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Finite Element Modelling on The Tensile Performances of Boxed-Flange Cold-Formed Steel C- Section Connections

Fatin Khadijah Nazeri[1], A F Kamarudin[1]*

[1] *Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*

*Corresponding Author: fahmy@uthm.edu.my
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Abstract

Cold-formed steel (CFS) has gained significant attention due to its high strength-to-weight ratio, cost-effectiveness, and ease of fabrication. This study focuses on finite element modeling (FEM) of boxed-flange connections in CFS C-sections under tensile loading, using WELSIM software to simulate structural behavior. The research validates FEM results against experimental data, performs a parametric study on steel thickness and number of screws, and compares failure modes to optimize connection design. The findings indicate that increasing steel thickness and screws enhances load-bearing capacity and delays failure onset. The FEM model predicted a yield load of 24.23 kN for 1.00 mm thick connections with 4 screws, closely matching the experimental result of 23.50 kN. For 0.75 mm thick connections with 2 screws, the FEM model predicted 6.87 kN, compared to the experimental 7.00 kN. These results validate the efficiency of numerical modeling for structural optimization.

1. Introduction

The construction industry increasingly demands lightweight, cost-effective, and energy-efficient structural systems. Among the preferred materials is cold-formed steel (CFS), owing to its high strength-to-weight ratio and ease of fabrication (Hancock et al., 2003). CFS has gained wide acceptance in structural engineering due to its exceptional strength, lightweight nature, and efficiency in both design and construction. Produced through cold-working techniques—such as rolling, stamping, or bending at room temperature—CFS sections, especially C-, Z-, and box-shaped profiles, are commonly used for columns, beams, and floor systems in residential and commercial structures (Hancock et al., 2003; Pham et al., 2017). According to Chen (2012), the cold-forming process, particularly roll forming, allows steel to gradually acquire its final shape through a series of rollers, enhancing both precision and structural performance. These thin-walled elements offer excellent mechanical behavior, especially when used as built-up or boxed members. Liang et al. (2022) further emphasize that CFS offers several advantages over conventional hot-rolled steel, including greater dimensional accuracy, reduced material usage, and easier installation due to its lighter weight. The widespread use of CFS in framing systems and load-bearing walls highlights its role as a cost-effective and versatile solution in modern structural design.

CFS members, shaped into C-sections, Z-sections, and hat-sections, are widely used in residential, commercial, and industrial buildings (Yu et al., 2005). Connections are crucial in maintaining the structural integrity of CFS systems by effectively transferring loads. Boxed-flange connections, which reinforce C-section flanges using plates or stiffeners, improve tensile strength by increasing load capacity and reducing local buckling (Pham et al., 2017). Their performance depends on several factors such as section geometry, material properties, and loading conditions (Uzzaman et al., 2023). Understanding these parameters is essential for optimizing CFS structural systems. According to Martir and Estores (2023), bearing is not primarily controlled by a sufficiently large edge distance, the strength of the material, the diameter of the fastener, but also member thickness and the type of connection. Connection is the physical element that mechanically fastens the structural components and is concentrated where the fastening action occurs (Ye et al., 2020).

Experimental testing of boxed-flange connections can be both costly and time-consuming, often limited by the availability of test specimens. Finite element (FE) modeling offers a practical alternative, allowing for detailed parametric studies. A validated FE model enables in-depth evaluation of tensile performance across different geometric and material configurations, revealing insights that may be difficult to capture experimentally. Variables such as material thickness, connection design, and the number of fasteners significantly influence the load-bearing capacity and failure behavior of boxed connections, but their exact effects remain only partially understood. Therefore, a comprehensive FE analysis is essential for improving connection design and enhancing structural reliability.

This study aims to validate an FE model for CFS boxed-flange connections subjected to tensile loading, examine the influence of thickness and screw quantity, and compare the associated failure modes. The findings are expected to deepen the understanding of boxed connection behavior and contribute to the development of more efficient and reliable structural systems.

2. Methodology

To ensure the accuracy and reliability of this study, the methodology is structured into five key phases, as illustrated in the flowchart as shown Figure 1. These phases provide a systematic approach to analyzing the tensile behavior of cold-formed steel (CFS) boxed connections using finite element analysis (FEA) in WELSIM.

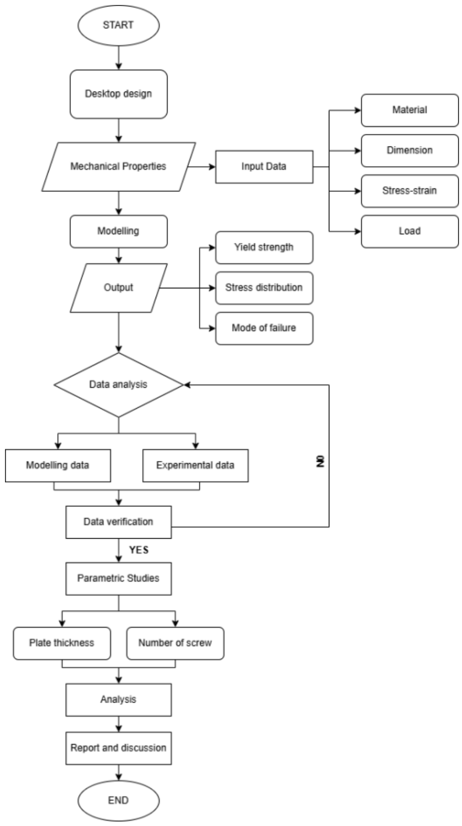

Fig. 1 *Flowchart for the methodology of the study*

The study begins with data collection to establish accurate input parameters for the numerical model. Mechanical properties of the cold-formed steel (CFS), including Young's modulus, Poisson's ratio, yield strength, and ultimate tensile strength, are gathered. Additionally, precise measurements of the C-section dimensions, box confinement, and screw hole sizes are recorded. This phase ensures that the numerical model is based on realistic material properties and geometric details.

Next, a finite element model is developed in WELSIM to simulate the behavior of the boxed connection under tensile loads. The built-up section is designed using stiffening plates connected by screws, with variations of two or four screws per connection. Key factors such as connection geometry, overlap length, fastener spacing, and

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boundary conditions are carefully considered to capture stress distribution and possible failure modes, including yielding and connection failure.

To verify the model's accuracy, simulation results are compared with experimental data from literature or laboratory tests. The validation process assesses parameters such as load-deformation behavior, stress distribution, and observed failure mechanisms. If discrepancies arise, refinements are made to material properties, boundary conditions, or meshing strategies to improve the model's reliability.

Once validated, a parametric study is conducted to examine the effects of plate thickness and the number of screws on the connection's tensile performance. The results are analyzed, highlighting stress distribution, deformation patterns, and failure mechanisms. Findings are then compared with industry standards to ensure compliance with engineering guidelines. The study provides insights into optimizing CFS boxed connections, contributing valuable knowledge for structural applications.

2.1 Sample Preparation

For this study, WELSIM software is utilized to generate the numerical model and simulate the tensile test. The testing involves different sample specimens, categorized based on their thickness and screw configuration, as summarized in Table 1.

Table 1 *Sample specimen with labelling*

Thickness of CFS c-section (mm)	No. of screw (nos)	Specimen labelling
	2	C075-2
		C100-2
0.75	4	C075-4
1.00		C100-4
	6	C075-6
		C100-6

2.2 Tensile Stress

Type of analysis carried out is to determine the tensile properties of the screw fastener. Tensile stress is calculated by using the Equation 1 below.

$$\sigma = F/A \tag{1}$$

Where:
σ is the tensile stress
F is the applied yield and ultimate force
A is the cross-sectional area of the screw fastener

2.3 Tension Resistance

The tension resistance of a member is determined by its cross-sectional area and material strength as Equation 2 below. According to Eurocode 3:

$$N_{t,Rd} = \frac{F_{ya}A_g}{\gamma_{M0}} \tag{2}$$

Where:
F_{ya} is the average yield strength
Ag is the gross area of the cross-section

2.4 Shear Resistance

The shear resistance of structural elements can be determined using Equation 3 below.

$$N_{v,Rd} = 0.6 \times Pu_{screw} \tag{3}$$

Where:
$F_{v,Rk}$ is the characteristic shear strength of the screw

2.5 Bearing Resistance

Bearing resistance can be calculated using Equation 4 below.

$$F_{b,Rd} = \frac{\alpha f_u dt}{\gamma_{M2}} \quad (4)$$

Where:
fu is the tensile strength
α is the effective length of the screw in the direction of the tensile force

2.6 Screw Connection

The design of screw connections follows guidelines outlined in EN 1993-1-8. The shear and tensile capacities of screws must be evaluated based on their diameter, spacing, and arrangement. The shear resistance of screws can be calculated using Equation 5 below.

$$F_{v,Rd} = min(F_{p,Rd}, F_{b,Rd}) \quad (5)$$

Where:
$F_{p,Rd}$ is pull-out resistance
$F_{b,Rd}$ is bearing resistance

2.7 Design Layout

The layout design builds upon the desktop design phase, where all parameters are systematically calculated and applied to the sample layout as specified. Based on previous tensile studies, Figures 2 illustrate connection configurations utilizing two screws and four screws. These figures present detailed plan, side, front, and isometric views, with all dimensions clearly specified to ensure accuracy in the analysis.

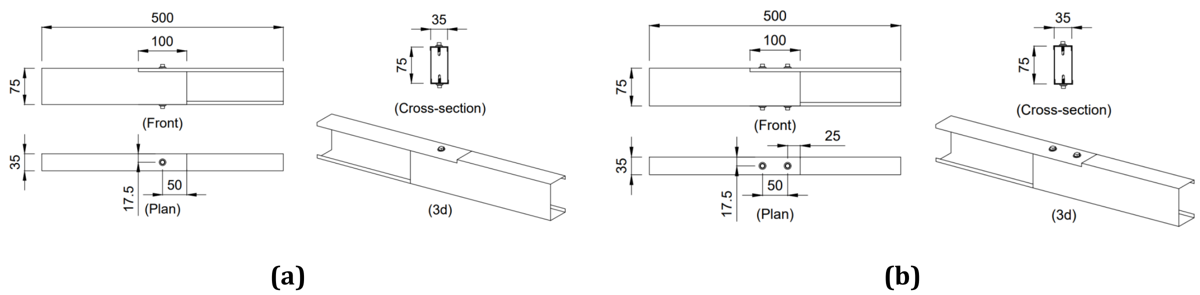


Fig. 2 *Design layout (a) Sample with 2 screw; (b) Sample with 4 screw*

2.8 Numerical Modelling

The numerical analysis of cold-formed steel (CFS) boxed-flange connections was conducted using WELSIM, a nonlinear finite element software that simulates structural behavior and failure mechanisms. This software allows for the evaluation of deformation, stress, strain, and buckling behavior. The model was developed based on previous experimental research to ensure accuracy. After validation against experimental data, additional simulations were performed by varying key parameters. WELSIM was used to account for nonlinear effects, time-dependent behavior, and plasticity. The modeling process focused on five main aspects: geometry, material properties, boundary conditions, loading, and contact interactions.

2.9 Geometry

In numerical modeling, geometry defines the structure's shape and physical characteristics, represented using line, plate, or solid elements. For the cold-formed steel (CFS) boxed-flange connections, a 3D model was developed in SolidWorks, incorporating actual surface dimensions and cross-sectional details. As shown in Figure 3, the geometry consists of C-sections and screws. A tetrahedral element type was used for discretization, with each element having four nodes and three degrees of freedom. To ensure accurate meshing, an adaptive refinement technique was applied, with mesh sizes ranging from 10 mm to 50 mm. The discretization of the CFS boxed-flange connections is illustrated in Figure 4.

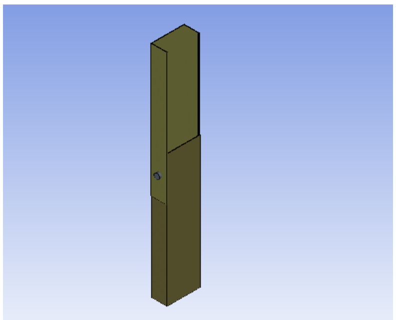


Fig. 3 *The three-dimensional model of CFS boxed-flange connections*

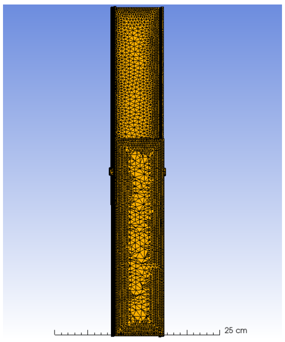


Fig. 4 *Discretization of CFS boxed-flange connections*

2.10 Material Properties

In WELSIM, the material properties of cold-formed steel (CFS) boxed-flange connections were defined using a plasticity model, incorporating both general and hardening properties. In the elastic region, the connection's strength depended on its general properties. Once the material reached its yield stress, strain hardening followed, represented by the stress-strain curve. Table 2 summarizes the general properties of CFS, while Table 3 details the material properties of carbon steel screws. Additionally, Table 4 presents the hardening properties based on the multilinear kinematic hardening approach.

Table 2 *Mechanical properties of cold-formed steel (EN 1993-1-3:2006 Eurocode 3)*

Mechanical Properties	Value
Young modulus (E)	200 GPa to 220 GPa
Poisson's ratio (ν)	0.3
Yield strength (f_y)	210 MPa to 550 MPa
Ultimate yield stress (f_u)	320 MPa to 550 MPa
Density (ν)	7850 kg/m^3

Table 3 *Material properties of carbon steel screws (EN1993-1-1, Clause 3.2.6)*

Property	Value
Density	7850 kg/m^3
Poisson's ratio (ν)	0.3
Young Modulus (E)	210 GPa
Bulk Modulus	166667 MPa
Shear Modulus	76923.1 MPa

Table 4 *Hardening properties of CFS boxed-flange connections*

True Strain, ε_T (%)	True Stress, σ_T (MPa)
0.000	0.00
0.005	309.43
0.009	521.29
0.010	580.16
0.012	592.13

2.11 Constraint

In numerical modeling, constraints define boundary conditions to ensure stability and accuracy in finite element analysis. For the CFS boxed-flange connections, a fixed support was applied at the bottom, restricting movement in all directions (x, y, and z axes) to simulate real experimental conditions. This setup prevented displacement while allowing reaction forces to develop at the constrained area. No constraints were applied at the top or along the height, allowing natural deformation under loading.

2.12 Contact Surface

To ensure proper interaction between components, contact surfaces must be accurately assigned in numerical modeling. In WELSIM, three types of contact surfaces are available: perfect bonded, friction, and frictionless. For the CFS boxed-flange connections, a perfect bonded contact was used to ensure efficient energy transfer and structural stability under incremental compression loads. To prevent convergence issues, the C-section was set as the master, while the steel plate and rivets were designated as targets, minimizing the risk of sliding or separation.

3. Result and Discussion

This chapter presents the Finite Element Analysis (FEA) results using WELSIM to evaluate the structural performance of boxed-flange cold-formed steel C-section connections. The analysis considers different thicknesses (0.75mm, 1.00mm) and screw configurations (2, 4, and 6 screws). The FEA model was validated by comparing the results with experimental data.

3.1 Validation of finite element model

The accuracy of the finite element model was evaluated by comparing the yield strength (Fy) and displacement (d) from WELSIM simulations with experimental data. Table 5 summarizes the percentage differences between the numerical and experimental results.

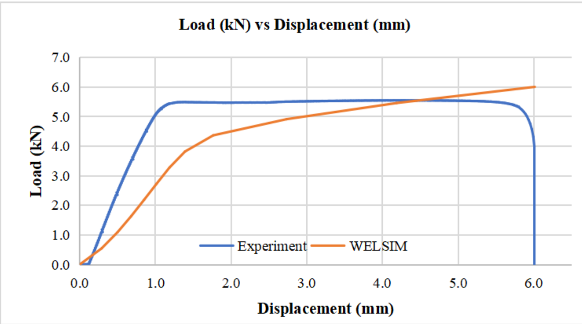
3.2 Percentage error analysis

Table 5 shows that the percentage error in yield strength (Fy) ranges from 18.13% to 26.21%, while displacement (d) varies between 17.04% and 29.82%. The higher deviation in displacement is influenced by factors such as material modeling limitations in WELSIM, mesh sensitivity, and idealized boundary conditions that may not fully replicate experimental constraints. Despite these variations, the results remain within the acceptable error range of 20-30% for nonlinear finite element simulations, as supported by previous studies (Webo et al., 2022; Ching & Hu, 2016).

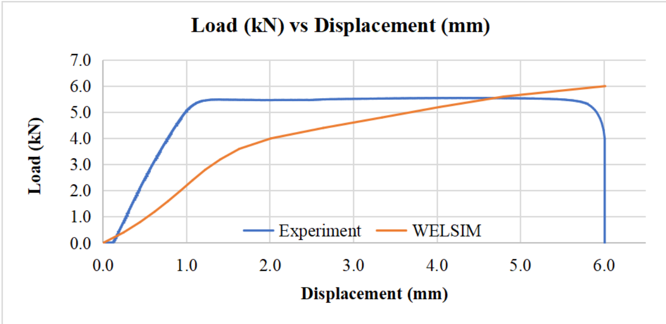
Table 5 *Percentage error in FE vs. experimental results*

Thickness (mm)	Number of Screw	Parameter	Experimental	WELSIM	Percentage Difference (%)
0.75	2	Fy (kN)	5.4837	4.3636	20.42
		d (mm)	1.3761	1.7655	28.30
	4	Fy (kN)	5.4206	4.0000	26.21
		d (mm)	1.3336	1.6314	22.33
	6	Fy (kN)	-	4.4000	-
		d (mm)	-	1.5843	-
1.00	2	Fy (kN)	7.6774	6.2857	18.13
		d (mm)	1.5154	1.9674	29.82
	4	Fy (kN)	7.6981	5.8500	24.01
		d (mm)	1.5366	1.7985	17.04
	6	Fy (kN)	-	6.6000	-
		d (mm)	-	1.9363	-

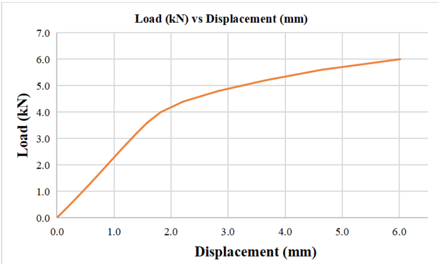
The differences ranging from 18% to nearly 30% fall within the generally accepted range for nonlinear finite element modeling. However, due to limited resources, certain assumptions such as idealized boundary conditions may have oversimplified the actual test setup. In practice, supports and grips often experience minor movements or slippage, which are not captured in the model. Although this boundary condition is standard and logical for tensile simulations, it may not fully reflect the real-world complexities observed during experimental testing. To further illustrate the comparison, Figure 5 and Figure 6 presents a graphical representation of the experimental vs. FE model results for yield strength (Fy) and displacement (d).



(a)

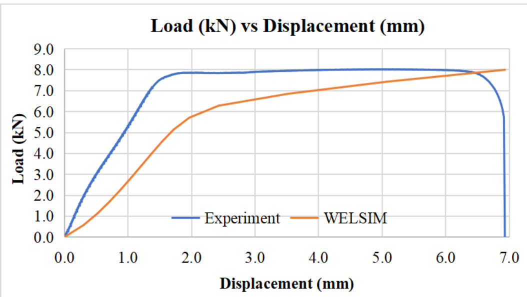


(b)

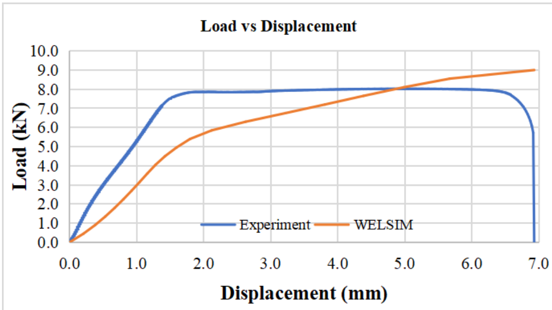


(c)

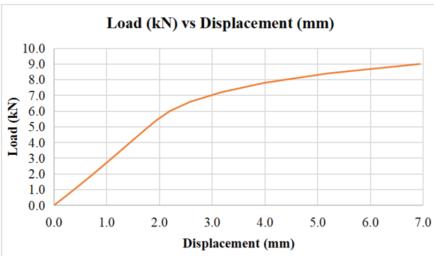
Fig. 5 *Load vs displacement: (a) 0.75mm thick with 2 nos, (b) 0.75mm thick with 4 nos, (c) 0.75mm thick with 6 nos*



(a)



(b)



(c)

Fig. 6 *Load vs displacement: (a) 1.00mm thick with 2 nos, (b) 1.00mm thick with 4 nos, (c) 1.00mm thick with 6 nos*

3.3 Comparison of Failure Modes

To analyze the structural performance of CFS boxed connections, failure modes from WELSIM simulations were compared with experimental results. This section examines the failure mechanisms for different thicknesses and screw configurations in detail as shown in Figure 7, Figure 8, Figure 9, and Figure 10.

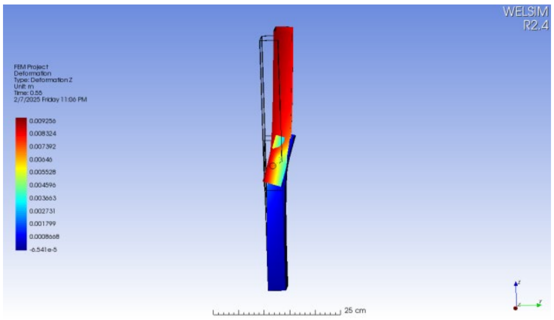


Fig. 7 *Deformation from WELSIM of 0.75mm thick with 2 screw*

Fig.8 *Deformation from experiment of 0.75mm thick with 2 screw*

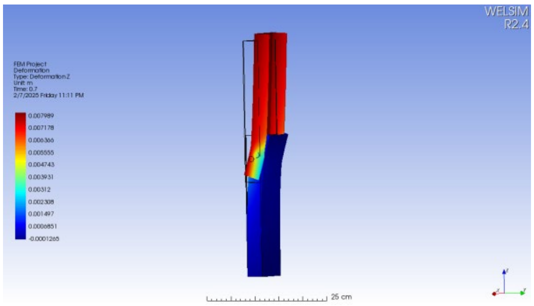


Fig. 9 *Deformation from WELSIM of 1.00mm thick with 2 screw*

Fig.10 *Deformation from experiment of 1.00mm thick with 2 screw*

3.4 Comparison and Validation

The WELSIM simulation closely matched experimental results, especially in predicting buckling failure. However, since screws were modeled as bonded contacts, failures like screw pull-out and tilting were not captured. Some differences were noted, such as earlier deformation in experimental samples due to material imperfections. Additionally, the failure mode for the 6-screw configuration remains theoretical and needs further validation.

Figure 4.1 shows the deformed shapes and stress concentrations from the analysis. For thinner sections (0.75 mm), failure mainly occurred due to local flange buckling. The bonded contact assumption prevented the model from capturing screw pull-out and hole elongation. More screws reduced deformation but increased stress around screw holes.

For thicker sections (1.00 mm), stress was concentrated around the screw holes. The model did not account for hole elongation or bearing effects due to the bonded contact assumption. While more screws improved load distribution, they also caused higher stress concentrations, which could impact long-term performance.

Overall, adding more screws improves stability but does not eliminate failure risks. Further testing is needed to determine the best screw configuration that balances strength and durability.

4. Conclusion

This study successfully modeled and validated the finite element (FE) analysis of cold-formed steel (CFS) boxed connections under tensile loading using WELSIM. The FE model was compared with experimental results, focusing on material thickness, screw configurations, and failure modes. The validation showed that the FE model provided reasonably accurate results, with errors in yield strength and displacement ranging from 18.13% to 29.82%. These differences were mainly due to material modeling limitations, mesh sensitivity, and idealized boundary conditions. However, the results remained within an acceptable error range, confirming the model's reliability.

The parametric study demonstrated that increasing material thickness from 0.75 mm to 1.00 mm significantly improved load-bearing capacity and reduced local buckling. Similarly, adding more screws improved

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load distribution and reduced stress concentration, but beyond a certain number, additional screws did not provide significant structural benefits.

Failure mode analysis revealed that local buckling, plate bending, and screw pull-out were common failure mechanisms. While the FE model accurately predicted deformation patterns and stress distribution, it did not fully capture screw tilting and bearing failure due to the bonded contact assumption. Additionally, the failure behavior of the 6-screw configuration remains theoretical since it was not experimentally tested.

Overall, this study confirmed the FE model's accuracy within an acceptable range and provided insights into the structural behavior of CFS boxed connections. The findings highlight the importance of thickness and screw configurations in improving connection strength and stability. Further experimental validation is needed to refine and optimize the structural design..

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Conflict Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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This guide contains examples of common types of APA Style references. Section numbers indicate where to find the examples in the Publication Manual of the American Psychological Association (7th ed.).

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