Mechanical Performance and Feasibility Study of Steel Plate-Bolted Glulam Trusses

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Abstract

To promote the application of engineered timber in medium- and long-span structural systems, this paper investigates the mechanical performance and feasibility of steel plate-bolted glulam trusses. The proposed structural form combines glulam members with double-sided steel gusset plates and through bolts, forming a mechanical connection system capable of transferring axial force, shear force, and a certain degree of bending moment at the joints. The material compatibility of glulam, structural steel plates, and dowel-type bolts is discussed first, followed by an analysis of the truss configuration, load-transfer mechanism, preliminary experimental response, numerical simulation strategy, and design feasibility. The results indicate that the steel plate-bolted connection can provide a clear load path, reliable assembly conditions, and improved joint restraint for glulam trusses. Preliminary static loading observations show that the failure process is mainly governed by joint slip, local timber embedment, splitting around bolt holes, bolt bending, and local cracking of critical members, while the global truss response retains an evident staged development. Refined numerical modelling can effectively reproduce the overall load-displacement trend and reveal stress concentration near bolts and steel plates. Theoretical interpretation based on dowel-type connection yielding and joint bending resistance further supports the feasibility of this structural form. Overall, steel plate-bolted glulam trusses show good potential for green building structures, especially where structural efficiency, prefabrication, maintainability, and low-carbon material use are required.

Keywords

Steel Plate-Bolted Connection; Glulam Truss; Steel Gusset Plate; Dowel-Type Fastener; Mechanical Performance; Numerical Simulation; Green Timber Structure.

1. Introduction

Against the background of low-carbon construction and the growing demand for sustainable structural systems, engineered timber has received increasing attention in buildings, bridges, and public facilities [1]. Glued laminated timber, commonly referred to as glulam, is one of the most widely used engineered wood products because it has a high strength-to-weight ratio, good dimensional stability, and favorable processing and prefabrication characteristics [2-4]. Compared with conventional solid timber, glulam can be manufactured with more uniform material properties and larger member sizes, which makes it suitable for modern timber structures requiring both mechanical reliability and architectural expression.

However, when the span increases, ordinary glulam beam members may face limitations such as excessive depth, relatively large deflection, and inefficient material use. Truss systems provide an effective alternative because they convert global bending effects mainly into axial forces in the chords and web members. In this way, the material can be used more efficiently, structural self-weight can be reduced, and the span capacity can be improved. For glulam trusses, the performance of the joint is particularly important. The joint region controls not only the local load transfer between members, but also the overall stiffness, deformation capacity, and failure development of the entire truss.

Steel plate-bolted connections are a practical solution for glulam truss joints. Steel gusset plates provide a compact and stable joint region, while bolts work as dowel-type fasteners to transfer forces through local embedment between the bolt shank, timber hole wall, and steel plate. Compared with traditional timber joints, this connection form has clearer force transmission, better constructability, and greater convenience for inspection and replacement. It also allows a certain degree of semi-rigid behavior, which is more consistent with the actual response of large timber truss joints than ideal pin-jointed assumptions.

This study is structured in terms of the material properties, structural configuration, load-transfer mechanisms, preliminary validation, numerical analysis, and prospective applications of steel plate–bolted glulam trusses, aiming to evaluate the mechanical performance and engineering feasibility of this connection system and to provide a concise reference for its application in modern glulam truss structures.

2. Material Properties and Connection Feasibility Analysis

2.1 Basic Mechanical Properties of Materials

Glulam is the primary load-bearing material in the truss system. It is manufactured by bonding laminations along the grain direction, and therefore its mechanical behavior is strongly anisotropic. The strength and stiffness parallel to the grain are much higher than those perpendicular to the grain. This feature is favorable for truss members because the chords and web members are mainly subjected to axial tension or compression along the member axis. At the same time, the anisotropy of timber must be carefully considered in the joint region, where local embedment, splitting, and cross-grain tensile stress may occur around bolt holes [5, 6].

Steel gusset plates serve as the main connecting components in the joint. Structural steel has high strength, stable mechanical properties, and good ductility. When steel plates are arranged on both sides of glulam members, they can reduce eccentric force transfer, restrain local rotation, and distribute bolt forces more evenly. In multi-member joints, such as those where chords, vertical web members, and diagonal web members meet, the stiffness and layout of the steel plates play an important role in maintaining a stable force-transfer path.

Bolts are typical dowel-type fasteners. Under lateral loading, the bolt transfers force mainly through bearing contact with the timber hole wall and the steel plate. The mechanical performance of a bolted joint is therefore controlled by the bolt diameter, timber thickness, steel plate thickness, bolt yield strength, timber embedment strength, hole clearance, and bolt spacing. For thin steel plate double-shear connections, possible yield modes usually include timber embedment-dominated yielding and bolt plastic hinge development within the timber member [7, 8].

2.2 Connection Feasibility Analysis

From the viewpoint of mechanical compatibility, glulam members, steel gusset plates, and bolts form a complementary connection system. Glulam provides a lightweight and renewable structural body; steel plates provide local restraint and connection stiffness; and bolts provide a removable and standardized mechanical fastening method. The steel components compensate for the relatively weak cross-grain tensile resistance of timber, while the timber members reduce the overall structural weight and improve the environmental performance of the system.

The connection also has clear advantages in fabrication and construction. Glulam members and steel plates can be prefabricated with predrilled holes, and the complete truss can be assembled using conventional bolts. This construction method is suitable for factory production and on-site assembly.

Compared with fully bonded joints, bolted steel plate connections are easier to inspect, tighten, repair, and replace during service. These features are important for medium- and long-span timber structures where joint reliability and maintainability are major design considerations.

Nevertheless, the feasibility of this connection form depends heavily on proper detailing. Bolt spacing, end distance, edge distance, plate thickness, washer arrangement, and moisture protection measures all affect the joint strength and stiffness. If the end or edge distance is insufficient, splitting may occur along the grain. If the steel plate is too thin, local plate deformation may reduce connection efficiency; if it is too thick, the connection may become overly stiff and transfer excessive local pressure to the timber around bolt holes. Therefore, a balanced design between bolt yielding, timber embedment, and joint deformation compatibility is essential.

3. Glulam Truss Configuration and Working Mechanism

3.1 Basic Configuration Characteristics

The steel plate-bolted glulam truss considered in this paper is composed of upper chords, lower chords, web members, steel gusset plates, and through bolts, see Fig. 1. The chords mainly resist the global bending effect of the truss, whereas the web members transfer shear forces and maintain the geometric stability of the system. At the joints, double-sided steel gusset plates clamp the glulam members, and bolts pass through the timber and plates to form a multi-bolt connection region.

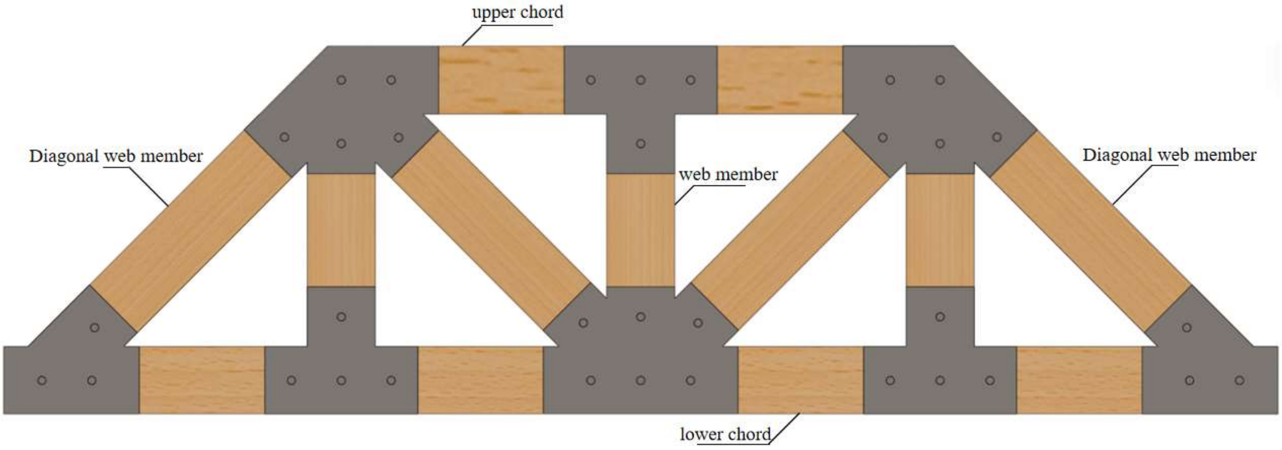

Fig. 1 Steel plate-bolted glulam trusses

This structural concept may be described as a glulam truss body combined with steel-restrained mechanical joints. The glulam members define the main structural form and provide an exposed timber appearance, while the steel plates and bolts undertake the local connection function. This arrangement is especially suitable for prefabricated timber construction because individual members can be processed separately and then assembled into a complete truss through mechanical fastening.

Different diagonal web-member combination patterns can be adopted according to the span, load path, and architectural requirements. In this study, the web-member combination was mainly considered in terms of an M-shaped arrangement and a parallel-symmetric arrangement, hereafter referred to as the P-shaped arrangement. In addition, the joint connection mode was taken as another structural variable, namely a connected joint configuration or a disconnected joint configuration, see Table 1. These two variables affect the contact condition between timber members and influence the development of local slip, bearing deformation, and stress redistribution. Thus, the final mechanical response of the truss is determined by both the global web-member arrangement and the local joint connection mode.

Table 1. Design parameters of trusses

Type	Truss Type
M-L type	M-shaped diagonal webs, joints connected
M-D type	M-shaped diagonal webs, joints disconnected
P-L type	Parallel symmetric diagonal webs, joints connected
P-D type	Parallel symmetric diagonal webs, joints disconnected

3.2 Analysis of Load-Bearing Mechanism

Under vertical loading, the global bending moment of the truss is mainly transformed into axial compression in the upper chord and axial tension in the lower chord. The web members transfer shear forces between the chords and stabilize the overall geometry. This mechanism allows the structure to achieve a relatively large span with a smaller amount of material than a solid beam. However, the actual response differs from that of an ideal pin-jointed truss because the bolted joints have finite rotational stiffness and measurable slip.

At each steel plate-bolted joint, the force in the glulam member is transmitted from timber to bolts through local embedment, then from bolts to steel plates, and finally to the other connected members. Because several members enter the same joint at different angles, the joint is usually subjected to combined axial force, shear force, and bending moment. The load transfer is therefore not purely axial. Local bolt forces, timber-to-timber contact, and steel plate restraint may all participate in the redistribution of internal forces.

The loading process of the truss can be divided qualitatively into several stages. In the initial stage, the response is mainly controlled by member axial stiffness, initial contact, bolt-hole clearance, and local embedment stiffness. As the load increases, joint slip and bolt-hole bearing deformation become more evident, causing a reduction in apparent stiffness. Near the ultimate state, local damage around the joints or critical members may develop rapidly. This staged response indicates that the global behavior of the truss is closely coupled with the local behavior of the bolted joints.

4. Preliminary Experimental Verification and Performance Analysis

4.1 Analysis of Failure Modes

Preliminary experimental verification can be carried out through static loading tests on full-scale or scaled glulam truss specimens. In a typical test scheme, the truss specimens may be designed by varying the diagonal web-member combination shape, such as the M-shaped arrangement and the parallel-symmetric, or P-shaped, arrangement, together with the joint connection mode, namely connected and disconnected configurations. The specimens are then subjected to a concentrated load at mid-span. During the loading process, key responses such as load-deflection curves, joint vertical displacement, member strain, local slip, and visible damage are recorded. These observations provide direct evidence for evaluating the mechanical behavior of steel plate-bolted glulam trusses.

The observed failure modes are usually related to the interaction between global member forces and local joint damage. In some specimens, cracks may initiate near bolt holes and extend along the grain direction because of local tensile stress perpendicular to the grain. In other cases, embedment crushing around bolts may appear first, accompanied by gradual joint slip and bolt bending. For trusses with relatively high joint restraint, local cracking of chords or web members may occur after the joint region has redistributed part of the load. These failure modes are consistent with the typical behavior of dowel-type timber connections, in which timber embedment, bolt yielding, and splitting compete with each other [5-7].

From a structural safety perspective, a progressive failure process is more desirable than sudden brittle splitting. When local embedment deformation and bolt bending develop gradually, the joint can still provide a certain load-carrying reserve and failure warning. By contrast, insufficient end distance, poor bolt arrangement, or excessive local stress concentration may cause abrupt crack propagation.

Therefore, the experimental failure characteristics demonstrate the necessity of considering both member-level strength and joint-level deformation compatibility.

4.2 Evaluation of Mechanical Performance

The mechanical performance of steel plate-bolted glulam trusses can be evaluated mainly through ultimate load capacity, deflection behavior, strain development, and damage progression. Experimental observations indicate that both the diagonal web-member combination shape and the joint connection mode have a noticeable influence on the overall response. In particular, when the web members form a reasonable M-shaped combination and the joint is arranged with an appropriate connected or disconnected configuration, the truss tends to show better load-carrying capacity and deformation capacity. This is because the internal force distribution is more favorable and the joint region can participate more effectively in load redistribution.

The load-displacement response generally shows a clear staged development. At the beginning of loading, the curve is approximately linear, indicating that the glulam members and bolted joints work together effectively. As the load increases, the curve gradually becomes nonlinear due to bolt slip, timber embedment deformation, and local damage near the joint. Before final failure, the deformation increases rapidly and the stiffness decreases obviously. This behavior suggests that the serviceability performance of the structure should not be assessed only by member stiffness, but should also include the slip and rotational stiffness of the joints.

Strain measurements further reveal the internal force characteristics of the truss. The chord members generally exhibit significant axial tensile or compressive strain, while web members show different strain levels depending on their angle and position. Near the critical joints, strain development may become more complex because of bolt group action and local stress redistribution. These results confirm that steel plate-bolted glulam trusses cannot be fully represented by an idealized pin-jointed model. A semi-rigid joint interpretation is more appropriate for describing their actual mechanical performance.

4.3 Numerical Simulation Techniques

Numerical simulation provides an effective method for observing the stress distribution and deformation mechanism that are difficult to measure directly in experiments. A refined finite element model of the steel plate-bolted glulam truss can be established using ABAQUS or similar software. In such a model, glulam may be represented as an anisotropic material, steel plates and bolts may be described using elastic-plastic material models, and the contact relationships among glulam, steel plates, bolts, and timber interfaces should be carefully defined.

The contact setting is one of the key aspects of numerical modelling. Normal hard contact can be used to allow pressure transfer and separation between contact surfaces, while tangential frictional contact can represent relative sliding. For the steel plate-bolted glulam truss, the major contact pairs include glulam-to-steel plate, glulam-to-bolt, glulam-to-glulam, and steel plate-to-bolt interfaces. Reasonable contact parameters help the model reproduce local bearing, separation, slip, and stress concentration near the bolt holes.

After verification against experimental load-displacement curves and failure observations, the numerical model can be used for parametric analysis. The thickness-to-diameter ratio and steel plate thickness are two important parameters. A change in thickness-to-diameter ratio may significantly affect bolt plastic development, timber embedment, and the nonlinear behavior of the truss. By comparison, increasing steel plate thickness may improve local restraint but does not necessarily lead to a proportional improvement in global load capacity if the controlling weakness has shifted to timber embedment or splitting. Therefore, numerical simulation is useful not only for verification, but also for clarifying the mechanism behind different design parameters.

5. Comprehensive Feasibility Analysis and Prospects

5.1 Analysis of Comprehensive Advantages

From the structural perspective, steel plate-bolted glulam trusses combine the efficient force-transfer characteristics of truss systems with the reliability of mechanical fasteners. The truss form allows global bending effects to be resisted mainly through axial forces, while the double-sided steel plates and bolts provide compact and controllable joint connections. This combination improves material utilization and makes the structure suitable for medium- and long-span roofs, public buildings, pedestrian bridges, and prefabricated timber systems.

From the construction perspective, the system has strong potential for industrialized production. Glulam members and steel plates can be fabricated in advance with relatively high accuracy, and the final assembly can be completed using ordinary bolting procedures. This reduces on-site wet work, simplifies construction, and improves quality control. The mechanical connection also makes the structure easier to inspect and maintain, which is an advantage for long-term service.

From the analytical and design perspective, the mechanical behavior of the joint can be interpreted using the European yield model for dowel-type timber connections [7, 8]. The single-bolt yield capacity can be used as a basis for evaluating the resistance of a bolt group, and upper- and lower-bound approaches can be introduced to estimate the bending resistance of the joint under combined action. Comparisons with design methods in Eurocode 5 and GB 50005 can further support the rationality of the proposed design framework [8, 9].

From the environmental perspective, glulam is a renewable engineered wood material and can reduce the reliance on high-carbon structural materials. Steel is used mainly in the joint region where high local strength, stiffness, and ductility are needed. This selective use of materials reflects an efficient hybrid structural strategy: timber is used for the main structural body, and steel is used where concentrated force transfer and local restraint are required.

5.2 Future Research Directions

Although steel plate-bolted glulam trusses show good feasibility, several issues still require further investigation. First, the semi-rigid behavior of the joint should be quantified more accurately. The rotational stiffness, slip stiffness, and degradation law of bolted joints under different loading levels are essential for predicting global truss deflection and internal force redistribution. Practical design methods should be able to include these effects without becoming too complex for engineering use.

Second, long-term performance and durability need more attention. Timber creep, moisture variation, bolt loosening, corrosion protection of steel plates, and repeated loading may change the stiffness and load-transfer mechanism of the connection during service. For outdoor structures, bridges, or buildings exposed to variable humidity, durability measures should be integrated with structural design.

Third, fire performance, dynamic behavior, and post-damage repair should be studied in greater depth. Although glulam has predictable charring behavior, exposed steel plates and bolts may heat up quickly in fire. Protective detailing and replaceable connection components may therefore be necessary. In addition, standardized joint modules, simplified design tables, and validated numerical models would help promote the practical application of steel plate-bolted glulam trusses in green building structures.

6. Conclusion

Through the above analysis, the following main conclusions can be drawn:

Firstly, the combination of glulam members, steel gusset plates, and bolts is mechanically feasible. Glulam provides a lightweight and renewable structural body, while steel plates and bolts enhance joint restraint, load transfer, and construction reliability. The three components can form a complementary system suitable for modern timber truss structures.

Secondly, the diagonal web-member combination shape and the joint connection mode have a significant influence on the mechanical response of steel plate-bolted glulam trusses. A reasonable selection between the M-shaped and parallel-symmetric (P-shaped) web-member combinations, together with a clear connected or disconnected joint configuration, can improve load distribution, increase deformation capacity, and reduce local stress concentration. The joint should be regarded as semi-rigid rather than ideally pinned or fully rigid.

Thirdly, preliminary experimental observations and numerical simulations indicate that the main failure modes include timber splitting near bolt holes, embedment crushing, bolt bending, local steel plate deformation, joint slip, and member cracking. These risks can be effectively controlled by proper bolt spacing, end and edge distances, plate thickness, contact detailing, and moisture protection.

Finally, steel plate-bolted glulam trusses have good prospects in green building structures. They combine structural efficiency, prefabrication potential, maintainability, and environmental benefits. With further improvement in joint stiffness modelling, durability design, and standardized calculation methods, this structural form is expected to provide a practical solution for medium- and long-span timber engineering applications.

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