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Finite element analysis of Glued-in rod connections according to the number of rebars

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ABSTRACT

Amid growing environmental concerns, timber construction has gained attention as a sustainable alternative in structural engineering. Among the various joining techniques, Glued-in rod (GIR) connections, in which steel rods are adhesively bonded into predrilled holes in engineered wood members using adhesive, offer notable advantages, including superior fire resistance and high stiffness due to the fully embedded configuration. In this study, the structural behavior of GIR connections bonded with epoxy adhesive was investigated through finite element analysis, focusing on the effect of the number of inserted rods. The results showed that increasing the number of rods improved the ultimate load capacity and enhanced energy dissipation. However, localized stress concentrations near the reinforcement caused crack initiation and propagation along the timber–rod interface. To improve the reliability of GIR connection design, further studies considering bonded length, adhesive thickness, and stress distribution are recommended.

1 . INTRODUCTION

With increasing emphasis on environmental sustainability, timber has re-emerged as a viable construction material due to its renewability, low embodied energy, and favorable strength to weight ratio. Engineered wood products, such as glued laminated timber (GLT) and cross laminated timber (CLT), have further expanded the applicability of timber in modern construction. However, the use of conventional mechanical fasteners in timber structures may limit joint stiffness, reduce durability, and compromise aesthetic and fire performance. To address these limitations, the Glued in

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rod (GIR) connection system has been introduced as a high performance alternative. This technique involves inserting steel rods into predrilled holes in the timber and bonding them with structural adhesives, forming a continuous and concealed load transfer path. The GIR system enhances structural efficiency, reduces reliance on metal surface connectors, and enables improved fire resistance and architectural integration. Owing to these advantages, GIR connections are increasingly applied in both new timber construction and the strengthening of existing structures.

2. FINITE ELEMENT ANALYSIS

2.1 Finite element model

In this study, a finite element model was developed to analyze the flexural performance of Glued-in rod connections, based on the experimental configuration proposed by Oh et al. (2025). The experiment utilized Korean larch glued laminated timber with a strength grade of 10S-30B. The beam member had a cross-sectional dimension of 200 mm × 300 mm. Eight SD400 rebars with a diameter of 22 mm were embedded into 24 mm predrilled holes at the bottom of the beam. Each rebar was embedded to a depth of 300 mm along the longitudinal axis of the beam and fixed with a welded end plate at the bottom of the specimen. The detailed geometry of the specimen is shown in Figure 1.

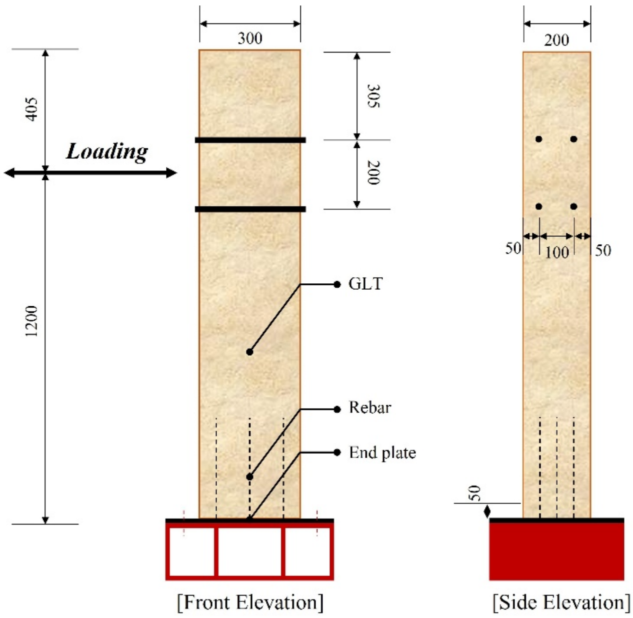
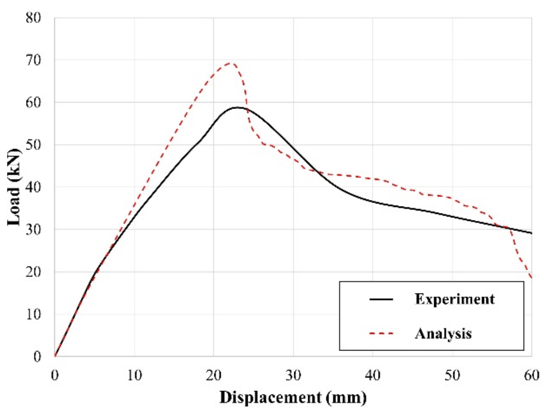


Fig. 1 Configuration of the previous experiment

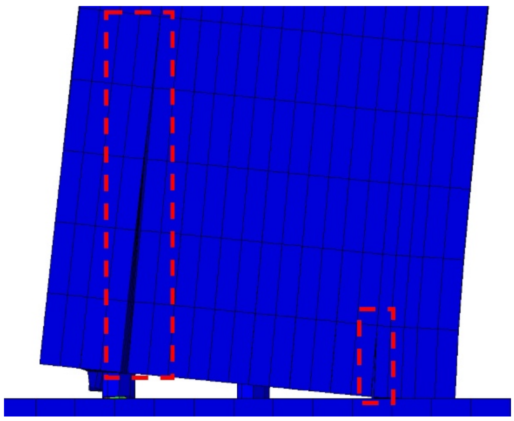
The finite element model was developed using ABAQUS version 6.13, and the modeling procedure followed the experimental configuration. The glulam beam was modeled with a cross-section of 200 mm × 300 mm and a total length of 1605 mm, incorporating lamination layers with a thickness of 30 mm. Phenol-Resorcinol-Formaldehyde (PRF) resin was used as the adhesive between laminae. The material properties of the 10S-30B Korean larch glulam were modeled as an orthotropic material with the following elastic constants: longitudinal modulus E_1=9,000 MPa, transverse moduli E_2=E_3=300 MP, shear modulus G_{12}=G_{13}=290.6 MPa, G_{23}=18.75 MPa, and Poisson's ratios v_{12}= v_{13}=0.4, v_{23}=0.02. The SD400 reinforcing bars were modeled as isotropic steel with an elastic modulus of 201,000 MPa and Poisson's ratio of 0.3. The yield and ultimate strengths were set to 400 MPa and 500 MPa, respectively. The end plate was modeled using SM355 steel with a thickness of 15 mm. The material properties of the end plate were defined as an elastic modulus of 210,000 MPa, Poisson's ratio of 0.3, yield strength of 355 MPa, and ultimate strength of 500 MPa. A 1 mm thick adhesive layer was applied between the glulam and the rebar. The adhesive interfaces were modeled using a cohesive zone model (CZM) employing a traction–separation law to define the load–displacement relationship. The epoxy adhesive properties were referenced from Oh (2024), with an elastic modulus of 2,600 MPa and Poisson's ratio of 0.2. The cohesive properties at the interfaces between timber–adhesive and adhesive–steel were defined as follows: the maximum normal stress σ_n^{max}=3 MPa, and the maximum shear stresses σ_s^{max}=σ_t^{max}=10 MPa. The stiffness parameters for each failure mode were assigned as: K_n (Mode **I**, Opening) = 2,600 MPa/mm, K_s (Mode **II**, Shearing) = 1,083.3 MPa/mm, and K_t (Mode **III**, Tearing) = 1,083.3 MPa/mm. The rebars and end plate were connected using a *Tie Constraint* to simulate welded conditions.

2.2 Analysis results

To verify the reliability of the developed finite element model, the analysis results were compared with experimental data in terms of maximum load, displacement, initial stiffness, and stress distribution. These comparisons are summarized in Figure 2 and Table 1**.**



(a) Load-Displacement curve



(b) Crack patterns based on FE model

Fig.2 Analysis results

Table 1. Results of experiment and analysis

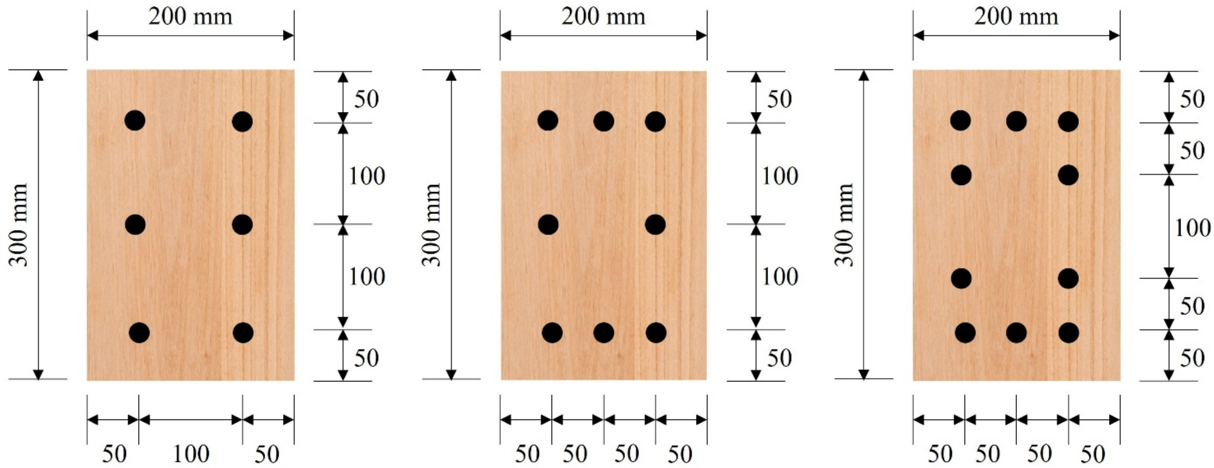
	Stiffness K_i (kN/mm)	Maximum load P_{max} (kN)	Displacement δ_{max} (mm)
Experiment	3.9	58.4	24.0
Analysis	3.8	68.8	22.1
Error(%)	3.6	17.7	7.9

The initial stiffness obtained from the experiment was 3.92 kN/mm, while the analysis yielded 3.78 kN/mm, resulting in a discrepancy of less than 4%. The error in maximum load was 17.7%, and the displacement at maximum load differed by 7.9%. These differences are attributed to the fact that the exact material properties used in the experimental study were not fully specified, necessitating the use of generalized values from relevant literature and standards. Despite these discrepancies, the stress distribution obtained from the numerical analysis exhibited a nonlinear load–displacement response with a gradual post-maximum load reduction, closely resembling the experimental behavior. As the applied displacement increased, separation was observed at the interface between the glulam and the end plate, followed by progressive debonding between the rebars and the timber. This led to the development of cracks along the grain direction of the glulam. At the final loading stage, additional micro-cracking occurred due to bearing stresses between the glulam and the end plate, resulting in a reduction of the applied load. These observations demonstrate a strong correlation between the experimental and numerical results, thereby validating the reliability of the proposed finite element model.

3. PARAMETRIC STUDY

3.1 Parametric study

Based on the validated finite element model, a parametric study was conducted to evaluate the effect of the number of rebars on the structural performance of the GIR connections. The analysis was performed for configurations with 6, 8, and 10 rebars. The objective of this study is to identify an optimal design strategy that enhances structural performance while minimizing material usage. Furthermore, by analyzing the failure modes of the connections, the study aims to establish safer and more efficient design guidelines. The details of the parameters are summarized in the Figure 3.



(a) G-1.2-6 (b) G-1.2-8 (c) G-1.2-10

Fig. 3 Overview of parametric analysis

3.2 Results of the parameter study

The finite element analysis results for GIR connections with varying numbers of rebars are presented in Figure 4, Figure 5 and Table 2. The load–displacement curves indicate that the maximum load capacity increased with the number of rebars. This trend is attributed to the fact that the rebars serve as the primary tensile elements resisting flexural loads; thus, an increased number of rebars leads to improved overall structural performance of the connection. In addition, the models with more reinforcement exhibited enhanced energy dissipation capacity and deformation ability, resulting in a more gradual strength degradation and ductile failure behavior. In the G-1.2-6 model, premature load drop was observed due to debonding at the interfaces between the rebars and adhesive, and between the adhesive and the glulam. Subsequently, localized bearing failure occurred at the bottom of the glulam, showing a brittle failure pattern. This behavior appears to result from insufficient reinforcement, which limited the distribution of applied loads. Conversely, in the G-1.2-10 model, although cracks initiated around the densely spaced two-row rebar arrangement due to stress concentrations, the remaining bars were able to redistribute the load, leading to a ductile response. The parametric analysis revealed that the primary factor contributing to strength degradation in GIR connections was debonding at the adhesive interfaces—specifically, between rebars and adhesive, and between adhesive and timber. When the number of rebars is insufficient, load tends to concentrate on fewer rebars, accelerating adhesive failure and resulting in brittle fracture. In contrast, when an adequate number of rebars is provided, even if local debonding occurs, the remaining rebars can redistribute the load, promoting a more ductile structural behavior.

Table 2. Results of different number of rods

Name	Load (kN)	Displacement (mm)
G-1.2-6	61.6	20.3
G-1.2-8	68.8	22.1
G-1.2-10	86.4	27.6

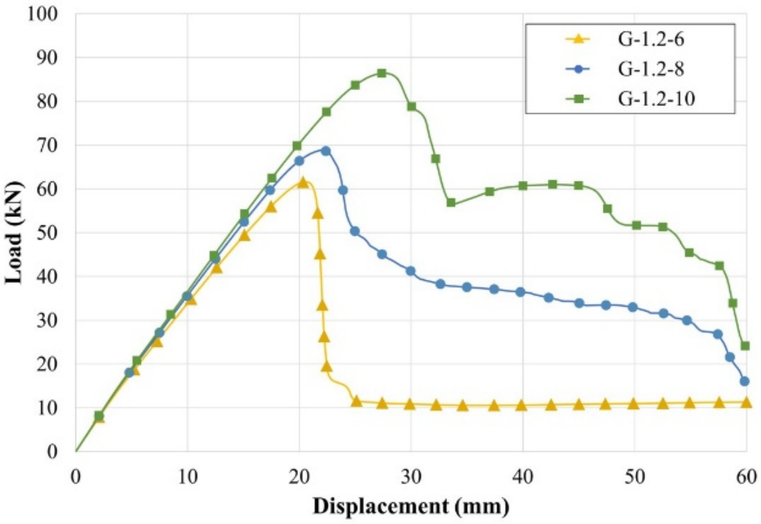
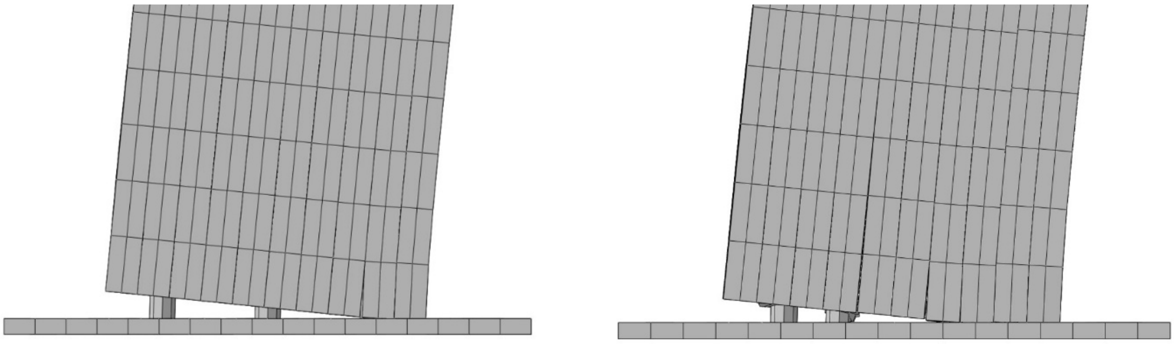


Fig. 4 Load-Displacement curve for different number of rods



(a) G-1.2-6 (b) G-1.2-10

Fig. 5 Crack patterns based on different number of rods

4. CONCLUSION

This study conducted a finite element analysis on the flexural performance of Glued-in rod connections based on the experimental work by Oh et al. (2025), focusing on varying the number of rebars. The following conclusions were drawn.

1. The load–displacement curve of the finite element model showed good agreement with the experimental results. The shape of the curve and the failure mode, characterized by the formation of a gap between the glulam and the end plate and by crack propagation along the rebar lines, was accurately reproduced.
2. The parametric study showed that increasing the number of rebars improved structural ductility and energy dissipation by distributing stress more evenly across the adhesive interface and within the glulam. However, if sufficient cross-sectional space is not provided, local stress concentrations may occur due to rebar interference. Therefore, increasing the number of rebars should be considered only when adequate cross-sectional dimensions are ensured.
3. The validated finite element model can be used to investigate additional parameters, such as rebar embedded length, cantilever beam length, and glulam cross-sectional size. These analyses are expected to provide foundational data for designing timber connection systems in domestic timber construction.

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