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Finite Element Analysis of the Stiffness of a Plug-in Device Connection with a Modified Stiffener

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ABSTRACT

Modular steel construction offers significant advantages in fabrication efficiency, installation speed, and structural adaptability; however, the performance of inter-module connections remains a critical concern, particularly under lateral loading conditions. This study aimed to evaluate the mechanical behavior and stiffness characteristics of a modified plug-in device connection incorporating a U-shaped stiffener with bolted stiffener-to-column connections. The research employed finite element analysis using ANSYS Mechanical. Numerical models were first validated against previous experimental studies using two reference connections, SC1 and SC2, before analyzing the modified model, SC_Mod. The validation results showed differences of 7% and 9% between the numerical and experimental results, confirming the acceptable accuracy of the developed models. The SC_Mod connection achieved an initial translational stiffness of 21,500.46 kN/m and rotational stiffness of 26,739.38 kNm/rad. Compared with SC1, the translational and rotational stiffness increased by 243% and 163%, respectively, while increases of 127% and 82% were observed relative to SC2. The modified connection reached a maximum load of 633.5 kN, with yielding occurring at approximately 22.6 mm deformation and failure occurring at 120.39 mm. These findings demonstrated that the bolted U-shaped stiffener configuration substantially improved connection stiffness, load transfer capacity, ductility, and constructability, making it a promising alternative for steel modular building connections while preserving the practical advantages of modular construction systems.

INTRODUCTION

Technological advances have facilitated planning and implementation processes in the construction industry, including the development of buildings using modular systems. Modular construction maximizes off-site prefabrication, where building components are manufactured in controlled factory environments and transported to construction sites in a structurally complete condition. Monash University published the Handbook for the Design of Modular Structures, which aims to provide guidance for modular building design and offer integrated solutions and practical experience for industry, government, and the public (Peng, 2021).

Modular building construction has the potential to transform the construction industry because approximately 80–95% of modules can be assembled in factories, providing various advantages, including improved time and cost efficiency (Zohourian et al., 2025). However, the application of modular systems in high-rise buildings continues to face challenges, particularly in ensuring structural performance under lateral loads caused by earthquakes and wind. In modular buildings, intermodular connections are critical components because they transfer axial forces, shear forces, and bending moments between modules, thereby influencing the overall structural behavior.

Various studies have developed modular connection systems, including welded connections, bolted connections, post-tensioned connections, self-locking connections, and plug-in device connections. Among these systems, plug-in device connections provide advantages in terms of fabrication and installation efficiency because assembly can be performed from within the module. Chen, Liu, and Yu (2017) developed a plug-in device connection and demonstrated its satisfactory structural performance through experimental testing and numerical analysis. Further research by Peng (2021) showed that the Finite Element Method (FEM) could effectively represent connection behavior with acceptable accuracy after validation against experimental results. Several review studies have also summarized developments in modular building connections. Rajanayagam et al. (2021) provided a comprehensive review of various modular connection systems, while Lacey et al. (2018) and Ye et al. (2021) reviewed the structural response and stability of multi-story modular buildings, respectively. Furthermore, Chen et al. (2019) investigated the rotational stiffness of intermodular connections, while Chen et al. (2021) reviewed the development of self-locking connections in steel modular buildings, and Sendanayake et al. (2021) examined improvements in lateral performance through innovative intermodule connection configurations.

However, previous studies have generally focused on evaluating existing connection performance, including stress distribution, deformation behavior, ultimate capacity, and failure mechanisms. The development of modified connection configurations to improve stiffness characteristics remains relatively limited. In addition, modifications to stiffener-to-column connections, such as replacing welded connections with bolted connections to better align with modular construction principles, have not been extensively investigated. This condition indicates a research gap regarding the influence of connection configuration modifications on the stiffness characteristics and mechanical behavior of modular connections.

Based on these considerations, this study proposed a modified plug-in device connection by incorporating a stiffener connected to the column using bolts. The analysis was conducted using the Finite Element Method, beginning with validation of the numerical model against previous experimental results. The modified connection was then evaluated based on translational stiffness, rotational stiffness, stress distribution, deformation characteristics, and failure mechanisms to determine the effects of the proposed modifications on connection performance. The novelty of this study lies in developing a modified plug-in device connection configuration by adding a stiffener while changing the stiffener-to-column connection system from welded to bolted connections. Unlike previous studies that primarily evaluated plug-in device connections in their original configurations, this study investigated the effects of these modifications on translational stiffness, rotational stiffness, stress distribution, deformation behavior, and failure mechanisms through finite element analysis.

Based on this background, the research problem was formulated as follows: determining the mechanical behavior of a modified plug-in device connection with a bolted stiffener connection based on finite element analysis and evaluating the influence of the modification on stress distribution, deformation, and failure mechanisms. Accordingly, this study aimed to analyze the mechanical behavior of the modified plug-in device connection using the Finite Element Method and identify the stress distribution, deformation patterns, and failure mechanisms occurring in the modified connection. The study was limited to a single intermodular connection specimen subjected to monotonic loading using ANSYS Mechanical software. It did not consider fabrication processes, welding defects, installation tolerances, corrosion effects, fatigue behavior, temperature variations, or global structural behavior of modular buildings. The results were expected to provide a reference for developing modular connection designs with improved mechanical performance while maintaining the advantages of fabrication efficiency, installation ease, and dismantling capability in accordance with modular construction principles.

This research was expected to provide scientific and practical contributions. Scientifically, the study contributed to the development of plug-in device modular connections through geometric modification by adding stiffeners and implementing bolted stiffener-to-column connections based on Finite Element Method analysis. It also provided information regarding the mechanical characteristics of modified connections, including translational stiffness, rotational stiffness, stress distribution, deformation behavior, and failure mechanisms. Practically, the findings could serve as a reference for academics, researchers, and construction practitioners in evaluating modular connection designs using finite element analysis. Furthermore, the results could support future research on modular connection configuration optimization and the development of improved plug-in device connection systems that enhance mechanical performance while maintaining construction efficiency.

METHOD

This research began with a literature review to establish the theoretical foundation, analytical methods, and recent developments in steel modular buildings and intermodular connection (IMC) systems. The review also examined finite element analysis (FEA) approaches for evaluating rotational stiffness, moment capacity, stress distribution, and connection failure mechanisms. Furthermore, the literature review was used to determine numerical modeling parameters in ANSYS Mechanical, including connection geometry, material properties, boundary conditions, contact definitions, loading conditions, and model validation procedures. The overall research stages followed the workflow presented in Figure 1.

Figure 1. Research Flowchart

Local Connection Modeling Using the Finite Element Method

Local connection modeling was performed using the finite element method to obtain failures that approximate the experimental test results. The modeling was based on the research of Chen, Liu, & Yu (2017) for a modular connection specimen with a plug-in device (SC1) and Peng (2021) for a modular connection specimen with a plug-in device using a stiffener (SC2). Both studied connections were remodeled and the results were validated so that the developed models could be used as the basis for modeling a modified connection (SC_Mod), namely a plug-in device connection with the addition of a U-shaped stiffener connected to the column using bolts, replacing the welded connection in the reference model. The specifications of the three models are presented in Table 1.

Table 1. Finite Element Modeling Specifications for the Three Connection Models

Model	Element Component	Fy (MPa)	Fu (MPa)	Cross-Section Dimension
SC1	Column	465	600.3	HSS 150x150x8
SC1	Floor Beam	465	600.3	HSS 150x250x8
SC1	Roof Beam	465	600.3	HSS 150x150x8
SC1	Beam Connection Plate	465	600.3	Plate 150x430, t=16mm
SC1	Plug-in Device	465	600.3	HSS 128x128x20
SC1	Bolt	640	749	M24 Grade 8.8
SC2	Column, floor/roof beam, connection plate, plug-in device, bolt	465–640	600.3–749	Same as SC1
SC2	Stiffener	465	600.3	Plate, t=16mm (welded connection)
SC_Mod	Column, floor/roof beam, plug-in device	465	600.3	Same as SC1
SC_Mod	Beam & column bolt	640	749	M24 Grade 8.8
SC_Mod	Column connection plate	465	600.3	Plate, t=10mm
SC_Mod	Stiffener (modified)	465	600.3	U-profile, t=10mm (bolted connection)

Steel Material Model

The behavior of steel is modeled nonlinearly using the true stress–true plastic strain relationship in ANSYS Mechanical, which provides a more realistic representation than engineering stress–strain because it considers the actual cross-sectional area changes during plastic deformation. According to Wang et al. (2021), the strain hardening, stress, and ultimate strain values for high-strength steel are obtained through equations (1) - (3):

$$\varepsilon_h = 0{,}032 - 0{,}01(f_u/f_\gamma) \quad \dots (1)$$

$$f_u = 205 + 0{,}85 f_\gamma \quad \dots (2)$$

$$\varepsilon_u = (1 + f_\gamma/315) \quad \dots (3)$$

where f_γ is the steel yield stress (MPa), ε_h is the hardening strain, f_u is the ultimate stress of the steel (MPa), and ε_u is the ultimate strain. The conversion of engineering stress-strain data to true stress-true strain was performed using the equations $\varepsilon_t = \ln(1+\varepsilon)$ and $\sigma_t = \sigma(1+\varepsilon)$ following ANSYS (2022), resulting in a more accurate representation of material behavior in nonlinear plastic analysis.

The selection of the true stress-true plastic strain approach in this study was based on the consideration that the plug-in device connection experienced significant plastic deformation in the critical region before reaching failure, as shown in the analysis results of the SC_Mod model, which reached a maximum deformation of 120.39 mm. Under these high strain conditions, the use of the engineering stress-strain model has the potential to produce inaccurate capacity estimates because it does not account for the reduction in cross-sectional area (necking) that occurs with increasing plastic strain. Thus, the use of the true stress-strain relationship in this study is consistent with the approach recommended by Wang et al. (2021) for the nonlinear analysis of high-strength steel materials under loading conditions close to the ultimate state.

Element Mesh and Interactions Between Elements

Mesh control was applied with a hexagonal pattern to all structural components (columns, beams, bolts, and connections) in accordance with Peng (2021), using C3D8R solid elements (eight-node three-dimensional solid elements with reduced integration methods and hourglass control features), in line with the approach of Ma, Xia, Chang, & Xu (2021) who used similar elements in ABAQUS software. Referring to the model simplification by Khan & Yan (2020), which showed a difference in numerical results of only 5% between solid elements and beam elements, this study used shell elements in ANSYS to streamline the computational process.

The contact interactions between elements refer to Khan & Yan (2020), namely surface-to-surface contact with finite sliding settings, hard contact in the normal direction, and a penalty friction formulation in the tangential direction. A comparative study of three friction coefficient values (0.2, 0.3, and 0.4) showed that 0.2 resulted in a lower load capacity than the experimental results, while 0.4 provided a higher load capacity. The 0.3 value was subsequently selected as the optimal friction coefficient for the contact surfaces, except for the bolt contact, which was modeled frictionless. The contact between the plug-in device and the sliding column used frictionless contact, while the welded joint contact used bonded contact.

The use of shell elements in this study also considered computational efficiency, considering that the nonlinear analysis process with inter-element contact and loading up to failure requires a significant number of solver iterations. With a maintained level of accuracy—as indicated by the difference in the validation results of the SC1 and SC2 models against experimental data which is below 10%—this model simplification approach is considered adequate for use in the initial development and evaluation stages of connection configuration modifications, before continuing with more detailed modeling and experimental testing in the next research stage.

Boundary Conditions, Loading, and Validation Criteria

Referring to Peng (2021), Chen et al. (2017), and Khan & Yan (2020), movement restrictions were applied to the column ends in the lateral and vertical directions, while the beams were restricted in the vertical direction and against rotation. The applied loads consisted of controlled lateral displacement loads in the longitudinal direction and axial loading using a ratio of 0.2 to the structure's yield capacity of 1430 kN. The failure pattern of the FEM model was validated against failure patterns from previous experimental tests (Chen, Liu, & Yu, 2017; Dai et al., 2024) as a requirement for model validity before being applied to the modified model. The initial translational stiffness value was obtained from the initial slope of the force-to-displacement curve, while the initial rotational stiffness value was obtained from the initial slope of the moment-to-rotation curve from the finite element analysis.

Failure Pattern Verification as a Validation Criterion

In addition to comparing force-displacement curves, FEM model validation also considers the agreement of failure patterns with experimental results as an additional criterion. Dai et al. (2024), who studied modular joints using stiffeners, demonstrated that the failure patterns between the experimental results and the FEM model were similar, namely the occurrence of local buckling at the floor beam support area. Similarly, Chen, Liu, & Yu (2017) conducted experimental testing on modular joints and compared them with the FEM model results, which showed a failure pattern consisting of fracture at the stiffener welded joints. The agreement of the failure patterns in these two reference studies reinforces the premise that the finite element modeling approach, element types, meshes, contact conditions, and boundary conditions applied in this study are appropriate for representing the actual behavior of modular joints before being applied to the SC_Mod model.

Supporting Software

This study used ANSYS 2022 software to model modular joints to obtain translational and rotational stiffness values, both during the model validation stage (SC1 and SC2) and during the analysis stage of the modified model (SC_Mod). All modeling stages, starting from determining geometry, material properties, contact conditions, boundary conditions, loading, to extracting force-displacement and moment-rotation curves, are carried out in an integrated manner in the software.

RESULTS AND DISCUSSION

Material Model and Data Validation

The material in the finite element model uses a nonlinear approach, referring to Wang et al. (2021) and ANSYS (2010). The material stress and strain values, both in the form of engineering stress-strain and true stress-strain, are obtained using equations (1)–(3), as presented in Table 2. The true stress-strain model is used because it can accommodate changes in cross-sectional area after the material experiences necking, thus providing a more realistic representation of material behavior under high strain conditions.

Table 2. Stress and Strain Values for Steel Material

σ Engineering (MPa)	ε Engineering	σ True Stress-Strain (MPa)	ε True Stress-Strain
0	0	0	0
465	0.002325	466.0811	0.002322
465	0.019091	473.8775	0.018911
600.3	0.130013	678.2901	0.122229
600.3	0.231325	739.1031	0.208091

FEM Model Validation Against Experimental Tests

Validation was conducted on two reference models, SC1 (Chen, Liu, & Yu, 2017) and SC2 (Peng, 2021), by applying monotonic loading in the form of a 12 mm displacement to the top column of the specimen. Based on previous experimental tests, the SC1 model failed at the beam-column weld, while the SC2 model failed at the stiffener-column weld. The FEM modeling results for both models indicated failure locations consistent with the experimental results, characterized by stress concentration in the weld area and the formation of a gap between the plug-in device and the top column.

Comparison of the FEM-derived force-displacement curves with the experimental results revealed a difference of 7% in the SC1 model and 9% in the SC2 model. Therefore, both FEM models were deemed valid (less than 10%) for use as a basis for modeling modified joints. The results of the ultimate moment and rotation at the validation points of both models are presented in Table 3.

Table 3. Results of FEM Model Validation against Experimental Tests

Model	Failure Location (Experimental)	Ultimate Moment (kNm)	Rotation (rad)	Difference FEM vs Experimental
SC1	Beam-column weld connection	239.52	0.074	7%
SC2	Stiffener-column weld connection	363.64	0.082	9%

Modified Connection Behavior (SC_Mod)

The SC_Mod model uses the same main cross-section as models SC1 and SC2, with modifications such as changing the stiffener shape to a U-shaped profile and replacing the stiffener-column welded connection with a bolted connection. Monotonic loading with displacement control was applied until failure was reached. In the initial loading stage, the column entered a plastic state when the load reached a displacement of 22–22.6 mm with a force of 474.15 kN, characterized by stress beginning to appear in the column region adjacent to the stiffener. When deformation increased to 49 mm, the material reached a fully plastic state with a maximum load of 633.5 kN, accompanied by local buckling at the connection between the stiffener and the column. Final failure was characterized by maximum stress in the tension zone between the stiffener and the column, with the maximum deformation at failure reaching 120.39 mm. The von Mises stress in this critical region reached 760 MPa, well above the material's yield stress of 465 MPa, indicating that the material in this region had undergone significant plastic deformation before structural failure occurred.

The loading stages in the SC_Mod model demonstrate a sequence of structural behavior typical of ductile steel elements: beginning with the elastic phase, followed by an initial yielding phase at a deformation of approximately 22–22.6 mm, then a strain hardening phase until a maximum load of 633.5 kN is reached at a deformation of 49 mm, and ending with a post-peak softening phase until the structure fails at a deformation of 120.39 mm. The relatively long deformation range between the maximum load and final failure indicates that the SC_Mod connection has sufficient ductility capacity, allowing the structure to absorb additional energy before total collapse. This characteristic is important in the context of modular buildings that are potentially subject to cyclic lateral loads due to earthquakes, as the connection's ductility capacity also determines the structure's ability to deform without sudden loss of load-bearing capacity.

Comparison of Connection Stiffness Characteristics

A comparison between the three connection models shows that the SC_Mod model has a higher ultimate load than the two reference connections (SC1 and SC2). The translational stiffness (k_0) and rotational stiffness ($S_{j,ini}$) values for the three models are presented in Table 4.

Table 4. Comparison of Stiffness Values for the Three Connection Models

Model	k_0 – Translation Stiffness (kN/m)	$S_{j,ini}$ – Rotational Stiffness (kNm/rad)
SC1	6,272.66	10,155.46
SC2	9,463.99	14,714.63
SC_Mod	21,500.46	26,739.38
Increase of SC_Mod vs SC1	243%	163%
Increase of SC_Mod vs SC2	127%	82%

Table 4 shows that the highest translational and rotational stiffness values were obtained by the SC_Mod model, at 21,500.46 kN/m and 26,739.38 kNm/rad, respectively. Compared to the SC1 model, the SC_Mod connection increased translational stiffness by 243% and rotational stiffness by 163%, while compared to the SC2 model, the translational and rotational stiffness increased by 127% and 82%, respectively. These improvements indicate that the addition of a bolted U-shaped stiffener to the SC_Mod model improved the connection's ability to transfer forces and moments while reducing deformation caused by loading compared to the reference model's connection configuration.

The greater increase in translational stiffness compared to rotational stiffness indicates that the stiffener modification in this study was more effective in increasing the connection's ability to withstand translational deformation than rotational deformation, although both stiffness parameters still showed significant increases. In terms of failure mechanisms, the change in failure location from welded joints (in models SC1 and SC2) to the column area around the stiffener (in model SC_Mod) indicates that replacing welded joints with bolted joints successfully shifted the critical failure point away from the connection elements, potentially improving connection reliability while maintaining ease of installation and disassembly in accordance with modular construction principles.

Implications of the Change in Failure Mechanisms

The differences in failure mechanisms between the reference and modified models have important implications for the development of modular connection designs. In model SC1, failure occurred at the beam-column welded joint, while in model SC2, failure occurred at the stiffener-column welded joint; both conditions indicate that the welded joint element remains the weakest point in the reference configuration. Conversely, in the SC_Mod model, which uses bolted joints at the stiffener-column connection, failure shifted to the column area around the stiffener, with the von Mises stress exceeding the material's yield stress before the structure experienced full failure at a deformation of 120.39 mm. This shift in failure location is consistent with the capacity design principle of earthquake-resistant structures, where brittle connection elements such as welds are replaced by failure mechanisms in the main structural elements that tend to be more ductile, thus potentially increasing the overall reliability of the connection.

In terms of ease of construction, replacing welded joints with bolted joints at stiffener-column connections also aligns with the basic principles of modular construction, namely ease of fabrication, installation, and demountability. Welded joints are permanent and require skilled labor and strict welding quality control in the field, while bolted joints can be fabricated more precisely in the factory and installed more quickly on-site. Therefore, the results of this study demonstrate that modifying stiffeners with bolted joints not only increases the mechanical stiffness of the joints but also maintains—and potentially even improves—the ease of construction, one of the main advantages of modular systems over conventional construction.

Overall, the results of the finite element analysis in this study are consistent with the findings of Peng (2021) that adding stiffeners to plug-in device connections can increase joint stiffness compared to the configuration without stiffeners (SC1). This study extends these findings by demonstrating that further modifications to the stiffener shape and a change in the stiffener-column connection method from welded to bolted resulted in even greater stiffness increases compared to the SC2 model, thus strengthening the argument that stiffener configuration details—not just their presence—play a critical role in determining the final stiffness characteristics of plug-in device modular connections.

Positioning of Findings in the Context of Modular Connection Research Developments

The findings of this study are also relevant in the broader context of developing research on steel modular building connections. Several previous review studies, such as those by Rajanayagam et al. (2021) and Tsavdaridis & Corfar (2022), have identified that developing connection types that combine ease of installation with adequate structural stiffness remains a major challenge in inter-modular connection design. Research on bolt-based connections, such as that reviewed by Deng et al. (2018) on bolted connections with welded cover plates, and self-locking connections developed by Nadeem et al. (2021) demonstrates a similar research trend, namely the shift in connection mechanisms from welded elements to mechanical elements that are easier to assemble and disassemble. The results of this study reinforce this trend by providing quantitative evidence that replacing welded stiffener-column connections with bolted connections, combined with modified stiffener shapes, can result in significant increases in translational and rotational stiffness without compromising ease of construction.

From a building-scale perspective, various previous studies on the performance of modular buildings—both from a sustainability perspective (Abdul Nabi & El-Adaway, 2020), construction decision-making perspectives (Abdul Nabi & El-Adaway, 2020; Hwang & Kim, 2022), and the development of connection technology in general (Hu et al., 2025; Ahmed et al., 2025; Ghuge & Kale, 2026)—consistently place connection stiffness as a key parameter determining the feasibility of implementing modular systems in high-rise buildings. In line with this, the translational and rotational stiffness improvements obtained in the SC_Mod model in this study provide a quantitative indication that the proposed stiffener modification has the potential to support the application of plug-in device connections in taller steel modular building configurations, although further evaluation at the global structural level—as proposed in the suggestion section—is still needed to confirm its effect on the overall seismic response of the building.

CONCLUSION

Based on the finite element analysis results of the plug-in device connection with modified stiffeners, it can be concluded that modifying the connection geometry by adding U-shaped stiffeners connected using bolts significantly improved the stiffness characteristics of the connection compared with the reference connections. The modified configuration produced a stiffer structural response and enhanced resistance to deformation under loading conditions. The SC_Mod model achieved an initial translational stiffness of 21,500.46 kN/m and an initial rotational stiffness of 26,739.38 kNm/rad, representing increases of 243% in translational stiffness and 163% in rotational stiffness compared with the SC1 model, as well as increases of 127% and 82%, respectively, compared with the SC2 model. These results indicate that the proposed geometric modification improved force and moment transfer efficiency within the connection.

In the SC_Mod model, material yielding occurred at a deformation of 22.6 mm, while structural failure occurred at a deformation of 120.39 mm, with the von Mises stress in the critical region reaching 760 MPa. The finite element method (FEM) model was also able to accurately represent the mechanical behavior of the modified plug-in device connection, with differences of 7–9% compared with experimental results during the validation stage. Therefore, this approach can be applied as a numerical method for evaluating the stiffness characteristics of modular connections prior to experimental testing. Based on these findings, the addition of stiffeners using bolted stiffener-to-column connections is recommended as an effective alternative modular connection design to improve structural stiffness while maintaining fabrication and installation efficiency. Further research is recommended to investigate the influence of this connection modification on the global seismic response of modular building structures, while also considering fabrication processes, installation tolerances, and fatigue effects that were beyond the scope of this study. Such investigations would support the broader application of optimized connection designs in high-rise steel modular construction.

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