DESIGN AND NUMERICAL INVESTIGATIONS OF SEISMIC –RESILIENT PREFABRICATED STEEL BEAM-COLUMN JOINT (PSBCJ)

Arathi E Devadas [1], Dr. Alice Mathai[2]

[1]M.Tech Structural Engineering and Construction Management, Mar Athanasius College of Engineering, Kothamangalam, Ernakulam, Kerala, India
[2]Professor, Dept. of Civil Engineering, Mar Athanasius College of Engineering, Kothamangalam, Ernakulam, Kerala, India

---

Abstract - *Prefabricated Steel structure systems have great predominance in the sustainable construction industry. In recent times, the use of prefabricated steel framework for designing beam-column joints is broadly considered a boon for the structural industry. Focused upon these ideas, the article suggests the use of a new form of Prefabricated Steel Beam-Column Joint (PSBCJ) that can be implemented to make the structure earthquake-resilient in nature. This paper proposes a bolted connection that uses various structural measures to achieve excellent ductile behavior. The beam-column joint consists of a vertical circle tubular column containing a cantilever beam connected to an independent beam by flange and web splice connections. The specimen is developed initially and then analyzed under seismic loads in FE software. Mechanical characteristics such as moment rotation hysteresis curves and failure patterns of the connections were evaluated for their earthquake-resilient action effects. From the results, it was found that the new PSBCJ could withstand joint rotation of about 0.04 radians and at an ultimate rotation angle of 0.3 radians, it dissipated energy effectively by plastic deformation of the connection region alone. Meanwhile, the primary structural members such as beams and columns remained unaffected after the completion of loading. Since the primary components stayed elastic, the seismic efficiency of the joints can still be restored by replacing the splice connection after the seismic event.*

Key Words: Prefabricated Steel Beam-Column Joint, Seismic –resilience, Bolted connection, ABAQUS.

INTRODUCTION

The weakest links in buildings that are prone to significant ground shaking and damage is the beam-column joints. During strong earthquakes, plastic hinges are developed near the beam ends of a beam-column joint, which affect the energy dissipation efficiency and bearing capacity of the structure. Welded steel beam-column joints are susceptible to brittle failure, which occurs when seismic energy is transmitted directly to the connection region, overloading it and causing it to shatter quickly. [1]. The use of a large number of on-site welds complicates the joint design, makes the construction quality control process difficult and time consuming. To minimize brittle failure, various strong column and weak-beam concepts such as reduced beam sections and column tree connections are often used in structures to provide superior energy dissipation characteristics. Although such connections work effectively, they still wreak havoc to the major structural components of buildings using moment-resistant frames MRFs, giving hardship to inhabitants in the form of expensive repair and evacuation costs. In order to enhance seismic performance, joints dissipate energy by plastic deformation of each member. However, owing to post-earthquake energy dissipation, the beam and column have varying degrees of plastic deformation, making earthquake-resilience work difficult. To solve these challenges, a new **Prefabricated Steel Beam-Column Joint** structural system must be developed.

1.1 IS code provisions on Steel Beam-Column Joints

IS a Code provision on steel beam-column joints classifies them into simple, rigid & semi-rigid connections[3]. Special Moment frames are designed to withstand inelastic deformation to a joint rotation of 0.04 radians without degradation in strength & stiffness below full yield value (Mp).IS Code contains a provision regarding the addition of stiffeners to control plastic hinge formation. However, the IS Code lacks provisions to safeguard main structural components from severe damage as a result of seismic activity. As a result, the goal of this research is to avoid damage in key components of beam-column joints in structures. Improve IS Code requirements on steel beam-column joints, particularly for PSBCJ, and, more significantly, simplify and focus repair work on replacing only the dissipative parts rather than complete structural demolition.

2. INTRODUCING A NEW PREFABRICATED STEEL BEAM-COLUMN JOINT (PSBCJ)

The new Prefabricated Steel Beam-Column Joint is made up of a vertical hollow circular steel column that is rigidly joined in the center by a cantilever beam that extends out to join an independent beam on the right end. Bolted connections with flange and web splice plates are used to connect the cantilever and independent beams (Fig-1).

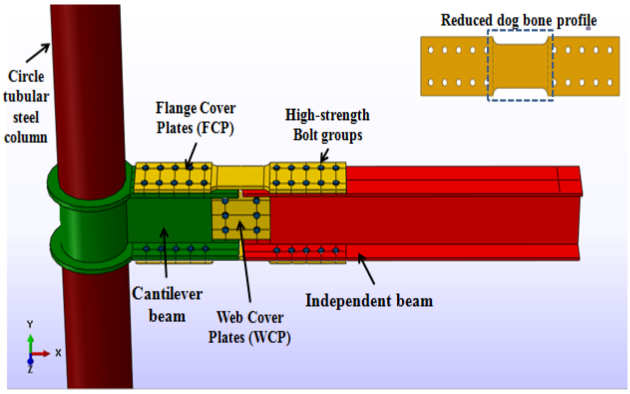

Fig 1: Prefabricated Steel Beam Column Joint with Bolted flange and web connectors

The bolted connection is an important part of the new seismic resilient PSBCJ. An annular baffle plate, a gap between the beams, a decreased dog bone profile on the flange cover plate, and the use of high strength friction-type bolts are all structural features that contribute to the semi-rigid behavior of the beam-column joints. [3].

2.1 Selected seismic criteria for the design of new bolted PSBCJ

1. Bolts at the connection location should have a shear bearing capacity greater than the force exerted on the joint during minor earthquakes to prevent the bolts from slipping.
2. To keep the connection plates elastic under a minor earthquake, the yield load P acting on the connection area should be slightly higher than the yield load acting on the independent beam end.
3. The Joint region should withstand a joint rotation of 0.02 or 0.04 radians without collapsing under strong earthquakes.
4. Post-earthquake, the major components of the joint should remain elastic, with only the connecting region being allowed to suffer plastic degradation.[3]

3 DESIGN OF A NEW PREFABRICATED STEEL BEAM-COLUMN JOINT (PSBCJ)

The theoretical derivation of designing PSBCJ was done in a check code manner according to the Chinese Code for Design of Steel Structures (SAC 2003)[4]. Material yield strength of connection devices was taken as 345MPa whereas the yield strength of other components including the beam and column was set at 235 MPa.

The total bending and compression forces acting on the flange cover plate owing to an independent beam end factored load P of 1000kN are taken into account in the design of the flange cover plate. Under minor earthquakes, stresses developed due to bending and overall stability should be less than or equal to the yield strength of flange cover plate f, so that flange cover plates remain elastic, according to chosen seismic criteria. As a result, it must satisfy the following equation.

i. Bending of connecting plates due to independent beam end load P is calculated using the following simple bending equation from SAC 2003[4].

$$\sigma_b = \frac{M*h}{I} \leq f$$

Here, h is the distance of plates to the neutral axis of the beam section, and I is moment of inertia of flange cover plate.

ii. Members bent in their principal plane of largest rigidity shall be checked for overall stability equation of (SAC 2003)[4].

$$\sigma comp = \frac{M}{\varnothing_b * W_x} \leq f$$

Here, $\varnothing_b$ is the stability coefficient and W_x is gross section modulus of the beam with respect to compression fibers.

For obtaining the plastic hinge formation load of the joint, resisting stress of the flange cover plate is considered in the above formula. The minimum value obtained will be the expected yield load of the new PSBCJ.

The shear bearing capacity N^b_v of the bolt group is used to determine the design theory of high-strength bolts for cover plates.

$$N^b_v = 0.9 * n * n_f * \mu * P$$

Here, n is the number of bolts, n_f is the number of load transmitting friction interface, μ is the friction coefficient of bolts and P is bolt pretension load. The shear bearing capacity of the bolts must be greater than independent beam end load acting on joint. The amount of bolts used would then have an adequate bearing capacity and would not cause slippage.

4 FEM MODELLING AND ANALYSIS OF THE SPECIMEN

The standard FE analysis software ABAQUS was used to model PSBCJ with a circular tubular column of height 3000 mm, an independent beam of length 1500 mm, and a cantilever beam of length 650 mm. C3D8R solid components were used to mesh beams, columns, connecting devices, and bolts. Surface-to-surface contact was chosen as the contact type. The rigidity of a column was thought to be infinite. With an incremental cyclic rotation of 0.01 rad, a displacement-controlled cyclic loading was generated.

Table 1: Main component of specimen

SL.No	Part	Dimensions
1	Flange and web cover plate	8mm
2	No. of bolts on single side of flange and web cover plate	10 and 3 respectively
3	Independent beam	300 x 200 x 8 x 12 mm

4	Cantilever beam	300 x 200 x 12 x 20 mm
5	Middle hollow circle column segment	315 x 20 mm
6	Top and bottom portion of hollow circle tubular column sections	315 x 15 mm

5 RESULTS AND DISCUSSIONS

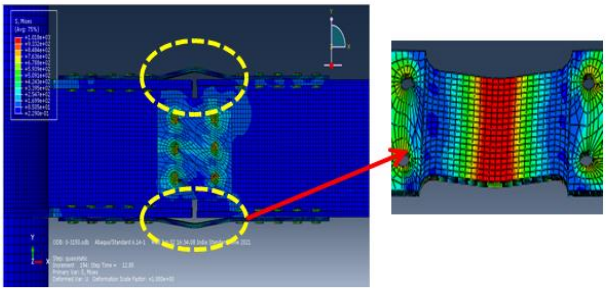

Fig 2: Numerical analyses result of PSBCJ

There was no visible buckling or relative slippage on the flange cover plates throughout the first phases of the joint rotation of 0.04rad, and the joint was in the elastic stage. However, as the cyclic loading increased, the independent beam rotated considerably and plastic buckling deformation was visible only on the flange cover plates. The major members, such as the beam and column, were unaffected, and the overall structure remained elastic. According to the findings of numerical analysis (Fig 2), the proposed design theory could properly predict the buckling behavior of the PSBCJ under cyclic load.

Flange cover plate buckled when joint rotation reached 0.3 rad. with a yield stress of 450 N/mm^2 (Fig **3**) which comes within the design connection material plastic yield strength of Q345 of class 1 holes as per Chinese steel code (SAC 2003) [4].

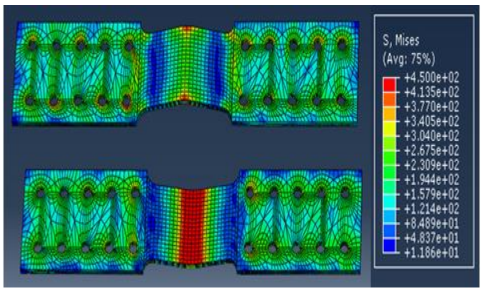

Fig 3: Plastic hinge formation at reduced dog bone profile of flange cover plate

Moment rotation hysteresis curve of flange cover plate near reduced dog bone profile (Fig 4) showed that energy dissipation is more on right end of independent beam than on left end cantilever beam.

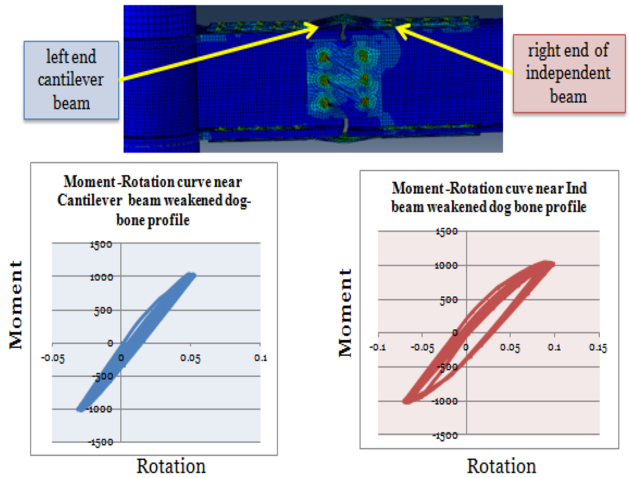

Fig 4: Moment rotation hysteresis curve of flange cover plates near reduced dog bone profile

After the cyclic analysis, both beams remained elastic, indicating that the stresses on the beams were minor. After cyclic loading, both members remained elastic (Fig 5).

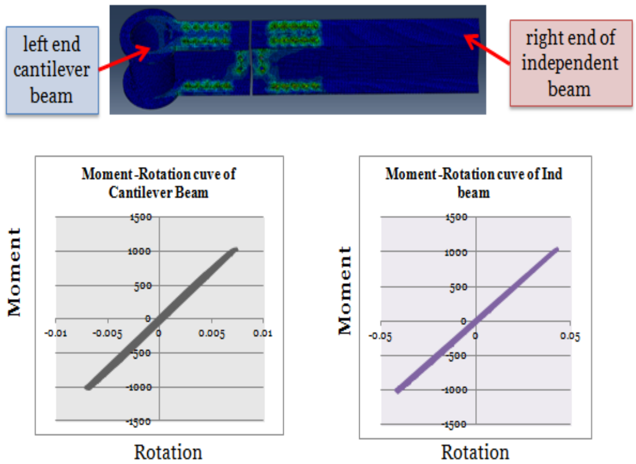

Fig 5: Moment rotation hysteresis curve of primary structural components of beam column joint

Moment rotation hysteresis curve of buckled flange cover plate showed that maximum stress occurred in the position reduced by the dog-bone profile on the flange cover plate indicating that flange cover plate showed high energy dissipation efficiency (Fig 1).

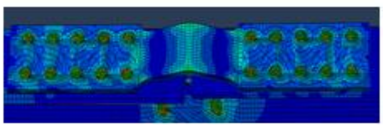

Fig 2: Buckled region of Flange cover plate

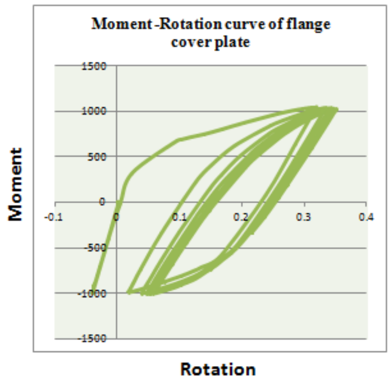

Fig 3 : Moment rotation hysteresis curve of Buckled Flange cover plate

5.1 FACTORS INFLUENCING FAILURE MECHANISM OF PSBCJ

The rigidity of a flange cover plate got reduced when it yielded. When too few bolts were provided, the bolts slipped too early and the beams collided (Fig 8). Thus, the joint did not meet the bearing capacity requirement of design theory.

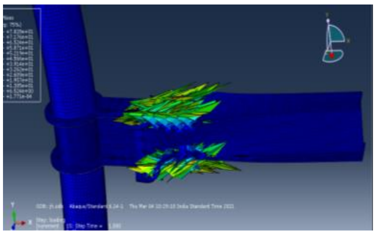

Fig 8 : Bolt slippage causing collision between beams

The buckling moment of flange cover plates is influenced by the middle bolt interval i e. the reduced dog bone length, which has an impact on the ultimate load and ductility of PSBCJ. When minor gaps were provided, the entire flange cover plate portion entered a plastic condition without buckling, and plastic regions appeared on the primary components of the beam-column joint (Fig 9).

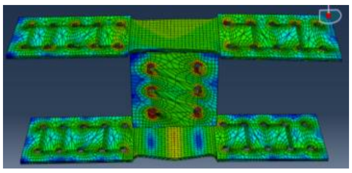

Fig 9 : Binding section with small middle bolt interval

When larger gap was provided the flange cover plate entered plastic stage, buckling failure occurred more towards the independent beam end (Fig 10).

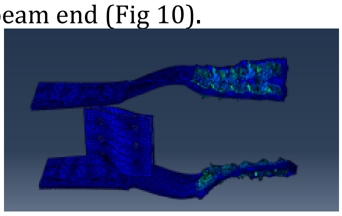

Fig 10: Binding section with large middle bolt interval

Thus, Numerical analysis showed that the performance of the PSBCJ is accountable when the value of the middle bolt gap is about 40times the thickness of the cover.

6 DESIGN RECOMMENDATION AND CONCLUSION

The newly designed PSBCJ showed good seismic behavior with a joint rotation of about 0.04 radians. After a heavy earthquake, only the replaceable connecting parts need to be replaced to recover the structure. Thus, with the use of newly designed PSBCJ, a structure could be made earthquake-resilient.

- Through proper design, plastic deformation of the joint can be localized on flange cover plates which are easy to replace and repair.
- Beam and column remained unaffected after cyclic load such that the structural function of PSBCJ can be restored.
- The numerical analyses showed that the proposed design theory could accurately predict the seismic behavior of PSBCJ.
- Bolts provided in PSBCJ showed good shear bearing capacity without slipping. It also improved the rotation ability of the independent beam.
- The value of the middle bolt interval influenced the buckling of flange cover plates as a result plastic damaged could be localized in between those spaces.
- Gaps provided between beams improved the rotation ability of the independent beam without damage.
- As the seismic design requirements were found safe they can be included in IS Code provisions.

ACKNOWLEDGEMENT

I want to convey my heartfelt gratitude to Dr. Alice Mathai, Professor Department of Civil Engineering, M.A. College of Engineering, Kothamangalam for her prompt guidance and help in completing this project.

REFERENCES

[1] Duane, K. 1998. “Lessons Learned from the Northridge Earthquake” 0296 (97): 249–60.
[2] Standard, Indian. 2007. “GENERAL CONSTRUCTION IN STEEL — CODE OF PRACTICE (Third Revision),” no. December.
[3] Zhang AL, Li SH, Jiang ZQ, et al. Design theory of earthquake-resilient prefabricated sinusoidal corrugated web beam-column joint. Eng Struct 2017;150 :665–73.
[4] SAC (Standardization Administration of the People’s Republic of China), 2003. Code for Design of Steel Structures, GB 50017-2003. SAC, Beijing, China (in Chinese).