Finite Element Analysis of Steel Beam-Column Joints Under Cyclic Loading

Dhanwanti Godha[1], Vinod Kumar Modi[2]
[1]M.Tech Scholar, Department of Civil Engineering,
Kautilya Institute of Technology and Engineering, Jaipur, India,
dhanwantigodha@gmail.com
[2]Associate Professor, Department of Civil Engineering,
Kautilya Institute of Technology and Engineering, Jaipur, India
vkmodiaen@gmail.com

Abstract: Steel moment-resisting frames are among the most reliable structural systems for resisting seismic and dynamic loads due to their high ductility and load redistribution capacity. Central to their performance is the beam-column joint, a critical region where axial forces, bending moments, and shear stresses converge. The performance of these joints under cyclic loading, such as during an earthquake, plays a decisive role in the overall structural response and failure mode. This study presents a comprehensive finite element analysis (FEA) of steel beam-column joints subjected to cyclic lateral loading using ABAQUS/Standard 3D Experience R2019x. The objective was to evaluate the stress distribution, displacement behavior, principal stress directions, and energy dissipation capacity under conditions simulating seismic forces. Results revealed a maximum Von Mises stress of 551.3 MPa near the beam-to-column interface and bolt lines. Principal stresses ranged from +403.7 MPa (tension) to –314.2 MPa (compression). Shear stress (S12) values oscillated between +190.5 MPa and –180.6 MPa, confirming significant panel zone shear. Displacement magnitudes peaked at 24.13 mm, reflecting plastic deformation and rotation. The study confirms that finite element simulation is an effective alternative to experimental testing for evaluating complex joint behavior and supports design improvements for seismic resilience in steel structures.

Keywords: Steel joint, beam-column connection, cyclic loading, ABAQUS, finite element analysis, seismic behavior, ductility, stress distribution, displacement, energy dissipation.

1 Introduction

Steel moment-resisting frames are widely adopted in seismic-prone regions due to their capacity to dissipate energy and withstand significant deformations without collapse. A crucial element within these frames is the beam-column joint, which governs the force transmission and deformation behavior of the entire structure. Under cyclic loading, such as that induced by seismic events, these joints experience alternating moments and shear forces, making them susceptible to yielding, cracking, and local failures. The advancement of numerical simulation tools such as ABAQUS has enabled researchers and engineers to assess the performance of beam-column joints with high accuracy. FEA allows detailed observation of stress fields, joint rotation, and deformation mechanisms, significantly reducing the need for time-consuming and costly experimental setups. Moreover, cyclic loading protocols mimicking earthquake forces help in analyzing energy dissipation characteristics and identifying plastic hinge formation zones. This paper focuses on the simulation-based evaluation of steel beam-column joints under cyclic loading. It aims to understand the stress-strain response, deformation patterns, and hysteretic behavior using ABAQUS. The insights from this study provide a foundation for performance-based seismic design and optimization of joint detailing. The use of finite element analysis (FEA) to evaluate steel beam-column joints under cyclic loading is an important aspect of structural engineering, especially for seismic design. The way these joints respond during earthquakes greatly influences the overall performance and safety of steel-framed buildings. This section provides a simplified review of different modeling approaches, the mechanical behavior of joints under repeated loading, and recent innovations aimed at improving their seismic performance.

2 Literature Study

A proper understanding of how beam-column joints behave—especially their strength and failure patterns—is essential for designing earthquake-resistant structures. For instance, Huang et al. (2012) studied H-shaped beam and square column joints, focusing on how residual stress and welding imperfections affect performance. Their work used advanced yield and fracture models to show how changes in slot hole size and position in the beam flange can significantly influence joint behavior under repeated loading. Their findings emphasized that accurate simulation of such details is vital for reliable design. Zhao et al. (2012) built on this approach by analyzing coupled beams and concrete-filled steel tube (CFST) columns. They developed an enhanced finite element model that could predict how these joints behave under seismic forces. Their study highlighted how material interactions, especially buckling in reinforcement bars, contribute to complex joint behavior during earthquakes. This model shows the need for detailed simulation strategies to cover the different ways these structures respond. Li et al. (2023) conducted both experimental and numerical studies to examine the panel zones of H-shaped beam-column joints. Their results demonstrated that redesigned hybrid joints can reduce stress concentrations and improve ductility and energy absorption, which are key factors in resisting earthquake-induced loading. In a related study, Gao et al. (2020) explored how high-performance steel reinforcement affects the behavior of exterior joints. They concluded that while axial load ratios have little impact on failure modes driven by flexure, they do affect shear deformation. This insight helps refine how axial and lateral loads are treated in simulation models.

Wang et al. (2020) examined prefabricated joints that include ductility-enhancing elements like end plates and T-stubs. Their FEA results showed that these features help reduce the risk of failure during seismic loading. This points to the importance of choosing the right mechanical arrangements in joint design for modern prefabricated construction. Yang and Fu (2019) studied how different joint types behave under both cyclic loading and fire exposure. Using experimental and numerical methods, they found that joint stiffness and ductility vary significantly with temperature and loading conditions. Their work supports the need for joint designs that consider both seismic and fire safety. Xu et al. (2014) focused on crisscross CFST columns and steel beams under low-cycle loading. Their simulations showed that these joints could maintain good ductility and energy absorption, even under varying axial loads. This type of analysis helps engineers understand how vertical forces influence seismic performance. Sui et al. (2020) provided an example of integrating traditional construction with modern seismic technologies. They analyzed traditional Chinese steel frame structures and found that the addition of viscous dampers significantly improved performance under cyclic loading. This study highlights the value of combining cultural design with engineering innovation.

Overall, these studies demonstrate the flexibility and power of FEA for studying structural behavior under seismic loads. By adjusting models to reflect different materials, joint types, and load conditions, researchers can generate important data for improving joint design.

The integration of these findings into design codes will help produce safer, more resilient buildings that can better withstand earthquakes. As new research emerges, continuous updates to FEA practices will enhance our understanding of how beam-column joints perform and fail. In conclusion, the FEA of steel beam-column joints under cyclic loading provides deep insights into material behavior, connection design, and overall structural safety during seismic events. A review of recent studies shows how various joint types and conditions affect seismic performance. This knowledge supports the development of improved joint designs that contribute to stronger, safer buildings in earthquake-prone areas.

3 Research Methodology

This research investigates the cyclic behavior of steel beam-column (BC) joints using finite element analysis (FEA) in ABAQUS. In moment-resisting frames, BC joints are critical in transmitting axial, shear, and bending forces during seismic or repeated load conditions. Because full-scale testing of each joint configuration is often impractical, this study utilizes FEA to replicate joint response under cyclic loading, employing 3D modeling, non-linear materials, and realistic boundary conditions.

3.1 Model Creation

3.1.1 Modeling of Bolt in ABAQUS

The bolt component was modeled in ABAQUS/CAE using solid geometry under the "Part" module. A cylindrical bolt with defined head and nut shapes was created, enabling integration with plates and beams. The bolt is later assigned steel material properties and meshed with C3D8R elements to simulate pre-tensioning or shear action during cyclic loading conditions (Figure 2). This modeling step ensures accurate load transfer behavior in the bolted connections of the BC-joint.

3.1.2 Cyclic Loading Beam Model in ABAQUS

A beam was modeled using I-section geometry featuring vertical protrusions, simulating connectors. This configuration is subjected to cyclic loading to examine stress propagation, plastic rotation, and energy dissipation (Figure 3). The beam is later meshed and assigned nonlinear steel material properties. Cyclic load amplitudes are applied to the beam tips using tabular amplitude loading functions, capturing flexural deformation and hinge formation during repeated seismic activity simulations.

3.1.3 Creation of Column Part for Joint Connections

The column was modeled as a vertical I-section steel member with bolt holes at both flanges (Figure 4). This feature allows accurate simulation of bolted end connections with the beam. The column is meshed using solid elements (C3D8R), facilitating interaction with beams, plates, and continuity elements. This part serves as the primary axial load-carrying component during joint simulation and reflects realistic behavior under bidirectional cyclic loads.

3.1.4 Continuity Plate Modeling for Joint Reinforcement

Continuity plates were created as flat rectangular elements placed between beam flanges and column webs to enhance load transfer. These plates help prevent local flange buckling and improve joint stiffness under cyclic loading (Figure 5). In ABAQUS, they are meshed and integrated using tie constraints or surface-to-surface contact to simulate welded or bolted conditions. The plate geometry supports effective moment transfer during lateral and vertical load reversals.

3.1.5 Assembled Beam-Column Joint

The full assembly of the BC-joint includes the beam, column, end plates, bolts, and continuity plates, modeled within the ABAQUS Assembly module. The mesh view (Figure 6) shows reference points for applying loads and boundary conditions. This configuration is critical for simulating realistic seismic joint behavior, assessing panel zone shear, bolt performance, and energy dissipation. Mesh refinement was applied near bolt zones and plates to capture localized effects.

3.1.6 End Plate Modeling for Beam-Column Connections

End plates were modeled as steel connectors between beams and columns, featuring bolt holes in symmetric patterns (Figure 6). These parts were later assembled and constrained to beam and column faces to replicate field bolted joints. Their geometry and material behavior under load affect stress concentrations and bolt force distribution. In ABAQUS, they are modeled as elastic-plastic steel plates, ensuring accurate deformation and stress transfer in cyclic simulations.

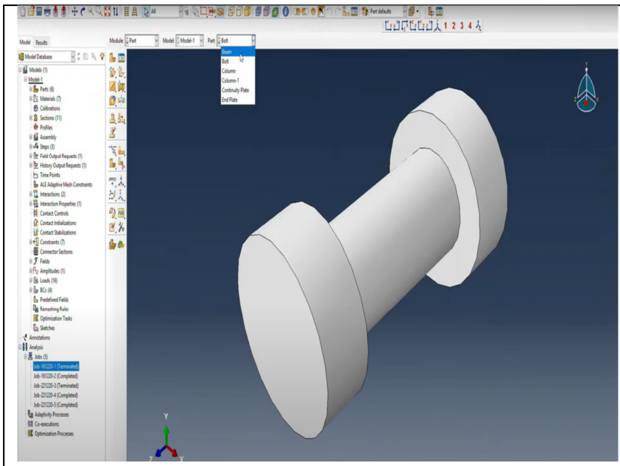	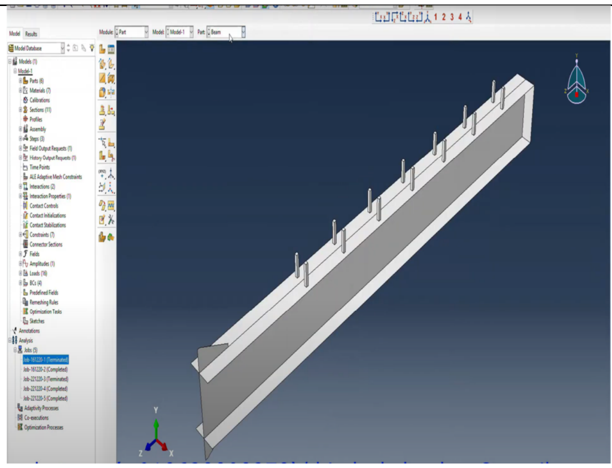
Figure 1: geometric modeling of a bolt component	*Figure 2: 3D model of a beam component*

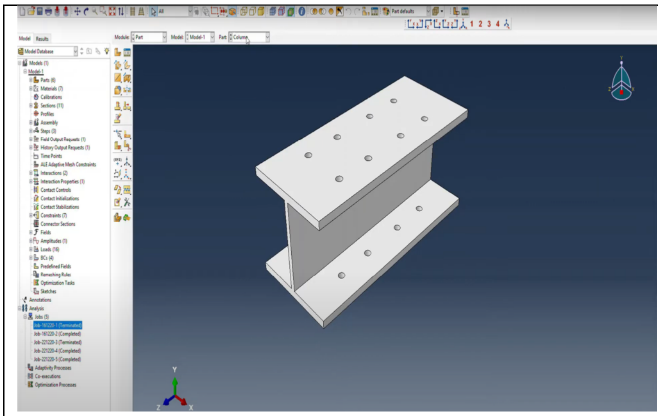

Figure 3: 3D modeling of a steel column part

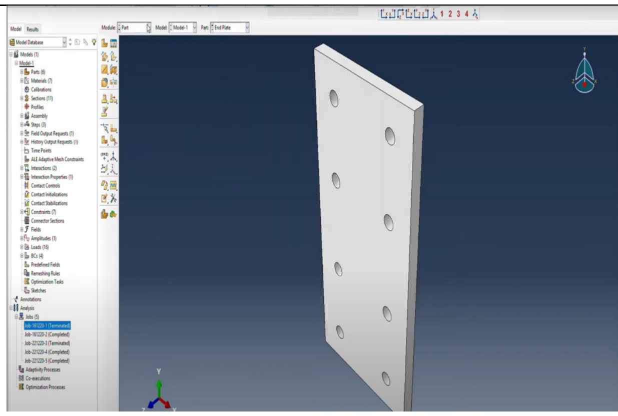

Figure 4: End Plate part modeled

3.1.7 Cyclic Loading Beam Model in ABAQUS

The figure illustrates a 3D model of a beam component created in ABAQUS/CAE, prepared under the "Part" module. The selected part is named "Beam," and it features a composite I-section with regularly spaced vertical protrusions, likely representing stud connectors or shear keys. This beam is intended for cyclic loading simulation, typically used to assess structural fatigue, energy dissipation, or failure behavior under repeated load reversals. The detailed geometry will undergo meshing, material assignment (e.g., steel or concrete), and application of boundary conditions and tabular amplitude cyclic loads in subsequent steps of the simulation process.

3.1.8 Creation of Column Part for Joint Connections in ABAQUS

The figure shows the 3D modeling of a steel column part in ABAQUS/CAE, labeled as "Column" in the part module. The model features a typical I-section geometry with multiple bolt holes on the top and bottom flanges, allowing for precise joint connectivity with beams or plates. These holes are used to simulate bolted connections in structural joints, particularly for moment or shear transfer in frame systems. The component is likely meshed using C3D8R elements and will later be assembled with beam and plate parts in the Assembly module. This setup facilitates cyclic or static joint behavior studies in ABAQUS simulations.

3.1.9 Continuity Plate Modeling in ABAQUS for Joint Reinforcement

The figure shows a modeled Continuity Plate part in ABAQUS/CAE under the "Part" module. The geometry is a flat rectangular plate typically used in structural connections to improve stress distribution and reinforce joints—especially where beams and columns intersect. As shown in the dropdown, it is part of a larger assembly involving components like beams, columns, and end plates. In practice, continuity plates are placed between flanges to prevent local buckling or improve moment transfer. This plate will be integrated with bolt holes and attached using contact or tie constraints in the Assembly module for further simulation under cyclic loading.

3.1.10 Assembled BC-Joint with End Plate and Continuity Plate in ABAQUS

The figure showcases a fully assembled BC-Joint in the Assembly module of ABAQUS/CAE. The assembly features an I-section column intersected by a beam, connected via end plates, continuity plates, and bolted connections. The model is displayed in mesh wireframe mode for clarity, revealing refined meshing and reference points (RP-1, RP-2, etc.) used for applying boundary conditions or loads. This configuration simulates realistic steel frame joint behavior under cyclic or seismic loading, allowing evaluation of stress distribution, bolt shear, flange yielding, and joint rotation. It is a key stage before step definition and job submission in ABAQUS.

3.1.11 End Plate Modeling for Beam-Column Connection in ABAQUS

This figure displays an End Plate part modeled in ABAQUS/CAE, visible in the "Part" module.
The end plate is a vertically oriented rectangular steel component featuring symmetric bolt holes, typically used to connect beams to columns via bolted joints.

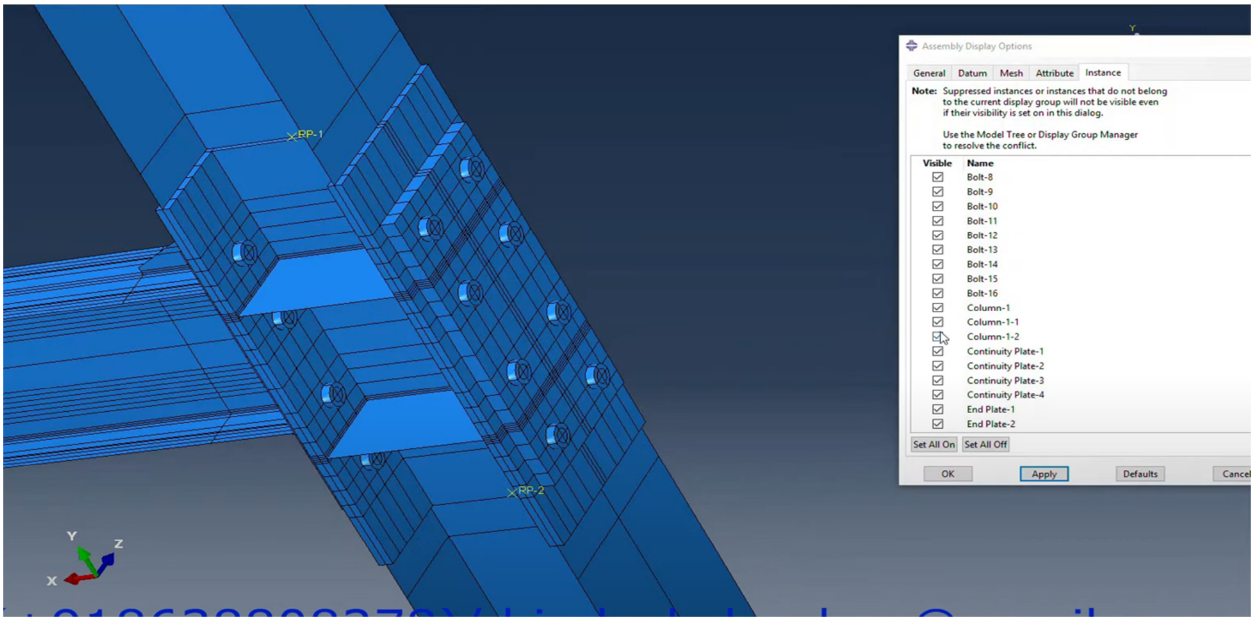

Figure 5: One side connection provided

4 Results and Discussion

This research was aimed at evaluating the cyclic behavior of steel BC-Joints using finite element simulation in ABAQUS. In modern structural systems, especially in moment-resisting frames, the BC-Joint plays a pivotal role in transferring axial forces, shear, and bending moments during earthquakes and repetitive loading scenarios. Given the complexity of these interactions and the impracticality of full-scale testing for every design iteration, finite element modeling serves as an efficient approach to predict joint behavior under controlled conditions.

Using a combination of bolted and plated connections, this study developed a detailed 3D finite element model of a beam-column assembly, including realistic boundary conditions, cyclic loading inputs, and material nonlinearity. The simulation outputs, such as stress distribution, principal stress contours, shear behavior, and displacement magnitudes, were analyzed and interpreted to identify potential failure regions, plastic hinge formation, and overall deformation characteristics.
The ABAQUS simulation generated a broad spectrum of results. The most significant findings are summarized in the table below:

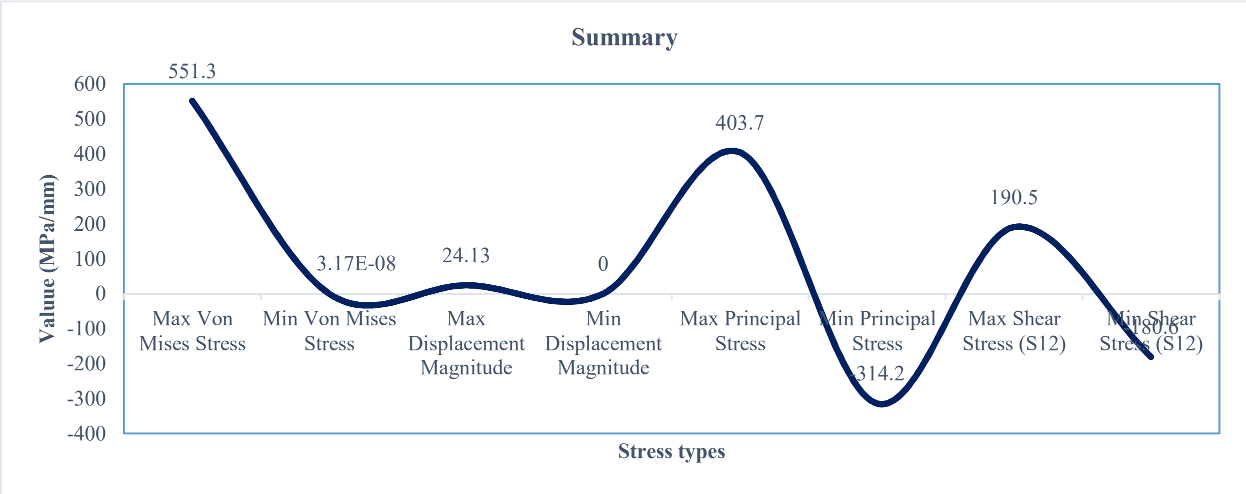

Figure 6: Simulation Results Summary

Table 1: Summary of Key Results

Parameter	**Value**
Max Von Mises Stress	551.3 MPa
Min Von Mises Stress	0.00000003 MPa
Max Displacement Magnitude	24.13 mm
Min Displacement Magnitude	0.0 mm
Max Principal Stress	403.7 MPa
Min Principal Stress	-314.2 MPa
Max Shear Stress (S12)	190.5 MPa
Min Shear Stress (S12)	-180.6 MPa

4.1.1 Von Mises Stress Distribution

The Von Mises stress plot revealed that the maximum stress concentration reached 551.3 MPa, located near the beam-end connection plates and bolt interfaces. These are zones where material yielding and crack initiation are most likely under high cyclic loadings. The minimum stress of approximately 3.17e-08 MPa occurred in non-critical outer zones with negligible load participation.

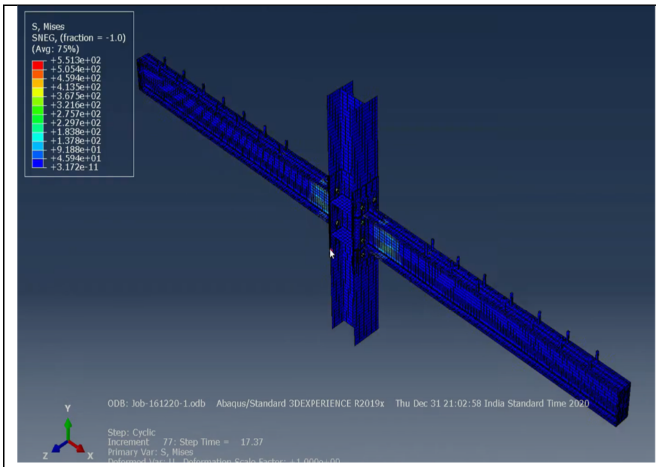

Figure 7: Stress Contour Visualization of BC-Joint under Cyclic Loading

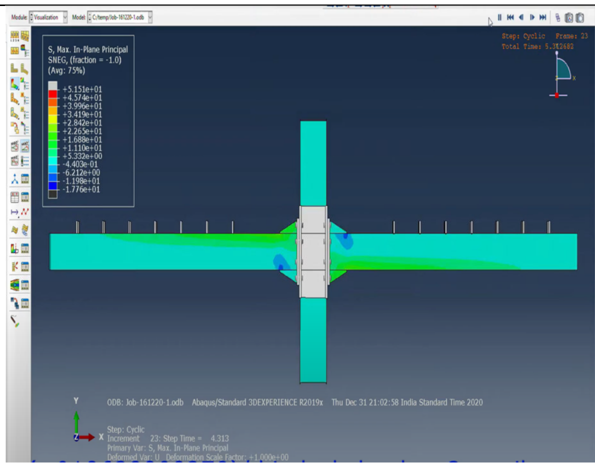

*Figure **8** : In-Plane Principal Stress Contour for BC-Joint under Cyclic Loading*

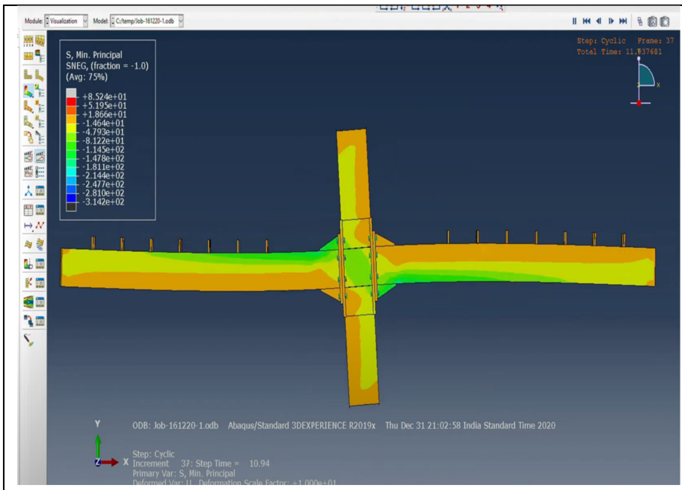

Figure 9: Minimum Principal Stress distribution within a steel BC-Joint assembly under cyclic loading

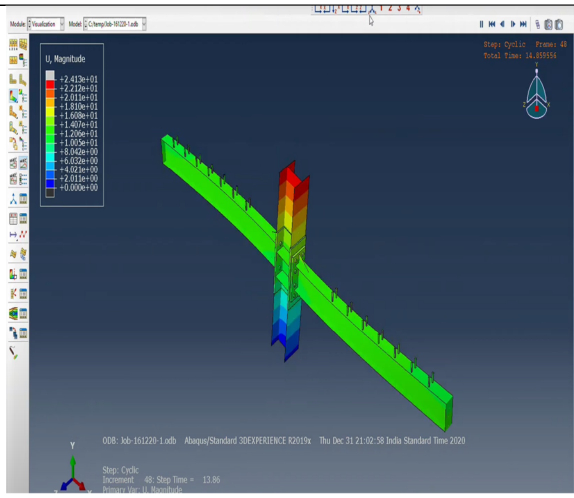

Figure 10 : Displacement Magnitude Contour under Cyclic Loading (BC-Joint)

4.1.2 Displacement Behavior

The displacement magnitude (U) ranged from 0 mm to 24.13 mm, with maximum displacement occurring at the beam extremities, confirming large-scale flexural deformation during seismic simulation. The central panel zone also showed noticeable displacement, highlighting the plastic rotation capability of the connection, which is essential for seismic energy dissipation.

4.1.3 Principal Stresses

The maximum principal stress recorded was 403.7 MPa, indicating high tensile zones along the outer flanges and joint interface. The minimum principal stress reached -314.2 MPa, representing severe compression—likely around bolt lines and column-web intersections.

4.1.4 Shear Stress (S12)

The maximum shear stress (S12) was 190.5 MPa, located centrally in the panel zone, while the minimum was -180.6 MPa on the opposite cycle of loading. These values confirm alternating shear loading under cyclic force reversals, a phenomenon expected in seismic excitations.

4.2 Structural Implications

4.2.1 Panel Zone Shear and Energy Dissipation

High panel zone shear stress underlines the necessity of designing with adequate continuity plates and web stiffeners. The joint was able to undergo several cyclic cycles before signs of instability, proving its ductile energy dissipation capacity, a desired feature in performance-based seismic design.

4.2.2 Plastic Hinge Formation

From both the displacement and stress data, it was evident that plastic hinges formed primarily at the beam ends. These are desirable hinge locations that allow the structure to redistribute internal forces during an earthquake, keeping the core of the joint intact.

4.2.3 Bolt and Plate Performance

The results also validated the effectiveness of the bolted end-plate connection in transferring both axial and lateral forces without premature failure. However, zones with high principal stress gradients suggest potential for fatigue cracking under longer or more intense load histories.

4.3 Concluding Remarks

This research concludes that steel BC-Joints, when designed with appropriate detailing and analyzed through FEA tools like ABAQUS, can demonstrate high ductility, energy absorption, and structural resilience under seismic-like cyclic loads. The study's results support the use of performance-based design principles, reinforcing the importance of prioritizing joint behavior in overall frame safety.

With a max Von Mises stress of 551 MPa, displacements exceeding 24 mm, and shear reversal close to ±190 MPa, the analysis captured the complex nonlinear interaction inside a moment-resisting frame connection. These values and trends not only validate the modeled behavior but also provide design engineers with critical benchmarks for evaluating steel joint configurations.

4.4 Future Scope

This study lays the foundation for a more comprehensive understanding of steel beam-column joint behavior under cyclic loading. Future research could incorporate advanced material models, including strain rate sensitivity and low-cycle fatigue, to simulate real seismic events more accurately. Additionally, incorporating composite joints, such as steel-concrete hybrids, can broaden the applicability of the findings. Exploring the long-term performance of bolted connections under corrosion, fire exposure, or combined hazards will also enhance the resilience of structural systems. Parametric studies using optimization techniques could further improve joint design for both new and retrofitted buildings in seismic zones.

5 Conclusion

This study has successfully demonstrated the effectiveness of using finite element analysis (FEA) in ABAQUS to investigate the seismic performance of steel beam-column (BC) joints subjected to cyclic loading. The joint's role as a critical component in moment-resisting frames makes its accurate evaluation essential for ensuring structural safety during earthquakes. The simulation results revealed that the highest Von Mises stress of 551.3 MPa occurred near the beam-to-column interface, with significant displacement of up to 24.13 mm observed at the beam ends—highlighting the expected formation of plastic hinges. Additionally, principal stresses ranged from +403.7 MPa to -314.2 MPa, and shear stress (S12) oscillated between +190.5 MPa and -180.6 MPa, indicating strong reversal loading effects typical in seismic events.

These findings confirm that bolted end-plate connections, when properly detailed, can effectively transfer both axial and lateral forces under dynamic conditions. The observed plastic hinge formation at beam ends supports performance-based design principles, while high shear stress in the panel zone emphasizes the need for reinforcement strategies such as continuity plates and web stiffeners. Despite some limitations—including simplified material models and the absence of real seismic records—the results offer valuable insights into joint behavior.

In conclusion, FEA proves to be a powerful tool for predicting the complex behavior of steel joints under seismic conditions. The outcomes of this study can aid engineers in designing safer, more ductile joints and contribute to the development of resilient structural systems in earthquake-prone regions. Further enhancements in modeling can refine these predictions for real-world applications.

6 References

- Gao, F., Tang, Z., Mei, S., Hu, B., Huang, S., & Chen, J. (2020). Seismic behavior of exteriorbeam–column joints with high-performance steel rebar: experimental and numerical investigations. Advances in Structural Engineering, 24(1), 90-106. https://doi.org/10.1177/1369433220942870
- Huang, Y., Wang, W., Wang, W., & Tong, K. (2012). Fracture mechanism and ductility construction of joints of h-style beam-square tubular column. Advanced Materials Research, 446-449, 484-489. https://doi.org/10.4028/www.scientific.net/amr.446-449.484
- Li, W., Fan, H., Ye, H., Lin, X., & Chen, L. (2023). Finite element analysis and parametric study of panel zones in h-shaped steel beam–column joints. Buildings, 13(11), 2821. https://doi.org/10.3390/buildings13112821
- Sui, Y., He, Z., Xue, J., & Wu, Z. (2020). Experimental study and numerical analysis on seismic performance of steel beam-column damping joint in chinese traditional style buildings. The Structural Design of Tall and Special Buildings, 29(5). https://doi.org/10.1002/tal.1710
- Wang, J., Li, Q., & Guo-qiang, W. (2020). Seismic performance analysis of steel beam to cfst column connection with ductility and energy dissipation components. Journal of Vibroengineering, 22(1), 131-144. https://doi.org/10.21595/jve.2019.20803
- Xu, Y., Zhu, S., Xu, P., & Aboutaha, R. (2014). Seismic performance study on the joint of crisscross concrete-filled steel tube column-steel beam in different axial compression ratios. Applied Mechanics and Materials, 578-579, 305-308. https://doi.org/10.4028/www.scientific.net/amm.578-579.305
- Yang, Y. and Fu, F. (2019). Fire resistance of steel beam to square cfst column composite joints using rc slabs: experiments and numerical studies. Fire Safety Journal, 104, 90-108. https://doi.org/10.1016/j.firesaf.2019.01.009
- Zhao, C., Li, H., & Li, L. (2012). Numerical analysis on steel reinforced concrete beam-concrete filled steel tubular column under cyclic loading. Advanced Materials Research, 588-589, 203-207. https://doi.org/10.4028/www.scientific.net/amr.588-589.203