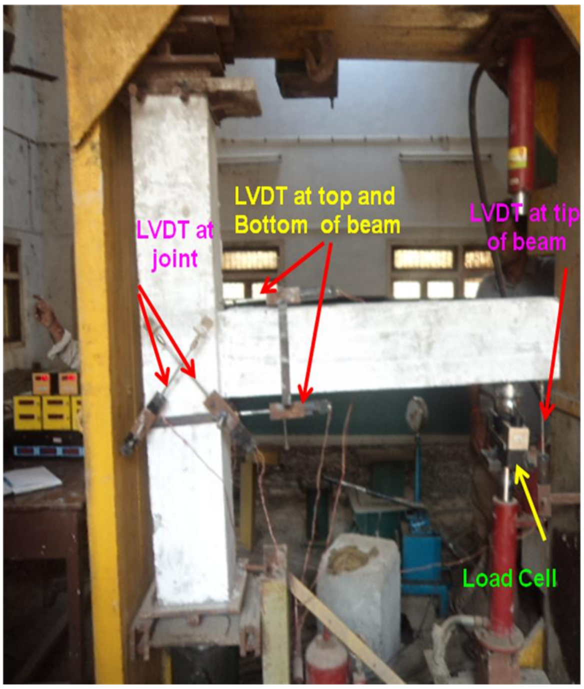
IV. Testing Of Specimen

To investigate the seismic performance and shear strength of designed reinforced beam-column joints, tests were carried out on 1/3 scale specimen under reversed cyclic loading. A steel reaction frame was used to support and load the test specimen. A schematic diagram of the test set up is shown in **Fig. 4**. For convenience in applying loading and testing, the T-shape specimen was arranged in loading frame such that the column member was in vertical position and the beam member was in horizontal position. Proper boundary conditions were provided in the set up to simulate the actual working situation of the beam-column joint as if it was a part of the frame structure. To satisfy the boundary conditions, rocker bearings assemblies were provided at the top and bottom ends of the column. This type of end connection simulated the hinges which are assumed to form at mid-heights of column and the mid-span of the beam in a building frame.

In the test, column of the specimen was subjected to axial loading corresponding to ratio of 40% of the column capacity. The axial load of 75 kN was applied to the specimen before horizontal displacement loading started, and it was maintained at the same level during the testing. The axial load was applied to the column by a 1000 kN hydraulic jack located at the bottom of the steel bearing, as shown in **Fig. 4 (a)**. A two set of hydraulic jack were employed to apply reversible cyclic loading at the bean end. The moment arm for all the specimen was 0.85m from the face of column. The same load history was used for all the tests on the exterior beam-column joints. Gradually increasing reversed cyclic loading was applied at the top of the beam, with the displacement increment in each step being 5 mm. The 5 mm displacement indicates 5 mm +ve as well as –ve displacement. The pre-set load history shown in **Fig. 4(b)** demonstrates the displacement for each cycle. The increment of 5 mm displacement was given in consecutive cycle up to the failure.

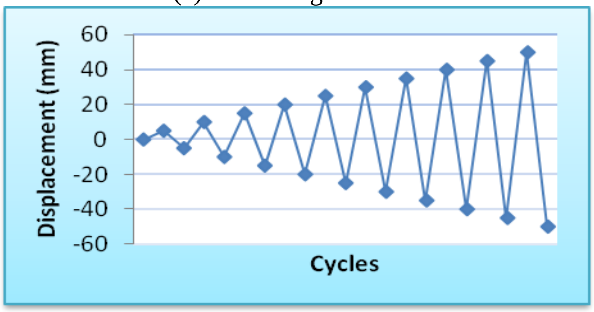
The response during testing was monitored by Linear Variable Differential Transducers (LVDTs). A configuration of five LVDTs was mounted unobtrusively on the column at the front face of the joint, along the top and bottom of the beam near the joint and at tip of beam. The column was mounted vertically with pinned supports at both ends. The axial load was applied using a hydraulic cylinder of capacity 1000 kN and transferred to column from the reaction against the loading frame. The lateral load was applied at the end of the beam through a pair of hydraulic jack. A load cell of capacity 100 kN situated between the hydraulic jack and the loading plate measured the static cyclic load Applied to the beam.

Different indicators were used to measure displacement, load and strain. LVDT was connected to single display unit of LVDT indicator to measure displacement of beam tip. Two display units were connected to respective LVDTs to measure displacement of beam top and bottom surface and joint shear distortion. All displacement indicators had least count of 0.001 mm. The load applied through hydraulic jack at beam end was displayed by load cell indicator of capacity 150 kN and least count of 0.01 kN. Indirectly this indicator measures the strain induced in the load cell during application of load. The strains produced in the reinforcement were displayed through strain gauge indicator as shown in **Fig. 4 (c)**.



(a) Experimental set-up

(c) Measuring devices



(d) Cyclic load history

Fig. 4 Testing of Test Specimen

V. Results And Discussions

The cyclic performance characteristics of the beam–column joints can be evaluated through hysteretic behaviors such as ductility, energy dissipation capacity, strength deterioration, and stiffness degradation.

5.1 Crack and Damage Pattern

Ten full displacement cycles were applied to the test specimen. In the first loading cycle, the specimen was loaded up to 9.63 kN up and 9.38 kN down to test the instrumentations. First flexural crack was observed during second cycle at displacement of 10 mm (drift ratio of 1.18%).

Fig. 5 Crack and Damage Pattern of Beam-Column Specimen

The corresponding restoring force was measured as 15.72 kN down. In the fourth cycle, a load of 24.95 kN was applied down and 22.58 kN up to the specimen and new flexural and flexural–shear cracks formed along the beam length. In the sixth cycle, vertical crack formed in the joint region at beam-tip load of 29.68 kN due to bond-slip of the beam bottom bars. During the eighth cycle, diagonal shear cracks developed in the joint region, and the specimen reached a load of 31.06 kN at a beam-tip displacement of 35.9 mm. Repeating the same cycle, the beam reached the same displacement but at lower load level and the beam bars started to slip out of the joint with an associated reduction in the developed strain in the bars. The final failure pattern is shown in **Fig. 5**.

5.2 Hysteretic Behaviour

The most important parameter for seismic performance of structural D-regions can be described by load–displacement hysteresis during the cyclic loading which can indicate the ductility capacity and energy dissipation efficiency of the component [2,3]. It is well proven that the beam-column joint of reinforced concrete structure is the single crucial component in dissipating seismic energy during earthquake. In view of this, load–hysteresis diagrams for each specimen are presented in **Fig. 6**. The hysteresis loops for the GLD specimen is thinner.

When the specimen was pushed up, the bond-slip cracks opened and the lateral load-carrying capacity deteriorated significantly; however, when it was pulled down, the diagonal shear cracks opened. This caused disintegration of the concrete, deterioration of the bond condition of the beam top bars and degradation of the lateral load-carrying capacity. The specimen GLD reached a maximum load of 35.17 kN up and 31.06 kN down. In effect, when pushing up on the beam, bondslip failure of the beam bottom reinforcement occurred and when pulling down, shear failure occurred. The lateral forces versus displacement hysteretic response measured are shown in **Fig. 6**. The strength and deformation capacity of the test specimen was quite poor and hence energy dissipation also.

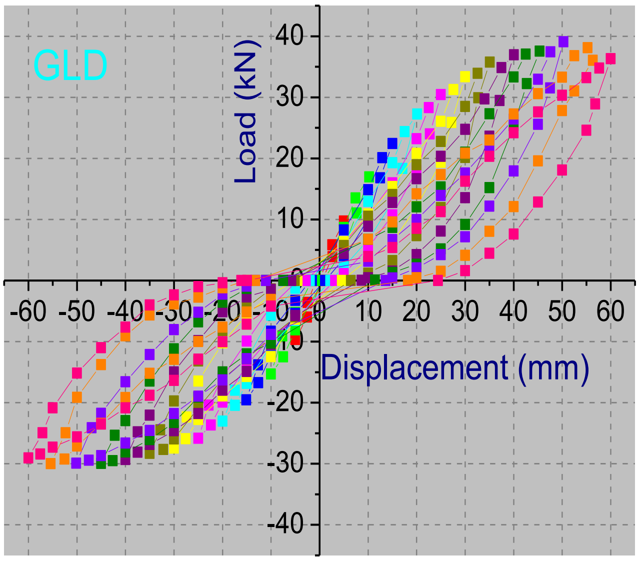


Fig. 6 Hysteretic Loop of Beam-Column Specimen

5.3 Ultimate Strength

The strength parameters are reported in **Table 3**. Load carrying capacity is considered as strength of the specimen. The load-displacement hysteresis loop for test specimen is poor and verifies weak performance of joint. The joint exhibited very low strength due to lack of critical reinforcement details in the beam-column joint. The maximum load in push direction occurred at a drift ratio of 5.56 % and had a value of 39.84 kN; in pull direction, the maximum load occurred at a drift ratio of 5.56 % and had a value of 31.06 kN. The maximum load for push and pull cycles are presented in **Table 3**. The load in the push displacement cycle is generally higher. The displacement loading on the unit is such that new increased displacement cycles are always applied in the push direction. Hence, lower value observed for pull cycle as it is followed by new, damaged state.

Table 3 Load Carrying Capacity of Test Specimen

Specimen Details	First Crack at Load (kN)	Maximum Load (kN)		Mode of Failure
		Push	Pull	
GLD 1	15.28	39.84	31.06	Beam flexure

VI. Findings And Concluding Remarks

One GLD exterior RC beam–column joint specimen was tested to study the behavior of the beam–column joints subjected to cyclic loadings. Based on experimental results, following observations are made:

1. The control specimen with no shear reinforcement in the joint and with inadequate anchorage for the beam bottom steel bars showed a brittle joint shear failure accompanied by slippage of the beam bottom bars.
2. The bond conditions of the beam top bars were affected by the disintegration of the concrete in the control joint, leading to a significant reduction in the load carrying capacity and the ductility of the joint.
3. First flexural crack was observed during second cycle at drift ratio of 1.18% with cyclic load of 15.28 kN down for specimen GLD.

4. The maximum load in push direction occurred at a drift ratio of 5.56 % and had a value of 39.84 kN; in pull direction, the maximum load occurred at a drift ratio of 5.56 % and had a value of 31.06 kN for GLD specimen.

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