

Review of Studies on Performance of Dowel Connections Loaded Perpendicular to Grain

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Abstract: Wood as a sustainable building material demonstrates significant advantages in terms of environmental protection, economy and functionality. Studies showed that adding 1.0m³ of wood could absorb 1.0kg of carbon dioxide, produce 730kg of oxygen, and fix 270kg of carbon, which plays an important role in ecological environment protection. In addition, in addition, wood has good thermal insulation performance, can adjust indoor humidity, beneficial to human health. China's wooden structure architecture has a long history. As an important technology in China's traditional architecture, mortise and tenon connection technology constitutes an important part of Chinese traditional architectural heritage through the insertion of wood components. As a prefabricated building form, modern wood structure has a history of more than 100 years in developed countries. The main forms include heavy wood structure, light wood structure, square wood wood structure and wood mixed structure. In recent years, wood structure architecture has attracted wide attention in scientific research and application in China. Whether for new construction or large-scale reconstruction projects, wood structure buildings are widely adopted because of their design flexibility, high strength and aesthetics, as shown in Figure 1.1. Modern wood structure buildings show the advantages of energy conservation and environmental protection, good earthquake resistance, convenient construction and safety and comfort, and its development is fully in line with the national sustainable development strategy.

Keywords: Tenon-and-mortise work; wood; fabricated.

1. Introduction

According to the comprehensive investigation and analysis of modern wood structure building collapse cases, about half of the failures are caused by node design errors or deficiencies, while a quarter of the failures are caused by errors in the construction site. Therefore, under the action of wood transverse direction load, it is particularly important to further study the splitting performance of steel plate bolt connection, which is of great significance to the design and application of wood structure pin connection.

2. Research Status

Fan Chengmou et al. [1-3] conducted theoretical studies on bolted connections in timber structures and simplified the formula for calculating maximum bending moments. Through their analysis, they determined the bearing pressure coefficient for the wood dowel to be 0.938 and the bending resistance coefficient for the steel dowel to be 0.9076. Huang Shaoyin et al. [4] carried out experimental research on the compressive strength of dowel slots in different tree species, along with tests on the bending strength of dowel shafts, thus determining the coefficients for wood dowel slot compressive strength and steel dowel bending strength.

Xu Deliang et al. [5-7] considered the aspect ratio of the bolt-bearing section's impact on failure modes through experiments on timber structures with steel filler plate bolted connections. They analyzed two types of connections: pure timber and steel flitch plate, assessing the influence of node geometric configuration on the load-bearing capacity of the connection points. Their findings indicated that in group bolt tests, the failure mode transitioned from longitudinal splitting in a single row of bolts to longitudinal cracking at the bolts on the sides as the number of bolt rows and bolts per row increased. Additionally, the load capacity of single-bolt

connections can be calculated using Johansen's yield model [8].

Zhang Shengdong et al. [9] conducted longitudinal compression tests using timber structure specimens with embedded steel plates and single dowel connections to explore the load-bearing performance and factors affecting the failure modes and load capacities of embedded steel filler plate dowel connections. By incorporating the European yield theory and applying the superposition principle, they derived a calculation model to estimate the compressive load capacity of connectors with multiple embedded steel plates and a single bolt aligned with the wood grain. Theoretical calculations closely matched experimental data, demonstrating high consistency.

Xiong Haibei et al. [10] conducted a series of experiments on single-bolt nodes with various bolt diameters and timber structure member thicknesses to investigate the effects of these parameters on failure modes. The results showed that increasing the slenderness ratio of the bolt effectively enhanced the ductility of the embedded steel plate single bolt longitudinal connections. However, when the slenderness ratio was too high, ductility did not continue to increase but instead decreased due to transverse tensile stress in the wood, leading to splitting damage.

Wang Mingqian et al. [11] studied the performance of glulam beam-column joints with embedded steel plates and bolt connections under pure bending and combined bending-shear loads through monotonic loading tests on 15 specimens. The research indicated that these specimens mostly failed due to wood splitting, and the presence of shear forces caused the moment-rotation curves to exhibit more significant non-linearity. As the shear-to-bend ratio increased, both the load capacity and ductility of the nodes during bending decreased. The comparison of various calculation models showed that the Van der Put model performed better in terms of accuracy, whereas the Jensen model and Eurocode 5 were more

conservative.

Liu Kezhen et al. [12] conducted dowel slot bearing tests on Siberian larch to explore the effects of dowel slot yield load strength and member size specifications, determining the yield load capacity for bolt connections and enhancing the design of timber structure connections. As the density of the Siberian larch material increased, so did the dowel slot yield load strength of its components. Additionally, Liu Kezhen [52] introduced two systems in timber structures: beam-column and lightweight wood structures, emphasizing the critical role of bolt connections in the safety and stability of timber structures. Bolt connections are responsible for transmitting vertical and horizontal loads, with failure modes including shearing and tearing of the wood and bolt yield failures, highlighting the importance of in-depth studies on these failure modes, especially to avoid brittle failures, crucial for designing safe and reliable timber structure connections.

Li Xiazhen et al. [13] discovered that the load-bearing capacity of single bolt connections is significantly influenced by parameters such as end distance, middle distance, and edge distance. However, a consensus on the group bolt modification factor for multiple bolt connections has not been reached. Additionally, studying the performance of bolts under different load conditions, considering the effects of bolt size and type on their load-bearing capacity, and examining the stability and safety of bolt connections under sustained loads are crucial for designing more reliable timber structure connection systems.

Zhang Gang et al. [14] analyzed the stress distribution around steel dowels, indicating that using a 5% offset method to determine dowel slot compressive strength is reasonable. Furthermore, by using Siberian larch of varying diameters and densities, they compared the strength calculation formulas of the European standard Eurocode 5, Canadian standard CSA086 [15], Chinese "Timber Structure Design Standard" GB 50005-2017 [16], and "Glued Laminated Timber Technical Specification" GB/T 50708-2012 [17].

Zhang Junzhen et al. [18,19] conducted dowel slot compressive strength tests based on the American ASTM D5764-97a(2007) method, analyzing the impact of variables such as lamina grade, test method, loading direction, and bolt diameter on the compressive strength of dowel slots in larch glulam. The studies showed that the yield strength of full dowel holes was higher than that of half dowel holes; among all the factors, lamina grade had the most significant impact on dowel slot compressive strength, followed by bolt diameter, while loading direction had the least impact.

Feng Li [20] conducted a thorough analysis of the shear load-bearing capacity of single screw joints, establishing a calculation formula suitable for modern bamboo structures, which was validated using experimental data. Moreover, theoretical analysis, experimental studies, and finite element analysis were performed on beam-column bolt connections to evaluate their lateral force resistance. Based on the analysis of single screw joints, further extensions to multi-bolt joints were made, considering uneven load distribution and proposing corresponding load capacity calculation methods.

Xu Bohan et al. [21] introduced common strength criteria for timber, including uniaxial strength criteria, Von-Mises theory-based strength criteria, and tensor polynomial-based strength criteria. They emphasized that choosing appropriate strength standards is crucial for simulating the mechanical performance of timber, as each standard has specific applicability and limitations. Timber structure connections

endure complex forces, typically involving the interaction of tensile and shear forces, which can lead to brittle failure.

Zhu Enchun et al. [22,23] addressed the issue that the dowel connection load-bearing capacity provided in the "Timber Structure Design Standard" GB5005-2003 might not be applicable to different strength grades of timber. Based on Johansen's dowel connection load-bearing capacity calculation method and combined with experimental studies, they proposed a dowel slot bearing length-based dowel connection load-bearing capacity formula. Using the American standard ASTM D5764-97a, they conducted dowel slot compressive strength tests and double shear bolt connection load-bearing tests on Northeast larch and *pinus sylvestris*, considering the impact of loading direction on strength and load-bearing capacity. By analyzing the experimental data on dowel slot compressive strength and using the newly proposed dowel connection load-bearing capacity formula for calculations, comparisons with experimental values were made. The analysis indicated that, considering the incomplete development of dowel plasticity, the incomplete development coefficient K_w should be set at 1.4.

Hui Zhuo et al. [24] proposed a new type of glued laminated timber node embedded with steel plates and end plate connections. Through comparative tests with traditional bolted connections under low cyclic loading, they verified the significant improvements in ductility and energy absorption performance of the new nodes, with the thickness of the end plate proving to be a critical influencing factor. Using the principle of virtual work, they derived the yield load calculation formula for the new nodes and conducted an in-depth analysis of the ultimate load-bearing capacity's failure mode and calculation methods. The research results showed that the derived calculation formula closely matched the experimental results, proving the accuracy and reliability of the calculation method.

Zhou Weiyu et al. [25] conducted dowel slot compressive strength tests and bolt connection node load-bearing tests on larch glulam. They studied the effects of loading direction, bolt diameter (10mm, 14mm, 18mm), and test method on dowel slot compressive strength, and investigated the impact of thickness ratio, steel dowel diameter, and thickness-to-diameter ratio on the load-bearing performance of bolt nodes.

Song Xiaobin et al. [26] investigated the applicability of various models, including the Van der Put, Larsen, Jensen, and Ballerini models, as well as standards like the European Code Eurocode 5 and Canadian standard, to the transverse tensile load-bearing capacity of bolt joints in timber structures, based on fracture mechanics theory. They proposed a calculation formula for the transverse tensile load-bearing capacity of bolt joints, considering the effective tensile area. The formula was validated with experimental data, which showed a good match between the calculated values and experimental results, highlighting the significant influence of bolt end distance on transverse tensile load-bearing capacity. However, the transverse tensile strength used in the paper was not specified and requires further validation.

You Jia et al. [27] conducted dowel slot compressive strength tests, considering the effects of dowel diameter and loading direction on the compressive strength of red pine dowel slots. The study found that the transverse compressive strength of wood dowel slots was influenced by the steel dowel diameter and the full dry density of the wood, while the longitudinal compressive strength of dowel slots was

significantly affected by the full dry density of the wood.

Wang Zhaohui et al. [28] explored the transverse load-bearing performance of Japanese cedar sawn timber and glued laminated timber through beam-end embedded steel filler plate single dowel connection tests. The study showed that after dowel shaft yielding occurred at the connection node, wood splitting cracks developed. Factors such as the transverse tensile strength, wood shear strength, load edge distance, and end distance influenced the formation of initial cracks. After the cracks formed, the steel dowels continued to provide support, resulting in good ductility of the connection nodes; the load-bearing capacity of the sawn timber and glued laminated timber components matched well with the values calculated using the European yield model.

Wang Xiaoting et al. [29] derived empirical formulas for the initial stiffness of timber bolted connections, and the transverse and longitudinal dowel slot compressive stiffness, based on elastic foundation beam theory. The initial stiffness was found to be two-thirds of the bolt connection stiffness, consistent with the conclusion of the European standard. The load-displacement curve models were fitted based on the three-parameter model proposed by Foschi, the four-parameter model proposed by Attiogbe, and a bilinear model.

3. Summary

The above studies show that the factors affecting the transverse splitting bearing capacity of the wooden connected with steel bolts are complex, and the related parameters are shown in Figure 1.3. Among them, the domestic and foreign scholars for section width b , section height h , connecting node effective load height h_e and connecting node relative height $\alpha = h_e / h$ factors, has achieved relatively mature theoretical achievements, however, the scholars on the number of connecting node N , connecting node spacing $2s$, fracture mechanics related parameters (GG_c) 0.5 on transverse splitting capacity calculation model has many different views, the calculation results also differ.

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