

# Numerical Evaluation of Stiffness in Bolted Steel-Wood-Steel Connections for Malaysian Glulam Timber Using Finite Element Analysis

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KEYWORDS	ABSTRACT
<p>Finite Element Analysis Steel-Wood-Steel Connections Glulam Keruing Timber ABAQUS</p>	<p>Accurate stiffness prediction for bolted timber joints is crucial for the reliable design of engineered timber structures. Conventional standards such as Eurocode 5 and MS 544: Part 5 often produce inaccurate stiffness estimations for Malaysian hardwood glulam due to the omission of key geometric factors. This study focuses solely on the numerical investigation of Steel-Wood-Steel (SWS) bolted connections in Malaysian Keruing glulam using finite element analysis (FEA) in ABAQUS 6.14. Three-dimensional orthotropic models were developed to simulate the load-slip behavior under parallel-to-grain loading. Parametric analyses were conducted to examine the influence of end distance, bolt spacing, row spacing, and timber thickness on initial stiffness. The numerical results were compared with predictions from Eurocode 5 and the regression-based stiffness equation developed previously. Findings indicate that end distance and timber thickness exert the most significant effects on connection stiffness, while the numerical model provides strong agreement with the proposed empirical equation. The validated FE model offers a practical framework for future optimization and design of bolted hardwood glulam joints.</p>

## 1. INTRODUCTION

The stiffness of bolted timber connections governs the deformation and overall stability of glulam structures. Design codes such as Eurocode 5 employ simplified empirical equations that depend mainly on timber density and fastener diameter, neglecting parameters that substantially influence stiffness, which is particularly for hardwood species like Keruing commonly used in Malaysia.

To improve predictive accuracy, this paper presents a purely numerical investigation of the stiffness behavior of Steel-Wood-Steel (SWS) bolted connections in Keruing glulam. Using numerical simulation platform, ABAQUS, the study models the mechanical response of joints subjected to parallel to grain loading and performs a detailed parametric analysis on critical configuration variables.

## 2. PROBLEM

Existing design standards for timber connections, such as Eurocode 5 and Malaysian Standard MS 544: Part 5, estimate joint stiffness primarily based on timber density and fastener diameter. However, these simplified equations do not account for key geometric parameters such as end distance, bolt spacing, row spacing, and timber thickness, factors that strongly influence stiffness behavior in bolted joints.

When these standards are applied to Malaysian hardwoods like Keruing glulam, the resulting stiffness predictions are often leading to potential inaccuracies in structural design, excessive deformation, or unsafe service performance.

Although previous experimental research has highlighted the importance of geometry on joint stiffness, there remains a lack of detailed numerical modeling that captures the orthotropic nature of Malaysian hardwoods and the complex contact behavior between steel, wood, and bolts.

Therefore, a validated finite element model (FEM) is needed to accurately simulate the load slip response of Steel-Wood-Steel (SWS) bolted connections, analyze the effects of key configuration parameters, and provide a reliable numerical basis for improving stiffness prediction methods for local glulam materials.

## 3. LITERATURE REVIEW

Previous numerical studies (Izzi et al., 2018; Karim et al., 2022) have demonstrated that finite element analysis can capture the nonlinear interaction between bolts, steel plates, and anisotropic timber materials. However, most models focus on softwoods or European species. Investigations by Rahim et al. (2022) and Petrycki & Salem (2023) confirmed that geometric parameters such as end distance and member thickness dominate stiffness behavior.

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Few efforts have been made to develop validated numerical models for Malaysian hardwood glulam, where high density and brittle behavior demand accurate contact definitions and orthotropic material representation. This study addresses this deficiency through comprehensive FEA modeling and validation against experimental stiffness data.

**4. NUMERICAL METHODOLOGY**

**4.1 Finite Element Modeling**

All simulations were performed using ABAQUS 6.14 in a double-shear SWS configuration. Half-symmetry was employed to reduce computational cost.

**Timber material:** Modeled as orthotropic elastic with three moduli of elasticity ( $E_1, E_2, E_3$ ), shear moduli ( $G_{12}, G_{13}, G_{23}$ ), and Poisson’s ratios ( $\nu_{12}, \nu_{13}, \nu_{23}$ ) corresponding to the longitudinal, radial, and tangential axes of Keruing glulam. **Steel plates and bolts:** Modeled as isotropic elastic materials ( $E = 210 \text{ GPa}, \nu = 0.3$ ).

**Contact interactions:** Surface-to-surface contact with hard normal behavior and penalty friction coefficient of 0.3 was defined between steel-timber and bolt-timber interfaces to replicate slip behavior.

**Boundary conditions:** One end of the steel plate was fixed, and displacement loading was applied parallel to the grain direction on the opposite plate to simulate tensile shear.

**Meshing:** The model used C3D8R elements with refined mesh (1–2 mm) around the bolt–hole interface to capture local stress gradients.

**4.2 Parametric Study**

The variables analyzed are listed below:

**Table 1** Variable of parameter

<b>Parameter</b>	<b>Levels Investigated</b>	<b>Description</b>
End distance ( $a_1$ )	100mm, 120mm,	Distance from bolt center to timber edge
Bolt spacing ( $a_2$ )	65mm, 130mm.	Distance between bolts along the load direction
Row spacing ( $a_4$ )	40mm, 80mm.	Distance between bolt rows perpendicular to load
Timber thickness	90mm, 100mm	Glulam member thickness

Each parameter was varied independently while maintaining constant material properties and boundary conditions to isolate its effect on stiffness.

**5. RESULTS AND DISCUSSION**

**5.1 Load Slip Response**

All FEA models exhibited linear elastic behavior at the initial stage, followed by gradual slip due to bolt-hole bearing deformation. The computed stiffness values closely matched the trends observed experimentally, confirming accurate contact and material modeling.

**5.2 Influence of Geometric Parameters**

**End Distance ( $a_1$ ):** Increasing end distance from 100 mm → 120 mm enhanced stiffness by approximately 40 - 50 %, attributed to improved load transfer and reduced bearing stress concentration.

**Timber Thickness:** Thicker members (60 mm) yielded up to 25 % higher stiffness due to larger effective shear area.

**Bolt Spacing ( $a_2$ ):** Moderate effect; excessive spacing slightly reduced stiffness as load sharing diminished.

**Row Spacing ( $a_4$ ):** Minimal influence within the studied range.

**5.3 Comparison with Design Standards**

Eurocode 5 consistently inaccurately stiffness values for the analyzed hardwood joints. Conversely, the numerical results agreed well with the newly proposed regression-based equation, with an average deviation below 10 %.

**5.4 Stress Distribution**

Contour plots revealed concentrated compressive stresses around the bolt contact zones, progressively spreading parallel to the grain direction as end distance increased. The stress distribution verified that failure is governed by local bearing deformation rather than global shear, matching typical experimental observations.

**6. DISCUSSION**

The finite element approach successfully captured the anisotropic response of Malaysian Keruing glulam. Sensitivity analysis confirmed that end distance and timber thickness are the primary stiffness-controlling variables. The strong agreement between FEA and the empirical equation reinforces the reliability of the model for predicting joint performance beyond the tested configurations.

The validated model offers potential for further parametric and optimization studies, such as:

- a) Investigating larger bolt diameters and multiple-row assemblies,
- b) Assessing nonlinear material effects or cyclic loading,
- c) Calibrating simplified stiffness equations for Malaysian design standards.

## 7. CONCLUSION

This study developed and validated a comprehensive finite-element model to evaluate the stiffness of Steel-Wood-Steel bolted connections in Keruing glulam. The key findings are:

Finite element simulations accurately replicate load–slip behavior and stiffness trends observed experimentally.

End distance and timber thickness exert dominant influence on initial stiffness.

Eurocode 5 overpredicts stiffness for Malaysian hardwoods, while the regression-based model shows close agreement with FEA.

The validated ABAQUS model serves as a robust platform for advanced design and parametric optimization of bolted hardwood connections.

Future work should incorporate nonlinear and time-dependent behavior to extend applicability to service-load and cyclic-loading conditions.

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