

Research Article

Numerical Investigation on Seismic Strengthening of Composite Two Way Beam- Column Joint

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Abstract

Beam-column joints are crucial structural components to ensure the overall stability of composite framed structures subjected to seismic loads. Many more research efforts have been dedicated to enhance the seismic behavior of beam-column joints. Due to limited research on composite beam-column joint, the effect of some parameters is not well documented on the current building codes. A total of eleven specimens including a control specimen were simulated by considering the effects of doubler plate thickness, haunch plate thickness and haunch configuration in a numerical research conducted using ABAQUS/Standard to investigate the performance of composite steel beam column joint under cyclic loading. Experimental results from other researchers validated the accuracy of the numerical model. Finite-element analysis results showed use of higher thickness doubler plate with better haunch thickness increased the load carrying capacity by 45.02% and 34.02% respectively. Moreover, using appropriate haunch configuration along the flange and beam column with haunch support improved the load carrying capacity and seismic resistance of the joint. With use of higher doubler plate and haunch thickness the stiffness and energy dissipation capacity of the joint showed improved result. These results verified that the composite beam column joint with the aid of doubler plate thickness, haunch plate thickness, better haunch configuration and supporting the joint with haunch helps the beam column joint to withstand the seismic action better.

Keywords

Beam-Column Joint, Beam Column, Haunch Support, Doubler Plate, Seismic Performance, Cyclic Loading

1. Introduction

1.1. General

The beam-column joint region is highly vulnerable to failure under extreme cyclic loads, such as those encountered during an earthquake. This kind of failure can lead to a complete structural collapse. Given its significant capacity for energy dissipation, the beam-column joint plays a vital role in resisting lateral forces. To ensure sufficient ductility, en-

ergy dissipation capabilities, and stiffness, various codes like ACI 318-14 and Eurocode-8 mandate the use of materials that help prevent the failure of the beam-column joint. However, introducing a high quantity of steel reinforcement in the joint area can lead to various construction issues, including bond problems, challenges during concrete pouring, and difficulties in consolidating the concrete due to congestion. Consequently, it is essential to assess material ductility

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properly to achieve optimal ductility of the beam-column joint and enhance the performance of the composite steel beam-column joint under different loading conditions. According to [1] reinforced concrete beam-column joints are divided into Type 1 and Type 2 categories according to the joint's loading circumstances and the anticipated deformations of the connecting frame components when lateral loads are applied.

Beam-column junctions were divided into elastic and inelastic joints by Paulay and Priestley [2] based on the structural response, including crack propagation in the joint region and failure mechanism under loading. It is desirable to make sure that reinforced concrete beam-column joints stay essentially within the elastic range during the structure's response. A joint may be strengthened to maintain its elasticity even after a significant number of load reversals if the beams and columns next to it do not experience inelastic deformations [2]. Smaller quantities of joint shear reinforcement are typically adequate in these situations. In actuality, these joints are uncommon and are categorized as elastic joints. Moment-rotation-temperature characteristics are collected in order to investigate the degradation of this type of steel joint at elevated temperatures [3]. Nonetheless, end-plate connections with through bolts [4, 5] and structural steel going through column sections [6, 7] are examples of connections with embedded elements.

The main objective of this study was to investigate the behavior of composite structural steel two-way beam column joint under cyclic loading using nonlinear finite element analysis. A more recent development in civil engineering is the use of haunch strengthened beam-column joints to withstand seismic activity. Therefore, this study adds to the body of knowledge on the effects of doubler plate thickness, haunch plate thickness and haunch arrangement under cyclic loading for researchers, designers, and academicians. It has the ability to increase the body of knowledge in the field of structural engineering, offer useful retrofitting alternatives, and greatly improve the seismic performance of composite structures.

1.2. Statement of the Problem

Beam column joint area is highly susceptible to failure due to extreme cyclic loading conditions like an earthquake. The failure can result in global structural collapse. Owing to its substantial energy dissipation, the beam column joint is crucial in withstanding lateral loads. To achieve adequate ductility, energy dissipation capacity and stiffness different codes like (ACI 318-14, Euro-code 8) require a material that contribute to withstand the failure of beam column joint. However, providing a large amount of steel reinforcement in the joint area leads to different construction defects such as (lack of bond, concrete pouring, and consolidation of concrete) due to congestion. As a result, this thesis was aimed to examine the effect of providing external haunch plate and doubler

plate strengthening under the basic parameters such as doubler plate thickness, haunch plate thickness and haunch configuration under cyclic loading.

1.3. General Objective

The main objective of this study was to investigate the behavior of composite structural steel two way beam column joint under cyclic loading using nonlinear finite element analysis.

1.4. Specific Objective

- 1) To analyze the behavior and performance of composite beam-column connections with adding of a haunch welded on the beam bottom flange in the vicinity of column under seismic loading.
- 2) To analyze the performance connections by strengthening the column web with double steel plates.
- 3) To investigate the influence of the haunch plate thickness variation on failure mechanism.
- 4) To determine the optimal configuration and placement of steel plates for seismic strengthening of composite beam-column connections.

1.5. Significance of the Study

The use of haunch strengthened beam column joint in order to withstand seismic activity is a recent field in civil engineering. So this research work further contribute to researchers, designers, and academicians about the effect of doubler plate thickness, haunch plate thickness and haunch configuration under cyclic loading. It have the potential to significantly enhance the seismic performance of composite structures, provide practical retrofitting options, and add to the body of knowledge in the discipline of structural engineering.

2. Research Methodology

2.1. Method for Numerical Model Validation

Experimental works helped to calibrate numerical models through appropriate and accurately modeling of the geometry, material property, boundary condition and loading in the nonlinear finite element analysis software. To ensure this, an experimental study reported by Loho et al. [8] on the performance of composite beam column joint under cyclic loading was selected from the literature. The specimen selected was modeled in ABAQUS as per the description of experimental works and results from the two methods of analysis were compared. The numerical model containing a result within the appropriate limit of difference with the experimental investigation was used for further parametric investigations.

2.2. Specimen Configuration and Design

Loho et al. [8] performed an experimental study on the composite beam column joint with steel haunch and extended end plate composite joint subjected to cyclic loading. Specimen denoted as specimen “Test G20” was taken from this experimental test study for the numerical model verification. According to Loho et al. [8] the standard specimen was intended according to ECCS 1986. As per the code a full-size specimen was suggested when assessing seismic performance over reversed cyclic load. In assessment of that, the column specimen was HEB200, beam IPE240, haunch IPE240 and slab 30x120x1000mm was used. The reinforced concrete slab was casted at the top flange of steel beam section and connected with shear stud. The slab was reinforced by 10 longitudinal rebar with diameter of 10 mm and by transverse rebar with diameter of 10 mm spaced each 10 cm. For all composite specimens, two doubler plates were connected to the column, as explained above, to strengthen the column web panel.

2.3. Details of Experimental Test

Full-scale composite steel beam column joint that was experimentally confirmed utilizing the stiffener plate, shear stud, and column panel zone strengthening characteristics under cyclic loading was chosen for the numerical model's calibration. Loho et al. [8] state that a composite steel beam-column joint was used to create the specimen. To strengthen the joint zone, steel haunches were positioned at the foot of the structural I-section beam column joint along the column web.

2.4. Material Property of the Specimen

According to Loho et al. [8] the concrete slab's reinforcing bar had a diameter of 12 mm longitudinally ($f_y = 300$ MPa) and 8 mm transversely ($f_y = 250$ MPa). According to the experimental protocol, the top of the structural steel column is pin linked, and the base of the column was secured to a fixed support. A basic simulation of members exposed to seismic actions was made possible by these test methodologies. The performance of the composite two-way beam column joint under cyclic loading was examined in the current study by examining the effects of doubler plate thickness variation, haunch plate thickness, haunch orientation, and haunch with and without haunch. Eleven specimens, including the control specimen, were created in order to accomplish this.

2.5. Loading, Boundary Conditions and Interactions

In parametric investigations, the two-side shear wall section was excluded during analysis by using the rigid body

modeling method, which also helps to reduce the processing time of the software. To absorb the cyclic loading simulation, one side of the beam was loaded, and the other side was loaded with the right side load. Z-axis rotation was set to free, whereas the other axis was fixed. In order to control out-plane deformation, the displacement in the Y-axis was set to the displacement amplitude value determined by the experiment, while the displacement in the X and Z-axes was fixed.

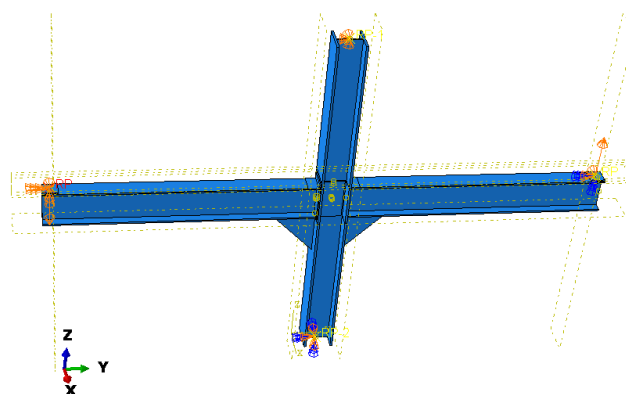


Figure 1. Loading and boundary condition.

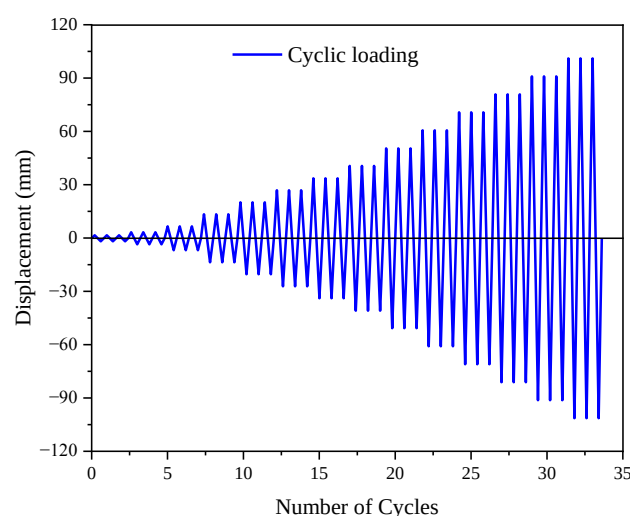


Figure 2. Cyclic loading protocol.

Based on the concrete's unit weight, the specimens' self-weight was incorporated into the numerical analysis as a body force. Using a numerical model and the ABAQUS FE code, [9] examined the beam-column behavior of composite connections. The findings showed that the moment capacity was only little impacted by the increase in slab concrete strength. ABAQUS/standard was used to do a nonlinear finite element analysis of the composite beam column joint by defining a set of steps to describe the issue history and analysis technique. To account for the impact of nonlinearity in

the numerical model, general analytical approach types were used at each level [10]. The simulation is carried out by ABAQUS/Standard by applying loads at various time increments during several stages. The load iteration continues until the convergence conditions are satisfied at each load increment by verifying an approximate equilibrium condition.

The stiffness matrix was modified to account for the model's nonlinear response prior to the start of the new step. The Newton Raphson equilibrium iteration method was used to find a suitable solution for each time increment [11]. The default automatic incrementation settings were utilized to automatically change the time increment sizes to effectively solve nonlinear issues by merely recommending the size of the first increment in each simulation phase.

Depending on the kind of study being done, ABAQUS provides a range of options for simulating the interface of different bodily contact components. Kinematic interactions between the various components must be described inside the finite element model to ensure strain compatibility between the various components. Stated otherwise, interactions must be defined in a way that causes one or more bodies to deform together as a result of reversing cyclic loading positioned between them. The finite element modeling in this study used two kinds of interactions. The bond between the steel reinforcement and the concrete was the first interaction.

The embedding approach, which ensures a perfect bond and displacement continuity between the concrete and steel, was used in this investigation between the reinforcement bars and the concrete. In order to roughly simulate load transfer across cracks through the rebar, the concrete model only included a simplified version of the interaction between concrete and reinforcement after cracking, such as bond slip [10, 11].

The second interactions were specified as a surface-based tie constraint, where a constraint is generated between a slave surface and a master surface on the model geometry. To prevent potential convergence issues, stiffer and coarser meshing material was assigned to the master surface. The displacements of one slave node in this method are connected to the displacements of several nodes on the master surface. Compared to previous interaction definitions, this leads to a reduction in stress discontinuities in the interaction's proximity, which are occasionally referred to as numerical distortion [10]. Since the beam and concrete body are represented by surfaces of inelastic and elastic solid bodies, tie constraints were employed to specify the interactions between these surfaces in the cyclic loading process.

The degree of element discretization and mesh size have a significant impact on the accuracy of finite element analysis outputs. The composite beam column joint models are meshed with varying element sizes to verify mesh size independence. The element type that governs the properties of the materials and explains how the structure reacts to loads is

allocated to a model during meshing. Therefore, mesh density has a significant impact on NLFEA accuracy, and the denser the mesh, the more accurate the numerical mode outputs.

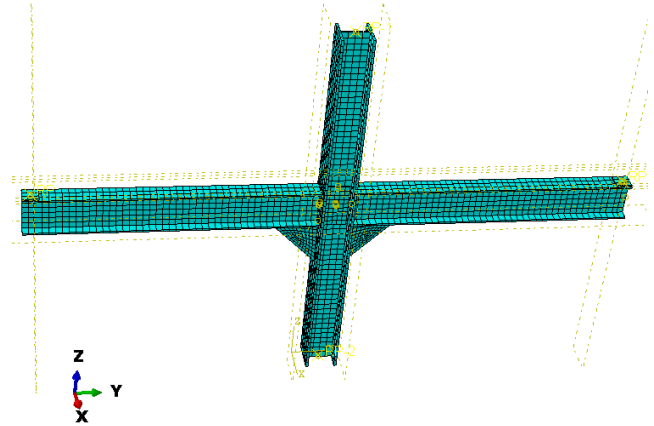


Figure 3. Cyclic loading protocol.

For the I-section of structural steel and concrete, mesh sizes of 25 mm, 35 mm, and 40 mm were utilized.

The study found that specimens with mesh sizes of 35 and 40 mm respond somewhat differently from the experimental value than specimens with other mesh sizes. However, specimens with a 25 mm mesh size need more computing time but produce more accurate results. As a result, this thesis study used a mesh size of 35 mm. According to Weight and McGregor [12], concrete exhibits elastic behavior up to 30% of its peak compressive strength under compression stress and up to its peak tensile strength under tensile loading. Concrete will permanently deform and lose its elastic stiffness if it is loaded above its elastic limit and then unloaded from the inelastic area, either from the softening portion of the stress-strain curve or from the strain-hardening portion [13]. Concrete damage plasticity (CDP), discrete crack model (DCM), and smeared crack model (SCM) are some of the materials models that have been used in the numerical modeling of concrete cracking. Shafaei et al. [14] conducted an experimental investigation of half-scale building BCJs, which were modeled by Arjmandi and Yousefi [15] the precision of the results is impacted when the mesh size is increased. The reason for this is that a larger mesh size reduces analysis time and influences the outcomes. The overall element size increases as the number of sizes decreases, requiring more time to analyze and interpret the data. Thus, the accuracy of the results is greatly impacted by the mesh size. When compared to other mesh sizes, the comparative study on the 35 mm and 40 mm mesh sizes reveals significant differences in the accuracy of the results.

3. Results and Discussions

3.1. Validated Load-displacement Response and Crack Pattern

3.1.1. Load-Displacement Response of Beam Column Joint

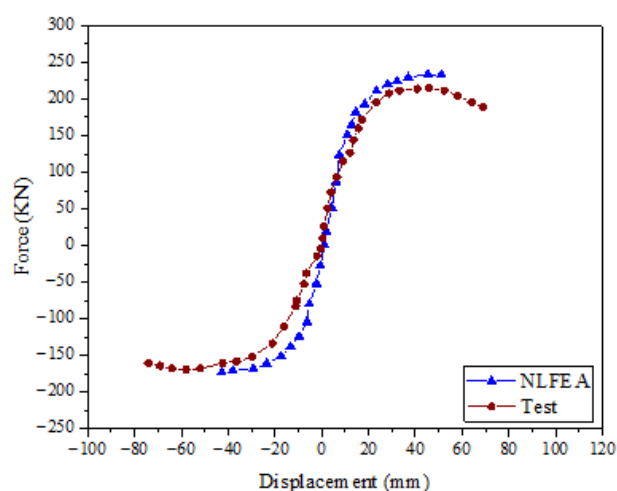


Figure 4. Cyclic loading protocol.

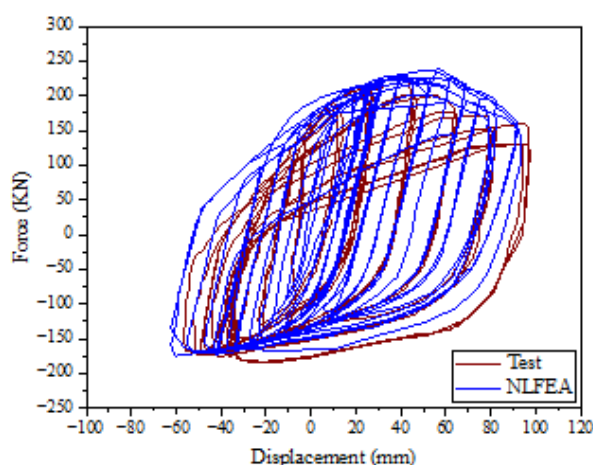


Figure 5. Cyclic loading protocol.

Load displacement result comparison in terms of hysteresis and backbone curves obtained from the nonlinear finite element analysis (NLFEA) evaluated against the experimental results of the specimen “Test G20” were displayed in Figures 4 and 5 respectively. Load displacement response of modeled specimen “Test G20” obtained by the NLFEA shows a satisfactory result similarity with the experimental results as shown in the figure. The average peak load obtained by the nonlinear finite element analysis of this specimen is 9.56% higher than the peak load presented by the

experimental result. Furthermore, after the bending and diagonal cracks occurred on the composite beam column joint area, the experimental stiffness value showed lower result compared to the finite element model analysis result. The higher stiffness in the nonlinear finite element results than the experimental results may result from more local buckling of the column flange sections reducing the stiffness of the beam column joint in the experimental test.

3.1.2. Crack Pattern and Failure Mode

Finite element model and experimental test result comparison of the specimen “Test G20” based on the formation of crack pattern and failure types also aided to confirm the applicability of the numerical models. So that, the commonly section of a composite beam column joint crack patterns in the numerical model were compared with the crack patterns observed in the experimental specimen. Figure 6 shows cracks and damages (tension and compression) at the beam column joint zone were displayed and compared with the experimental program.

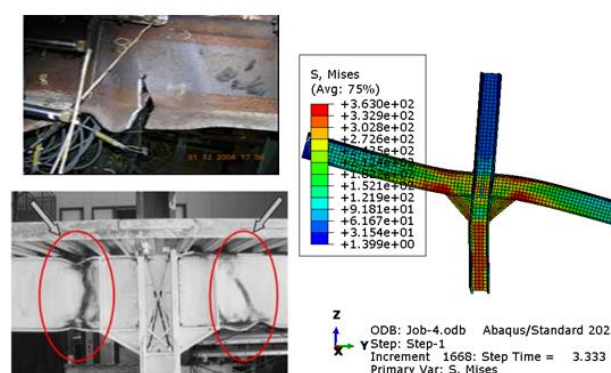


Figure 6. Cyclic loading protocol.

3.2. Parametric Study Results

3.2.1. Influence of Doubler Plate Thickness on Cyclic Behavior and Load Carrying Capacity

When evaluating the seismic performance of structural elements under cyclic stress, the load-displacement response is a crucial feature [16]. The ACI 374 cyclic loading methodology [17] is followed in this study's reversing cyclic loading simulations. When the applied cyclic drift pushes the steel beam, the loads' positive values indicate lateral resistance, and the loads' negative values indicate resistances in the opposite pull direction. Table 1 compares the peak loads of the simulated specimens with different aspect ratios. The observed ductile hysteresis response showed a decrease in rotational and shear capacity as the doubler plate thickness increased. This is in direct contrast to the behavior seen with a thinner doubler plate. This trend indicates a shift in the failure mode: the specimen with the thickest plate exhibited the predicted brittle shear failure, whereas the more ductile re-

sponse was characterized by flexural-induced shear failure.

Table 1. Summary of peak load capacities for doubler plate thickness of beam column joint.

Specimen	Peak load (KN)			Drift at peak Load (%)		Increase in peak load (%)		Average increase in peak load (%)
	Push	Pull	Average peak load (KN)	Push	Pull	Push	Pull	
	(+)	(-)		(+)	(-)	(+)	(-)	
Control	215.83	155.73	185.79	3.17	4.23	-	-	-
CBCJ-6 mm	160.71	120.44	140.25	2.02	3.40	-34		-28.13
CBCJ-15 mm	260.74	202.62	231.80	3.95	4.21	20.24	-22.7	25.78
CBCJ-20 mm	280	249.62	264.60	4.61	5.02	30.4	60.64	45.02

Effect of doubler plate thickness on stiffness and energy dissipation capacity

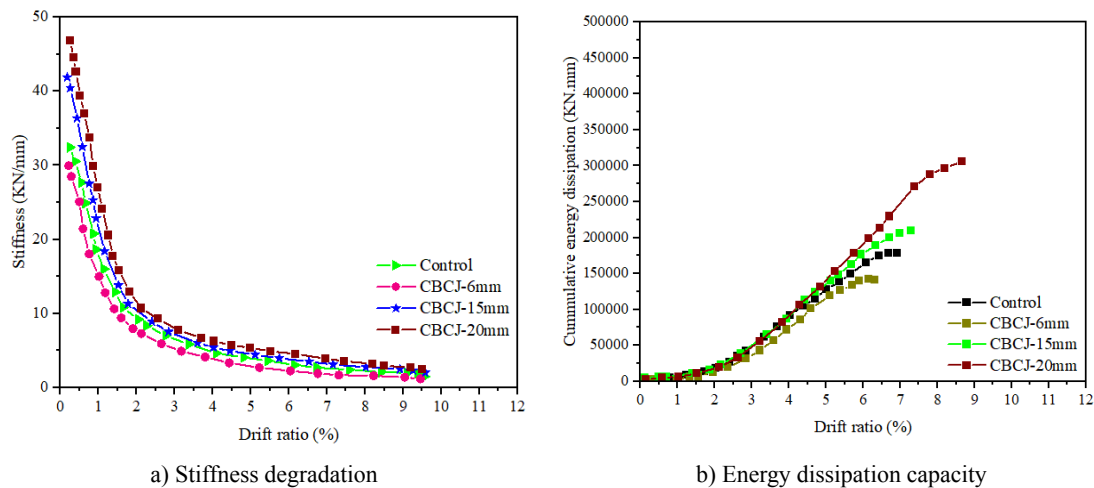


Figure 7. Stiffness and energy dissipation capacity.

Compared to the control specimen a lower rate of cyclic stiffness degradation was observed throughout the displacement cycle for CBCJ-6mm specimens. But after reaching ultimate load drift-ratio the stiffness degradation was stable and similar to the control specimen. As it can be seen from Figure 7a, specimen with lower doubler plate thickness, has less reserved stiffness values at the start of the loading cycle compared to the control specimen, however beyond 6% drift level the stiffness of these specimen exhibited almost equal to the control specimen. On the contrary, in the specimen with higher doubler plate thickness CBCJ-20mm, almost the nearest to the control specimen stiffness is observed throughout the displacement cycle than the lower plate thickness.

Figure 7b shows the cumulative energy dissipation capacity of specimens developed based on doubler plate thickness

strengthening the composite beam column joint panel zone. It is observed that all specimens dissipated a slightly the same growth of energy dissipation capacity before the drift ratio reached at 1.5% and then became larger and larger beyond 1.5% drift ratio. It can be seen from the figure that specimens developed with larger doubler plate thickness CBCJ-15mm showed better energy dissipation capacity than the specimen with lower CBCJ-6mm doubler plate thickness. The beam to column joint with highest doubler plate thickness CBCJ-20mm presented according to the simulation and shown on the graph and shows better energy dissipation capacity comparing to the other specimens. Generally the performance of composite steel beam column joint panel zone against seismic action is better at increase doubler plate thickness than smaller plate thickness.

3.2.2. Influence of Haunch Plate Thickness on Cyclic Behavior and Load Carrying Capacity

Since the haunch plate thickness significantly affected the

joint and shear capacity of the member, three specimens were used to examine its impact on the performance of the composite steel beam-column joint, as detailed in Table 2.

Table 2. Summary of peak load capacities for haunch plate thickness of beam column joint.

Specimen	Peak load (KN)			Drift at peak Load (%)		Increase in peak load (%)		Average increase in peak load (%)
	Push	Pull	Average peak load (KN)	Push	Pull	Push	Pull	
	(+)	(-)		(+)	(-)	(+)	(-)	
Control	215.83	155.7	185.79	3.17	4.23	-	-	-
CBCJ-5 mm	158.1	110.4	134.25	3.02	4.40	-26	-29.17	-27.53
CBCJ-15 mm	245.4	180.2	212.8	2.95	4.21	12.24	16.32	14.78
CBCJ-20 mm	260	230.2	245.6	2.61	4.02	20.4	48.64	34.02

When evaluating the seismic performance of structural elements under cyclic stress, the load-displacement response is a crucial feature [16]. The ACI 374 cyclic loading methodology [17] is followed in this study's reversing cyclic loading simulations. When the applied cyclic drift pushes the beam, the loads' positive values indicate lateral resistance; when the loads are negative, they indicate resistances in the opposite pull direction. A comparison of their peak loads is presented in Table 3.

Effect of Haunch Plate Thickness on Stiffness and Energy Dissipation Capacity

Figure 8a presented the peak-to-peak stiffness in terms of haunch plate thickness varied specimen from each first cycle

out of three loading cycles at each drift ratio. As shown in Figure 8a, the specimens with higher haunch plate thickness (CBCJ-20mm) were found to have a higher peak-to-peak stiffness than specimens with smaller haunch plate thickness in the early drift ratios. It was observed that stiffness degradation of specimens had a critical influence only in the initial loading cycles and the stiffness values after a 5% drift ratio of loading were approximately in the same value in specimens with different haunch plate thickness, but specimens with smaller haunch plate thickness exhibit slightly greater stiffness degradation than specimens with higher haunch plate thickness.

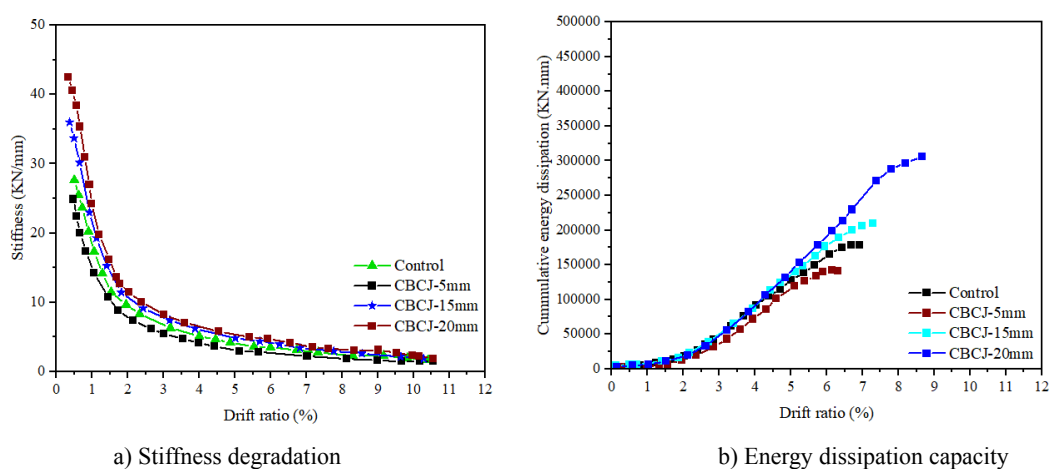


Figure 8. Stiffness and energy dissipation capacity.

The energy dissipation capacity of the specimens in terms of haunch plate thickness was presented in Figure 8b as

shown in the graph the composite beam column joint specimen supported with smaller haunch plate thickness exhibited

poor performance compared to the control specimen which was with higher haunch plate thickness. Based on the haunch plate thickness the higher energy dissipation capacity were

obtained using higher haunch plate thickness (CBCJ-20mm) as shown on the graph and lower energy dissipation capacity is observed from the smaller haunch plate thickness.

3.2.3. Influence of Haunch Configuration on Cyclic Behavior and Load Carrying Capacity

Table 3. Summary of peak load capacities for haunch configuration.

Specimen	Peak load (KN)		Average peak load (KN)	Drift at peak Load (%)		Increase in peak load (%)		Average increase in peak load (%)
	Push	Pull		Push	Pull	Push	Pull	
	(+)	(-)		(+)	(-)	(+)	(-)	
Column web	215.55	216.73	216.14	4.22	4.8	5.34	5.55	1.38
Column flange	252.61	236.64	225.65	3.56	4.61	3.81	5.17	14.13

According to Table 3, the maximum load level in the control specimen is recorded to be 252.61KN and 236.64KN, with a respective drift level of +3.56% and -4.61% in the push and pull load directions respectively. For a specimen with haunch configuration along the web the maximum load levels were recorded to be 215.55KN and 216.73KN in the

push and pull directions respectively, with corresponding drift levels of +4.22% and -4.80%. This numerical value indicate that, as the haunch plate aligned along the web the load carrying capacity reduced and the haunch plate which aligned along the column flange showed better result.

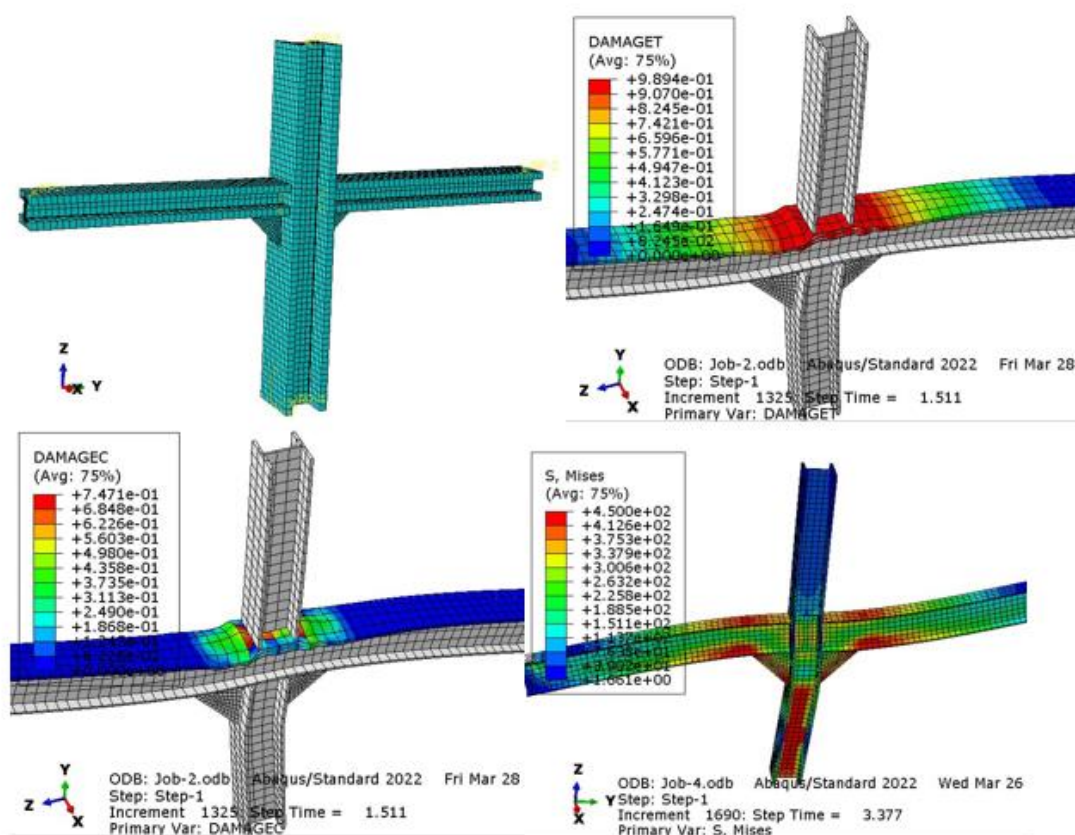


Figure 9. Meshing and finite element analysis result.

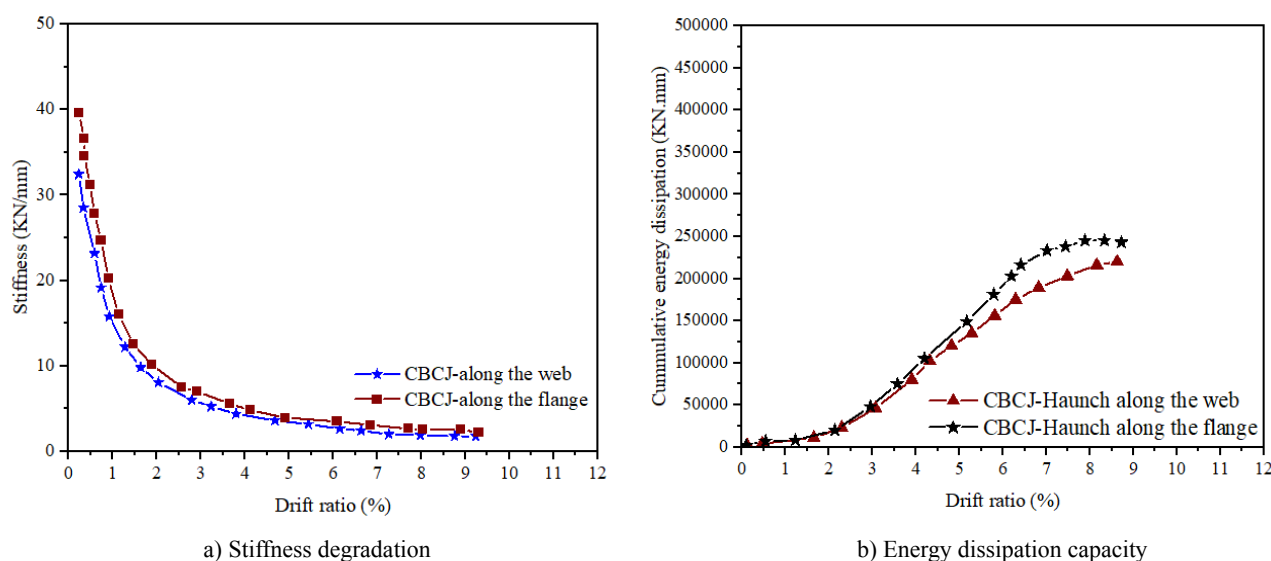


Figure 10. Stiffness and energy dissipation capacity.

Effect of haunch configuration on stiffness and energy dissipation capacity

Compared to the haunch configuration along the flange a lower rate of cyclic stiffness degradation was observed throughout the displacement cycle for specimen to which the haunch configuration is along the web. But after reaching ultimate load drift-ratio the stiffness degradation was stable and similar to the control specimen for both the configuration type. According to Figure 10a, the haunch configuration along the web with slower rate of stiffness degradation with less amount of stiffness is observed. Because of its less load carrying capacity and got less rigidity around the joint zone, consequently it has less amount stiffness. In the reverse when the composite beam column joint supported by the haunch aligned along the column flange, the joint becomes stiffer. The lower stiffness degradation rate with higher stiffness value is a desired behavior in the seismic loading condition. Figure 10b shows the cumulative energy dissipation capacity of specimens developed based on haunch configuration. It is observed that all specimens with and without haunch dissipated a slightly the same growth of energy dissipation capacity before the drift ratio reached at 1.5% and then became larger and larger beyond 1.5% drift ratio. It can be seen from the figure that specimens developed with haunch along the flange showed better energy dissipation capacity than the specimen with haunch along the web.

4. Conclusions

Final conclusion of a non-linear finite element investigation on the performance of a composite steel beam column junction under cyclic loads. In terms of load carrying capability, crack pattern/damage, stiffness degradation and energy dissipation capacity, the seismic behavior of a composite steel beam column joint evaluated. The research findings

based on the behavior of the composite beam-column joint are presented separately in the following sections. Using the nonlinear finite element analysis program ABAQUS, the study examined the effects of doubler plate thickness, haunch plate thickness, and haunch configurations of a composite steel beam column joint under cyclic loading. The findings of these numerical investigations allow for the following generalization.

- 1) The numerical model's validation showed that the non-linear finite element results are in good agreement with the experimental test result, provided that the initial stiffness of the cyclic response is slightly increased.
- 2) By employing doubler plates of varying thickness in the beam column joint panel zone, the beam column joint demonstrated enhanced seismic performance and good carrying capacity as the doubler plate thickness increased. Additionally, there was a noticeable improvement in the load supported by the beam-column joint.
- 3) According to the results of finite-element analysis, the composite steel beam column joint's load-bearing capacity was increased by 45.02% and 34.02% by employing doubler plates and haunch plates with a thickness of 20 mm. Thus, the joint panel zone was enhanced by the composite beam column joint with thicker haunch and doubler plate.
- 4) A composite steel beam column joint's stiffness and energy dissipation capacity increase as the thickness of the doubler and haunch plates raised.

Abbreviations

ACI	American Concrete Institute
CBCJ	Composite Beam Column Joint
DP	Double Plate

NLFEA	Nonlinear Finite Element Analysis
SCM	Smeared Crack Model
DCM	Discrete Crack Model

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Author Contributions

Getish Tesfaye Tsega is the principal author and Amru Abdella Halile and Kumera Daka Abajofe are the co-authors. The authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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