A Study on the Ductility of Bolted Beam- Column Connections

Shemy S. Babu[1], S. Sreekumar[2]
Department of Civil Engineering College of Engineering, Trivandrum, Kerala

ABSTRACT: *The behaviour of beam-column joint plays an important role in the response of a steel moment resisting framed structure especially under seismic excitation. Semi rigid connections like bolted joints, allow better energy dissipation and provide good response under lateral loads. In this paper the ductility and energy dissipation characteristics of semi rigid bolted connections using double web angle with top and seat angles is discussed based on experimental investigation. Non-linear analysis was also performed using finite element method to compare the results. The study revealed that ductile behaviour of beam-column connection is improved by increasing the number of bolts on the top and seat angles and the thickness of top and seat angles. The analytical results are in agreement with the experimental results.*

Keywords**:** *semirigid connections; beam column joints*

I. INTRODUCTION

Structural steel framework with welded joints was considered as one of the best moment resisting framed structural system till the 1994 Northridge earthquake. In the earthquake, many structural steel frames failed due to the occurrence of brittle fractures at the connections. This caused the loss of reliability on steel welded moment resisting frames. Since then, as an alternative, bolted connections, often called semi-rigid connections, are considered for design of steel moment resisting frames and retrofitting works.

The behaviour of beam-column joint plays an important role in the response of a steel moment resisting framed structure. It strongly influences the seismic behaviour and energy dissipation capacities of the moment resisting frames. The use of bolted joints allows more energy dissipation and provides a good response under lateral loads. In structural framework with semi-rigid joints, the characteristics of connections play a significant role in the energy-dissipation mechanisms. As rigid connections are more expensive and difficult to assemble and because flexible connections do not have the necessary resistance and stiffness to resist the lateral loads, use of semi-rigid connections using bolted angles is justified. Semi-rigid connections with angles connecting the web and flanges of the beam to the column flange are cheaper and simpler to assemble when compared to other conservative joint.

Various studies have revealed that semi-rigid steel frames have the potential to be used in buildings located in high seismic prone regions. It was found that bolted-angle connections have stable cyclic response and energy dissipation capacity depending on the size of the angles and bolts.

This paper is concerned with the study of structural response of a typical semi-rigid steel beam-column connection. In particular, the behaviour of double web angle bolted beam-column connection is experimentally investigated under monotonic loading using top and seat angle sections. Static half cycle load tests were performed to compare the energy absorption capacity of various connections. The effect of various joint parameters such as diameter of bolts, number of bolts on top and seat angle, thickness of top and seat angles etc. on energy dissipation capacity of the joint was studied experimentally. Analytical study on the behaviour of double web angle connections with and without top and seat steel angle sections simulating the experimental investigation was performed with the help of finite element software.

II. RELATED STUDIES

In recent years, a number of research works were carried out to study the behaviour of semi-rigid connections. This section deals with the review of the works related to the semi-rigid connections. Cheol and Young [1] conducted experimental investigation on the cyclic load behaviour of steel frames with bolted joints in comparison with welded joints for an exterior beam column joint. Three different types of connections viz. semi-rigid connection using high strength bolts, simple bolted connection and welded connection were considered in the study for varying effect of initial stiffness, maximum flexural resistance, failure modes, ductility and energy dissipation.

Chen et al. [2] discussed a new method of trimming the beam flanges in order to enhance the ductility of beam-column connection keeping the ultimate strengths unaltered and increasing the plastic rotation capacity and energy dissipation capacity.

Secer and Ozturk [3] studied the dynamic characteristics of semi-rigid frames and the influence of connection flexibility on the dynamic characteristics of frames analytically. Christopoulos et al. [4] presented characteristics of joints with post-tensioned energy dissipation connections. The beam-column connections were modelled as rotational springs attached at the ends of the members and the load carrying capacity, end member forces and deformation of frames with semi-rigid connections were determined using direct stiffness method. The influence of partial rigidity of beam-column connection on the behaviour and stability of frames was discussed (Frederick and Abuyasein, [5]). An expression for fixity factor, indicating the degree of rigidity of joint was derived in the study. Kartal et al. [6] conducted numerical studies for finding the response of frames with semi-rigid connections under different material and geometric idealization strategies.

III. EXPERIMENTAL INVESTIGATION

A schematic cantilever type test set up shown in Fig. 1 was adopted to study the semi rigidity behaviour of bolted beam-column joints. Ends of the column were supported and load was applied at the free end of beam member.

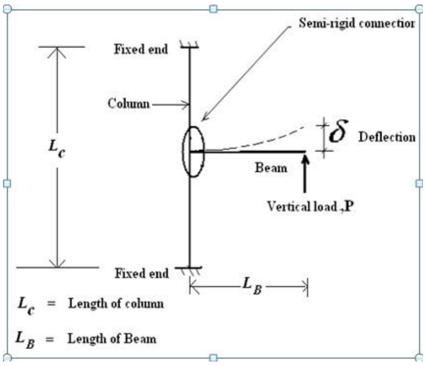


Fig. 1. Schematic diagram- Cantilever test set-up

The load was applied gradually and the deflections at three different points on the beam were measured. The cantilever test setup was arranged within the straining unit of 100t AVERY make universal testing machine. The column member was supported in the top and bottom compression plate of universal testing machine. Since the study was focused on the behaviour of connection, the use of convenient dimensions and boundary conditions adopted was justified. Considering the limitations in the space between the compression plates and connection facilities, suitable height and appropriate section was assumed for the column member. Standard steel section ISMB 200@25.4kg/m was used for beam and column members. The schematic diagram of the test setup is shown in Fig.2.

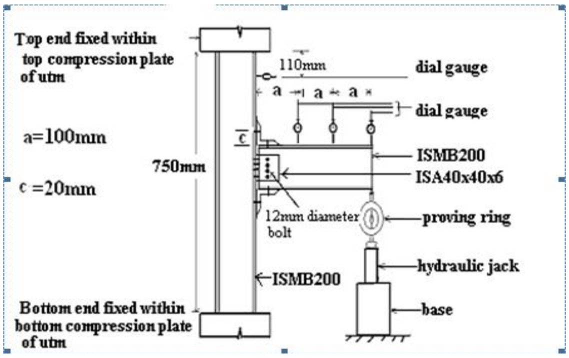


Fig.2. Schematic diagram-test set-up

The column was set free of initial stresses. The load was applied using a hydraulic jack and a proving ring of capacity 100kN was used for measurement. The dial gauges were fixed on the top of the beam member at the free end at a distance of 100mm, and 200mm from free end. A photograph of the experimental test setup is shown in Fig. 3. High strength structural bolts were used for connections.

The geometrical parameters varied in the study are the thickness of top and seat angle, number of bolts and the bolt diameter. The connection details of double web angle are given in Fig. 4. A gap of 6mm was provided between the column and beam to allow the rotation without damaging the column and beam members.

The ultimate condition was assumed as the closure of gap provided between the beam and column members or the failure of bolts whichever is earlier. The deflections at three points on the top of beam as shown in Fig. 2 were measured using dial gauges.

Table. I. Details of specimen tested

Specimen	Angle Sections	Bolt Diameter, d(mm)	Number of Bolts, n
S1	40X40X6	6	2
S2	40X40X6	10	2
S3	40X40X6	6	4
S4	35X35X3	6	4
S5	35X35X3	10	2
S6	35X35X3	6	2
S7	no angles at top and bottom double web angle connection		

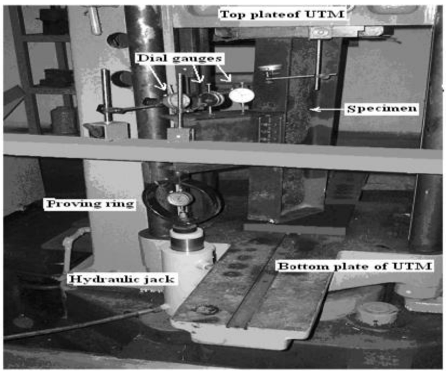


Fig. 3. Experimental setup

The connection details of the specimens tested are given in Table. I. The test specimen S1 had the connection with top and seat standard angle section ISA 40×40×6 using 2 numbers of 6mm diameter high strength bolt.

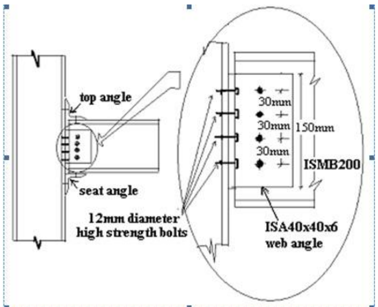


Fig. 4. Typical connection.
(Inset shows the details of web angle connection).

IV. DUCTILITY

Ductility plays an important role in seismic design. The joint behaviour has a direct influence on the ductility. The ductility factor is one of the parameters characterising the behaviour of a structure or joint in plastic range. Considering the rotation of joints, rotational ductility factor is given by (1).

$$\mu_r = \frac{\phi_u}{\phi_y} \quad (1)$$

ϕ_u is the rotation on ultimate state and ϕ_y is the rotation on reaching first yield point of joints.

ENERGY DISSIPATION CAPACITY

The connection stiffness F of beam is related with moment (M) and rotation of beam at the joint (θ) by (2). The connection stiffness of column assuming the connection to be at the centre of column given by (3) can be obtained from the analysis of a member fixed at both ends and subjected to a moment at the centre.

$$F = -\frac{M}{\theta} \quad (2)$$

$$\phi = -\frac{ML_C}{16EI_C} \quad \text{(anti-clockwise)} \quad (3)$$

ϕ is the rotation of the column at the joint, L_C is the length of column member, E is the Young's modulus of elasticity of the material, and I_C is the moment of inertia of column section.

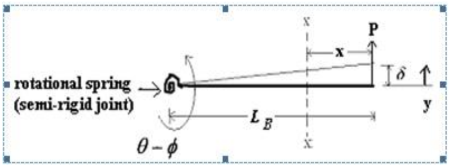


Fig. 5 Semi-Rigid Beam Member

The deflection of a member with one end free and other end connected semi-rigidly and subjected to point load at free end as shown in Fig. 5 is given by (4). I_B is the moment of inertia of the beam cross section. The clockwise rotation is assumed to be positive and downward deflection is considered negative.

$$\delta = \frac{PL_B^{\ 3}}{3EI_B} + \frac{PL_B^{\ 2}}{F} + \frac{PL_B^{\ 2}L_C}{16EI_C} \quad (4)$$

From (4) the beam connection stiffness, F, can be determined. Thus the beam rotation and column rotation can be determined by using (2) and (3). Using θ and ϕ, relative rotation at joint

($\theta_y = \theta - \phi$) can be computed. The moment-relative rotation curve can be then plotted. The energy dissipated by the connection is quantified by computing the area under the moment-relative rotation curve.

V. FINITE ELEMENT ANALYSIS

In the present problem, moment-relative rotation behaviour of bolted beam-column connection is studied numerically. As the members associated with the connection undergo large deformations and rotations, geometric and material non-linearity are to be accounted in the problem. Since all the experiments are performed under static loading condition, a static non-linear structural analysis is required for simulating the real problem. Conventional 3D brick elements are inadequate to represent the realistic contact behaviour in the column-beam interface and bolt-plate interface under incremental loading conditions. Contact problems can be efficiently handled with ANSYS.

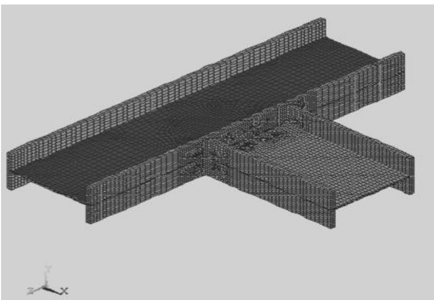


Fig. 6. Column-beam finite element mesh

Brick elements with 20 nodes, SOLID 95 available in the ANSYS element library, were used in the three dimensional modelling of beam, column angles and bolts. The contact surfaces including the areas anticipated to be in contact were defined and paired using contact elements, CONTA174 and TARGE170. For structural steel used, the yield stress was taken as 250 N/mm^2, ultimate tensile strength as 410 N/mm^2 and % elongation of 23 as per IS 2062:1999. For the high strength bolts used, yield stress of 640 N/mm^2, ultimate stress of 800 N/mm^2, and 12% elongation were adopted as per IS 1367 (Part 3):2002. The modulus of elasticity of steel was taken as 2×10^5 N/mm^2. The column and beam members were modelled and mapped meshing consisting of brick elements was performed as shown in Fig. 6.

VI. RESULTS AND DISCUSSION

Experimental Results

The moment-rotation behaviour of specimens with different geometric parameters of double web angle connection with top and seat angle sections discussed is depicted in Fig. 7. In the figure, two regions, elastic region followed by yielding, can be noted for all repeated test cases. The curves of specimens S1 and S2 shown in Fig. 7 indicates that as the diameter of bolt (d) is increased, ultimate moment and ultimate rotation increased. There was an increase of 67% in the ultimate moment when the diameter was increased from 6mm to 10mm.

Table. II shows the effect of the ratio of diameter of bolt (d) to thickness of angle (t) on energy dissipation. When number of bolt was doubled an increase of 508% in energy dissipation was observed for top and seat angle connection with d/t ratio 1 and an increase of 62% for top and seat angle connection with d/t ratio 2. As the number of bolts increased (specimens S1 and S3) there is an increase in the ultimate rotation with slight increase in ultimate moment. Hence the ultimate moment and ultimate rotation depends on the number of bolts as well as the diameter of bolts. The rotational ductility calculated by (1) and the energy dissipated are presented in Table. III. There is considerable energy dissipation capacity for all the connections with top and seat angles. The energy dissipation is also higher for angle with more thickness (t) and large number of bolts (specimen S3).

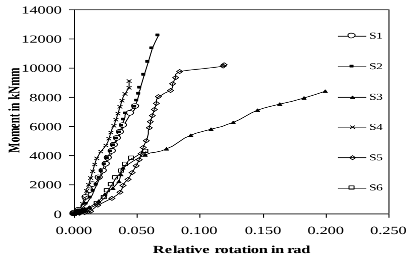


Fig. 7. Moment- relative rotation curve of specimens with Angle Sections

Table. II Energy dissipation for different d/t ratios

Specimen			Number of bolt	Energy dissipated (kNmm.rad)
S1	6mm thick	d/t =1	2	177.4
S3			4	1019.8
S4	3mm thick	d/t =1	4	195.4
S6			2	132.4

From Table II, on comparing joints with connection specimens S2 and S3, it is clear that the increase in the ductility is more if the bolt area is changed by increasing the number of bolts rather than increasing the diameter of individual bolt. It is clear from Table III that the ductility can be improved by increasing the number of bolts as well as the angle thickness.

Table. III. Energy dissipated by the connection

Specimen	Ultimate Rotation $\phi_u\,(rad)$	Yield Rotation $\phi_y\,(rad)$	Rotational Ductility $\mu_r \doteq \phi_u / \phi_y$	Energy Dissipated $(kNmm.rad)$
S1	0.0488	0.0151	3.23	167.72
S2	0.0671	0.0413	1.62	370.18
S3	0.1995	0.0382	5.22	1019.8
S4	0.0434	0.0175	2.48	185.45
S5	0.1192	0.0668	1.78	653.57
S6	0.0572	0.0239	2.39	114.90
S7				208.23

The moment-relative rotation curve under static half cycle loading of double web angle connection (specimen S7) in comparison with top and bottom seat angle connection (specimen S5) is depicted in Fig. 8.

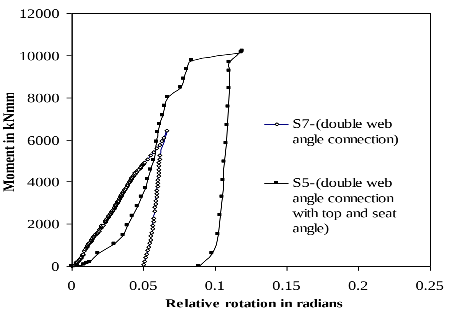


Fig. 8. Moment-relative rotation curve under

From Fig. 8, it is evident that the energy absorption capacity of the connection was improved by using top and seat angles. The energy absorption was increased by 180% by providing seat angles in addition to web angles for moment resistant connection under study. On testing the double web angle connection specimen S7, it was found that the bolts connecting the web angle were bent and the gap was closed. But for the specimen S5 with top and seat angle there was yielding of seat angle followed by breaking of bolt in the seat angle with relatively less bending of the bolts connecting the web angles. The leg of seat angle connecting to the column flange was yielded as shown in Fig. 9.

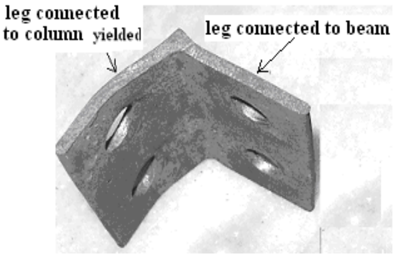


Fig. 9 Deformed seat angle

Finite Element Analysis using ANSYS10

Finite element model of one of the specimen S1 is shown in Fig. 10. In the nonlinear analysis, a maximum load of 30kN was taken and the solution was converged at the ninth sub step (corresponding load was 27kN). The deflected shape of the beam-column joint is shown in Fig. 11. The load-deflection and moment-rotation curves for specimen S1 obtained analytically and experimentally were compared in Fig. 12. Deflection at free end of beam is designated as dl in the graph.

For the specimen S2 the solutions get converged to a load of 39.5kN (14th substep). The moment-relative rotation curve for specimen S2 obtained analytically and experimentally was plotted as shown in Fig. 13. Similar behaviour was observed in the elastic range without much variation, but there was a deviation of less than 10% of analytical result from the experimental values was seen in the inelastic region. A clear indication of slip at bolt was observed near yield point during experiment and the effect was not simulated analytically. This has resulted in the deviation of analytical result from experimental result in post elastic region. The load-deflection curve for specimen S7 obtained analytically and experimentally was compared as shown in Fig. 14. For the specimen S6 the solutions get converged to a load of 15kN. The moment-rotation curve for specimen S5 obtained analytically and experimentally was plotted as shown in Fig. 15.

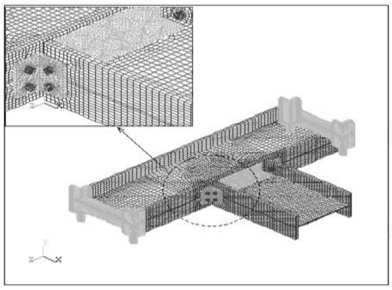


Fig. 10. Model of specimen S1

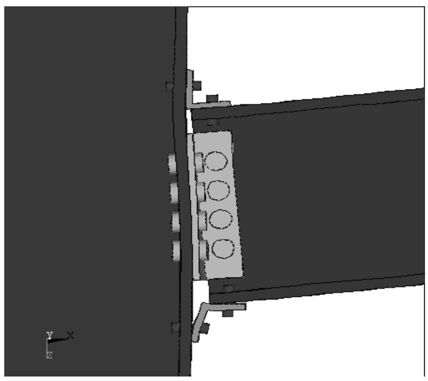
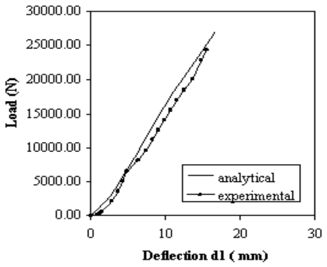
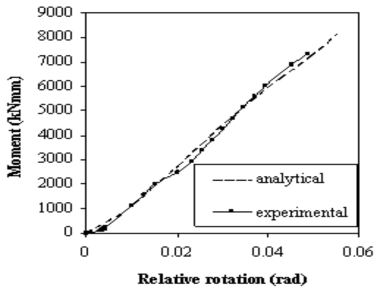


Fig. 11 Deformed model

There was only less than 10 % variation in the analytical result when compared with experimental result. On comparing the analytical and experimental results it can be seen that for same load (or moment), the deflection (or relative rotation) is more in the experimental result. This may be due to the slip in the bolt.



a) Load-deflection curve



b) Moment-relative rotation curve

Fig. 12 Specimen S1-6mm thick angle, 2nos 6mm bolt

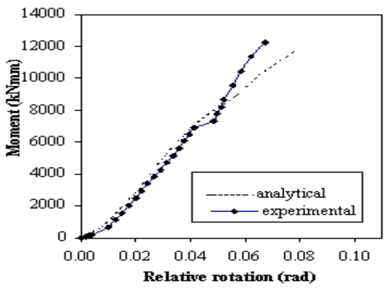


Fig. 13. Specimen S2-6mm thick angle, 2nos 10mm bolt

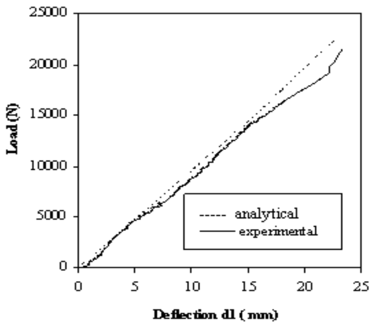


Fig. 14 Specimen S7-double web angle connection

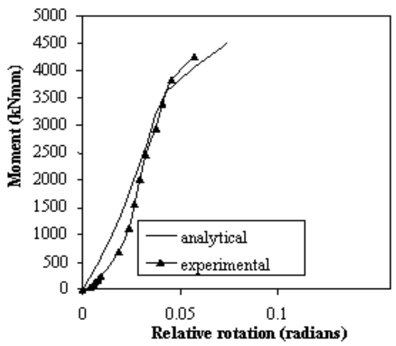


Fig. 15 Specimen S6-3mm thick angle, 2nos 6mm bolt

VII. CONCLUSION

Based on the experimental and analytical investigation conducted on bolted steel beam-column joint, the following conclusions are drawn.

- The use of top and seat angles improved the energy dissipation capacity. The energy dissipation of the connection increases as the thickness of top and seat angles and number of bolts increases.
- Increasing the number of bolts rather than increasing the diameter of bolt in the connection with top and bottom seat angles improves ductility.

The maximum difference observed between the analytical and experimental results is less than 10%.

NOTATIONS

E	- Young's modulus of elasticity of the material
F	- Connection stiffness of beam
I_C	- Moment of inertia of column section.
I_b	- Moment of inertia of the beam cross section.
L_C	- Length of column member
M	- Moment
Φ	- Rotation of the column at the joint
θ	- Rotation of beam at the joint
Φu	- Rotation on ultimate state
Φy	- Rotation on reaching first yield point of joints.
d_1	- Deflection at free end of beam.

REFERENCES

[1] Cheol, M.Y., and Young, M.K., "Cyclic Behaviour of Bolted and Welded Beam to Column Joints", International Journal of Mechanical Sciences, doi:10.1016/j.ijmecsci.2006.09.022.

[2] Chen, S.J., Yeh, C.H and Chu, J.M., "Ductile Steel Beam-to-Column Connections for Seismic Resistance", Journal of Structural Engineering, ASCE, Vol 122(11), 1996, pp 1292-1299.

[3] Secer, M. and A. U. Ozturk, "An Investigation for Semi-Rigid Frames by Different Connection Models", Mathematical and Computational Applications, Vol 10, No 1, 2005, pp 35-44.

[4] Christopoulos,C., Filiatrault,A., Uang,C.M., and Folz,B., "Post Tensioned Energy Dissipating Connections for Moment-Resisting Steel Frames", Journal of Structural Engineering, Vol 128(9), 2002,pp 1111-1120.

[5] Frederick, G.R., and Abuyasein, O.A., "Analysis of Frames with Semi-Rigid Joints", Computers and Structures, Vol 52, No 6, 1994, pp 1161-1168.

[6] Kartal M.E., Basaga H.B., Bayraktar A. and Muvafik M., "Effects of Semi-Rigid Connection on Structural Response", Electronic Journal of Structural Engineering, eJSE, Vol 10, 2010, pp 22-35.