

# Experimental Study on the Hysteretic Behavior of Laminated Bamboo Steel-Side-Plate Bolted Connectors

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## Abstract

In order to investigate the dynamic performance and seismic performance of bolted connections between glued laminated bamboo and steel plates under dynamic loading and to ensure their reliability, this experimental program took into account variables such as the thickness-to-diameter ratio, the bolt spacing parallel to the grain, and the bolt arrangement, and designed and fabricated 3 types, 9 groups, and 27 connections, on which hysteretic tests were carried out under low-cycle reversed loading. The test results show that in the single-bolt connections, the bolt failure mode gradually shifted from "bolt remaining straight" to a "single-hinge" failure mode, while the bamboo scrimber consistently exhibited the typical dowel-bearing (embedment) failure mode. The hysteresis curves of the specimens were all relatively full and spindle-shaped, indicating.

## Keywords

Bolted Glued Laminated Bamboo-To-Steel Plate Connection; Low-Cycle Reversed Loading Test; Hysteretic Behavior; Thickness-To-Diameter Ratio; Spacing Parallel To The Grain; Aligned and Staggered Arrangement

## 1. Introduction

Steel-side-plate bolted connections are one of the primary connection forms in modern steel structures. According to their loading characteristics, they can be divided into tension connections, shear connections, and combined tension-and-shear connections. In tension connections the bolts mainly carry axial tensile force, which is transferred through the clamping force between the plates and the connected members; such connections are commonly found in truss tension members and bracing members. In shear connections the bolts mainly resist shear through the shear strength of the bolt shanks and the bearing strength between the plates and the connected members, and are widely used at beam-to-column connections and member splices. Combined tension-and-shear connections, in

which the bolts carry both tensile and shear forces, are the most common type in engineering and appear, for example, in rigid-frame joints and bridge segment splices. In bamboo and timber structures, the mechanical behavior of connection joints plays a decisive role in overall structural performance and is crucial to the safety and reliability of the structure. Many factors affect the behavior of laminated bamboo steel-side-plate bolted joints, including the density and moisture content of the laminated bamboo, bolt diameter, bolt spacing parallel to the grain, bolt layout and number, and group effects. This thesis therefore designs and tests laminated bamboo steel-side-plate bolted connectors under low-cyclic reversed loading, taking the thickness-to-diameter ratio, the bolt spacing parallel to the grain, and staggered or parallel bolt arrangement as the main test parameters.

Because relevant specifications for laminated bamboo are still lacking, this thesis and the related research refer mainly to the existing timber structure codes at home and abroad. From 1955 to 1988, China issued three editions of timber structure design codes, which made preliminary provisions on material selection and connection methods for timber structures. With the rapid development of modern timber structures, GB 50005-2003 added special provisions for the materials, calculation, and connections of light-frame timber trusses, and the later GB 50005-2017 Standard for Design of Timber Structures, together with GB/T 50329-2012 Standard for Test Methods of Timber Structures, specifies structural materials, structural members, connection design, protection, fabrication and installation, maintenance management, and load capacity testing. The current state of engineering application nevertheless shows that some provisions still need further revision and improvement, especially those covering hybrid structures and modern connector types [1-2]. These codes and the experimental research carried out under them form the reference framework for extending bolted steel-side-plate connections from glulam to laminated bamboo.

Laminated bamboo has several advantages that traditional timber does not possess, which make it a promising substitute for glulam in connector structures. (1) It has superior mechanical properties: its strength and elastic modulus are generally higher than those of most solid wood, its shear and compressive resistance are strong, and the material is uniform and nearly free from such defects as knots and insect holes. (2) It offers higher resource efficiency: bamboo has a growth cycle of only 3-5 years, far shorter than the several decades needed by solid wood, regenerates rapidly, and more than 90% of the raw bamboo can be used, compared with a utilization rate of usually only 50%-70% for solid wood. (3) It is more stable: after high-temperature, high-pressure, degreasing, and desugaring treatment, laminated bamboo has low hygroscopicity and small deformation and is not prone to cracking or warping, making it suitable for humid environments or those with large temperature differences. (4) It has better environmental performance: its production avoids extensive felling of old-growth or slow-growing timber, generally

uses environmentally friendly adhesives with low formaldehyde emissions, and satisfies green-building requirements. (5) It has a unique and attractive grain: the straight, orderly bamboo-node texture gives it strong decorative value, and different lamination methods can produce various patterns.

At present, research on laminated bamboo at home and abroad has made steady progress, but few studies replace glulam with laminated bamboo in steel-side-plate bolted connectors, and little research has examined how such connectors inherit and develop the load-bearing and hysteretic behavior of bolted timber connections amid the current shortage of modern timber. Connector technology for bamboo structures is relatively mature overseas, and long-term experimental research on bamboo-structure connector systems has been carried out in Canada in particular, whereas domestic modern bamboo structures are still at an early stage of development and have accumulated comparatively little experience. Systematic experimental and numerical research on the load capacity and seismic performance of laminated bamboo steel-side-plate bolted connectors is therefore of practical significance for the conservation, utilization, inheritance, and development of bamboo-structure buildings.

## **2. Research and Prospects of Laminated Bamboo Steel-Side-Plate Bolted Connectors**

### **2.1. Research Status in China**

Chinese research on bolted connections first concentrated on glulam and other engineered wood members, and this body of work now provides the knowledge base for extending steel-side-plate bolted connections to laminated bamboo. Zhu Enchun et al. [3] tested bolted connections in larch and Mongolian pine members of mixed strength grades, proposed a bolt-hole bearing coefficient, and established a load capacity formula based on an elastic-plastic model of steel; by checking the proposed formula against the current code, they also obtained the resistance partial factors for different bolt yield modes and verified that the calculated results agreed well with the code values. Zhang Junzhen [4-5] reviewed the mechanical properties of bolted timber connections and carried out static shear tests on larch glulam, showing that bolt-hole embedment strength is governed mainly by loading direction, bolt diameter, glue-layer number, and fabrication process, and that finger-joint length affects the pressure values and their variation rules. Xu Deliang et al. [6] analyzed the failure modes of bolted glulam connectors and performed parallel-to-grain tensile tests on single-bolt and multi-bolt members. The results showed that single-bolt behavior is closely related to glulam thickness, with the best ductility at a thickness-to-diameter ratio of 4.375, and that a two-row bolt arrangement fails relatively uniformly and gives better ductility than other multi-bolt layouts. Zhou Weiyu [7] measured the embedment capacity of bolt holes parallel and perpendicular to the grain and showed that embedment strength is

much higher parallel to the grain than perpendicular to it, that changing the loading method has essentially no effect on embedment strength, and that the Foschi formula describes the measured load-embedment relationships well, with coefficients of determination above 0.8. Fan Chengmou [8] systematically studied the elastic-plastic behavior of bolted timber connections, defined the symmetric double-shear failure model that appears in the load-bearing failure modes of bolts, related the bolt-hole embedment strength to the parallel-to-grain compressive strength of timber, and proposed design calculation formulas whose results were in agreement with tests.

More recent domestic studies have addressed joint behavior under static and cyclic loading in full-scale beam-column systems. Wang Mingqian et al. [9-10] tested four groups of 22 glulam beam-column specimens with steel filler plates and bolts under static and low-cyclic reversed loading and showed that bolt strength and the bearing capacity of the timber around the bolt holes control joint behavior: larger bolt diameters increase the initial stiffness and ultimate moment, while clearance between bolts or bolt holes reduces joint stiffness, and stiffness drops significantly once cracking occurs. Their finite element analysis agreed well with the tests when the bolt diameter was 12-28 mm and the edge distance 30-70 mm. Liu Huifen [11] and He Minjuan et al. [12] found that self-tapping screws reduce and delay cracking of glulam beam-column joints and improve their ductility and total energy dissipation, while increasing the number of bolt rows enhances joint strength; cracks appeared earlier in specimens with ordinary bolted connections than in those reinforced with self-tapping screws. Wu Yajie and Xie Qifang [13] introduced friction-type joints and SMA plates into heavy glulam structures, tested three 1:2 scale friction-type beam-column joint specimens under horizontal low-cyclic reversed loading, and proposed a moment-rotation hysteretic model for this joint type, providing a reference for repairable heavy glulam frames. Chen Aijun et al. [14-15] carried out longitudinal shear tests on glulam steel-side-plate bolted connectors and found that increasing the thickness-to-diameter ratio changes the failure mode.

from single-hinge to double-hinge, that increasing bolt spacing raises the shear load capacity but reduces the initial stiffness, and that when the number of bolts is the same, staggered bolt rows give higher capacity while parallel rows give better ductility; their finite element results agreed well with the tests, the formulas in national codes tended to be conservative, and bolt washers had little influence on the shear behavior.

For laminated bamboo itself, Li Haitao et al. [16-17] reviewed the research and development of laminated bamboo production technology and systematically summarized progress on its basic mechanical properties. Through tests on side-pressed laminated bamboo, they described the compressive failure process in five stages (elastic, elastic-plastic, basically stable load, load-decreasing, and

residual load) and proposed simplified and refined compressive stress-strain models. Cheng Gensheng [18] studied laminated bamboo steel-side-plate bolted joints under compression parallel to the grain and identified shear failure, one-hinge yield, and two-hinge yield as the main failure modes; joint load capacity is strongly affected by bolt diameter, increases with member thickness, and is more sensitive to end distance, and a load capacity formula for such joints was proposed on the basis of the test values. Yang Dong [19] studied the mechanical properties of flattened bamboo boards and flattened laminated bamboo (LFB), then tested LFB steel-side-plate bolted joints, revealing their failure process and mechanism, and established a load capacity calculation model through finite element simulation and parametric analysis. These investigations supply the material data, test methods, and preliminary design formulas needed for research on laminated bamboo steel-side-plate bolted connectors.

## 2.2. Research Status Abroad

The theoretical basis of bolted timber connections was established by Johansen [20], who proposed the yield modes of bolted joints and expressed the joint load capacity through the local bearing capacity of the timber and the flexural capacity of the bolt, assuming that the joint finally undergoes ductile failure. Soltis [21] verified the yield theory through shear tests on 16 push-out specimens of bolted timber connections and found that, without changing the bolt diameter, the failure mode of the bolts gradually changes from brittle to ductile as the timber thickness increases. McLain and Thangjitham [22] derived a load capacity formula for bolted connections from loading tests and showed that bolt pretension can improve the load capacity of bolted timber members. Daudeville, Davenne, and Yasumura [23] studied the bolt-hole embedment behavior of timber and found that bolt diameter has the greatest influence on failure of the bolt holes, that larger edge and end distances improve the embedment capacity, and that the failure and stress states in their finite element models agreed with the test results. Jorissen [24] combined timber splitting failure with the yield theory to obtain the load capacity and failure modes of single-bolt connections and derived an early load capacity formula for multi-bolt connections. Doyle [25] tested bolted connections with different bolt diameters, spacings, and numbers of bolts and showed that group action reduces the load capacity per bolt: under parallel-to-grain loading each bolt in a group carried about 0.9 times the load of a single bolt, while without load the ratio was about 0.6. Wataru [26] found that an end distance below the minimum value causes brittle failure, that load capacity increases continuously as the end distance grows beyond the minimum, and that relatively large bolt diameters also lead to brittle failure. Popovski et al. [27] further showed that reducing the bolt diameter greatly improves the ductility and energy dissipation of timber-bolt connection specimens. Numerical and structural-level studies abroad have extended this field in several

directions. Heine [28] selected key points on the hysteretic curves and used a genetic algorithm to simulate the hysteretic behavior of bolted timber connections; the model reproduced the linear stage well, but convergence problems and long computation times limited it once the members entered the elastic-plastic stage. Hassanieh et al. [29] developed a three-dimensional continuum finite element model of steel-timber composite connections in which nonlinear timber failure was described by a stress-based criterion based on continuum damage mechanics, and showed that the model reproduced the load-slip response and failure modes of plywood-steel and cross-laminated timber-steel joints well. For bamboo systems, Zhang YT et al.

### 3. Main Research Content

Against the background of increasing attention to green building materials and environment-friendly structural systems, this thesis takes the laminated bamboo steel-side-plate bolted connector as its research object. Because the seismic and dynamic behavior of such connectors directly affects the safety of bamboo and timber structures, the thesis studies their stiffness degradation and hysteretic curves under low-cyclic reversed loading. The research content consists of the following two aspects.

(1) Low-cyclic reversed loading tests are conducted on laminated bamboo steel-side-plate bolted specimens with different thickness-to-diameter ratios, bolt spacings parallel to the grain, and staggered or parallel bolt arrangements. The load-displacement relationships, stiffness degradation curves, skeleton curves, and possible failure modes are analyzed to identify the main factors affecting the load capacity and seismic performance of the connectors and to provide a reliable basis for their design and application in China.

(2) An ABAQUS finite element model of the connector is established, and the correctness of the model is verified by comparing the simulation results with the test results. Parametric analysis is then performed on models with different bolt spacings parallel to the grain, thickness-to-diameter ratios, and staggered or parallel bolt arrangements, and the influence of each parameter on the load-bearing

### 4. Conclusions and Outlook

For the single-bolt specimens (Group S), the optimal thickness-to-diameter ratio is 6; that is, when the bamboo thickness is 60 mm and the bolt diameter is 10 mm, the overall seismic performance is optimal. An excessively small bolt diameter (8 mm) leads to premature global failure of the specimen, so that the load-bearing capacity of the bamboo is not fully mobilized. An excessively large bolt diameter (12 mm), in contrast, causes the bamboo to yield and fail prior to the bolt, with only negligible bolt deformation at failure, so that the synergistic interaction between the two materials is not fully exploited.

For the multi-bolt specimens (Group J), the optimal spacing along the grain is 200 mm. As the spacing increases from 100 mm to 200 mm, the overall seismic performance of the specimen improves progressively and the ultimate load-carrying capacity increases markedly. This is because a larger spacing along the grain strengthens the composite load-transfer interaction between the bolts and the bamboo, resulting in a pronounced increase in the overall stiffness of the specimen. However, as the spacing increases from 200 mm to 250 mm, the overall mechanical performance decreases appreciably, possibly because an excessive bolt spacing reduces the effective composite load-sharing zone between bolts in different rows, thereby degrading the seismic performance.

For a given spacing along the grain, the staggered arrangement improves the seismic performance of the specimen significantly more than the aligned arrangement. This is because the staggered layout allows the external load to be resisted by multiple offset cross-sections while effectively mitigating stress concentration around the bolt holes. Moreover, the staggered arrangement effectively mobilizes the bolts at the opposite loaded end, since it causes the individual bolts to yield successively and hence to participate in energy dissipation in sequence, thereby greatly enhancing the overall material utilization.

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