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Research Progress on Dowel-Type Connection Joints of Timber Structure

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Abstract

Dowel-type connections (bolts, dowels, self-tapping screws, etc.) are the most widely used joint forms in modern timber structures, and their mechanical properties directly affect the load-carrying capacity and deformation behavior of the overall structure. This paper reviews the research progress of dowel-type timber connections from three aspects: load-carrying capacity calculation theory, numerical simulation methods, and innovative connection technologies with durability issues. In terms of load-carrying capacity theory, the Johansen yield model remains the core foundation of various design codes. Recent studies have extended this model to new engineered wood products such as cross-laminated timber and glued laminated bamboo, as well as to extreme conditions like fire. Regarding numerical simulation, the classical finite element method is the most mature approach, while the peridynamics method shows unique advantages in simulating wood cracking and fracture. For innovative technologies, self-tapping screw reinforcement and all-wood connections (dowel laminated timber, rotational welding, etc.) have become important development directions, but the water resistance of rotationally welded joints remains a critical issue. Current research still has gaps in the load redistribution mechanism of multiple-dowel connections and long-term performance under complex environmental conditions. This review aims to provide a reference for the design optimization and future research of dowel-type timber connections.

Keywords

Timber structures; Dowel-type connections; Load-carrying capacity

1. Introduction

Timber structures have been increasingly widely used in modern construction due to their environmental friendliness, light weight, high strength, and favorable seismic performance. As a key component of timber structures, connections directly affect the overall load-carrying capacity and deformation behavior of the structural system. Among various connection types, dowel-type connections (including bolts, dowels, self-tapping screws, etc.) have become one of the most widely used connection forms because of their simple construction, clear load transfer, and ease of fabrication.

The load-transfer mechanism of dowel-type connections is complex, involving compression perpendicular and parallel to grain of the wood, bending yielding of the dowels, and the interaction between the two. Since Johansen [1] proposed the strength calculation model based on wood bearing and steel yielding, extensive research has been conducted on the load-carrying capacity theory, numerical simulation methods, and durability of dowel-type connections. This paper presents a review from three aspects: load-carrying capacity calculation theory and design code methods, numerical simulation methods, and innovative connection technologies with durability issues..

2. Load-Carrying Capacity Calculation Theory And Design Code Methods

The theoretical basis for calculating the load-carrying capacity of dowel-type connections is the yield theory proposed by Johansen, which is based on the following two fundamental assumptions: (1) the bearing stress of the wood reaches its ultimate bearing strength; (2) the steel of the dowel reaches its yield strength and forms a plastic hinge. Depending on the dowel diameter, wood thickness, and material strengths, the European Yield Model (EYM) classifies the yield modes of connections into four typical types, covering various scenarios from pure wood bearing failure to complete plastic hinge failure of the dowel, as shown in Figure. 1.

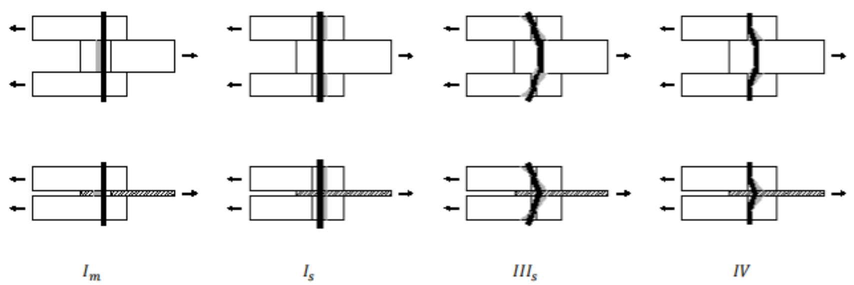

Figure 1. Typical yield modes

In 1949, Johansen proposed the European Yield Model (EYM) to calculate the load-carrying capacity of bolted connections under various configurations, and identified the bending capacity of the bolt and the dowel-bearing strength of the wood as the main influencing factors. The model assumes that wood and steel are ideal elastoplastic materials, and the formula for calculating the load-carrying capacity of bolted connections is derived through mechanical methods. McLain and Thangjitham [2] confirmed in 1983 that this model can accurately predict the load-carrying capacity of bolted timber connections, and Soltis [3] also verified its good applicability to the failure modes of bolted timber connections in 1986. J. Correal [4] and Fernando Ramirez et al. [5] respectively studied the mechanical properties and dowel-bearing strength of glued laminated bamboo, finding that its material properties are superior to those of ordinary wood. J. Hover [6] conducted experimental research on glued laminated bamboo bolted connections loaded parallel to the grain, and preliminarily analyzed their failure mechanism and load-carrying capacity. Nakashima et al. [7] derived a formula for calculating the load-carrying capacity of dowel-type connections in cross-laminated timber (CLT) based on the Johansen yield model, and used a rigid body spring model for numerical analysis to calculate the stiffness and nonlinear load-deformation relationship of the connections. The tensile test results showed that the proposed theoretical model can reasonably estimate the performance of the connections, providing theoretical support for the connection design of CLT structures.

3. Numerical Simulation Methods

With the development of computer technology, numerical simulation has become an important tool for the study of dowel-type timber connections. It compensates for the limitations of experimental research, such as high cost, long duration, and restricted loading scenarios, and enables accurate simulation of the load-transfer process, stress distribution, and failure modes of connections, thereby providing strong support for refining load-carrying capacity theories and optimizing design codes. Currently, numerical simulation methods for dowel-type timber connections are mainly divided into three categories, each with its own focus and continuously evolving towards refinement and multi-physics coupling.

3.1. Finite Element Method

The classical finite element method (FEM) is the most widely used numerical approach. In terms of finite element modeling, the anisotropic yield criterion proposed by Hill [8] combined with the orthotropic brittle failure criterion proposed by Hoffman [9] can effectively describe the elastoplastic behavior and damage evolution of wood in dowel-type connections. This method was applied by Audebert et al. [10] to the numerical simulation of multiple-dowel steel-to-timber connections with slotted-in steel plates, successfully capturing the coupled failure mode of plastic development in wood dowel bearing and dowel bending.

In recent research, significant progress has been made in refined modeling of dowel-type connections using LS-Dyna. Boli G.B.D.B. et al. [11] performed finite element modeling for the first time on steel-wood connections using a novel hybrid dowel made of densified wood-filled aluminum tubes, and developed a predictive comprehensive finite element model that showed good agreement with experimental results in terms of load-slip curves and failure modes. O'Ceallaigh et al. [12] conducted numerical simulations of the failure behavior of dowel laminated timber (DLT) beams using finite element software; the model successfully predicted the ultimate failure load and stiffness, and through parametric studies analyzed the influence of dowel diameter and spacing on the load-displacement response. Fu et al. [13] carried out finite element numerical simulation and design method research for dowel-type connections in laminated veneer lumber. Ou et al. [14] performed numerical modeling of spliced glulam joints with slotted-in steel plates and dowel-type fasteners.

3.2. Peridynamics (PD)

Peridynamics is a nonlocal meshless method whose governing equations are expressed in integral form rather than differential form. Mathematically, it naturally accommodates discontinuities and can simulate crack initiation, propagation, and branching without additional criteria, offering unique advantages in modeling anisotropic fracture of wood.

In terms of specific applications, Gan et al. [15] developed and extended an anisotropic wood model based on the peridynamics theoretical framework, and applied this method for the first time to analyze deformation and cracking damage of timber structures under dowel bearing loads. Referring to ASTM D5764-97a, two dowel diameters (8 mm and 24 mm) were selected to test glulam dowel-bearing specimens under parallel- and perpendicular-to-grain loading. The simulation results agreed well with experimental data in terms of crack location, load at failure, and load-displacement curves, with Pearson correlation coefficients all above 0.98, demonstrating that the peridynamics model can effectively predict the load-carrying performance under different dowel-bearing failure modes.

3.3. Other numerical simulation methods

The discrete element method (DEM) is mainly used for simulation at the wood particle level. Qyteti et al. [16] used DEM combined with a cohesive model to simulate shear cell experiments with cohesive wooden spheres, as well as numerical simulations of the pressing process of wood panels. Gubana et al. [17] applied DEM to the global analysis of stone masonry structures with timber floors, simplifying timber beams into a combination of multi-branch spring elements in ABAQUS Explicit to simulate the joint behavior within the overall structure.

4. Innovative connection technologies and durability issues

Beyond traditional metal bolted connections, self-tapping screws have been widely studied as both reinforcement materials and independent fasteners. Bejtka and Blass[18] found that self-tapping screws arranged in the perpendicular-to-grain direction can effectively suppress splitting failure of bolted connections, significantly improving ductility and energy dissipation capacity. He and Liu [19] confirmed through comparative tests that the ultimate moment, failure rotation, and energy dissipation of glulam post-to-beam bolted connections reinforced with self-tapping screws increased by 86%, 145%, and 641%, respectively, compared to unreinforced connections, and the ductility was 106% higher than that of connections reinforced with ordinary round bars. Mora et al. [20] reinforced small-scale glulam connections with slotted-in steel plates and dowel-type fasteners using self-tapping screws, pointing out that the reinforcement effect depends on the ratio between dowel yielding and row shear, with the most significant effect occurring in slender connections. Self-tapping screws also exhibit excellent connection performance in CLT structures. Hossain et al. [21] systematically studied the failure modes of self-tapping screw shear connections for CLT panels under monotonic and cyclic loading.

All-wood connections (i.e., metal-free and adhesive-free connections) are another recent hotspot. López et al. [22] reviewed assembly techniques such as wooden dowels, rotationally welded dowels, wooden nails, and dovetail joints. Mehra et al. [23] produced beam-column connections using compressed wood dowels and compressed wood plates, achieving significant flexural capacity and rotational stiffness, and this technique is applicable to both glulam and DLT members. In the field of rotational welding technology, Leban et al. [24] established quantitative relationships among rotational speed, temperature, and joint strength; Žulj I et al. [25] pointed out that the water resistance of welded joints remains a major bottleneck limiting outdoor applications. Xu et al. [26] proposed a simplified prediction model for the pull-out strength of rotationally welded dowels based on regression analysis.

Regarding durability, fire behavior has received extensive attention. Moss et al. [27] first conducted experimental studies on the dowel-bearing strength of wood at different temperatures, finding that it decreases in a bilinear manner with increasing temperature, providing a basis for extending the Johansen yield model to fire conditions. Audebert et al. [28] experimentally investigated the thermo-mechanical coupling behavior of steel-plate dowel connections, pointing out that dowel embedment failure is the dominant failure mode. Overall, systematic performance data for dowel-type connections under complex environmental conditions such as high temperature, high humidity, freeze-thaw cycles, and long-term creep remain scarce, which is a key bottleneck restricting code improvement and engineering application.

5. Conclusions and outlook

5.1. Conclusions

The Johansen yield model remains the theoretical basis for calculating the load-carrying capacity of dowel-type connections and has been extended to new materials such as CLT and glued laminated bamboo as well as fire conditions. The finite element method is the most mature numerical simulation approach; peridynamics shows significant advantages in simulating wood fracture (correlation coefficient > 0.98). Self-tapping screws can greatly improve joint ductility and energy dissipation (ultimate moment increased by more than 86%). All-wood connections (e.g., rotational welding) are promising but suffer from poor water resistance. Long-term performance data under complex environmental conditions are still lacking.

5.2. Outlook

Future efforts should improve load-carrying capacity models considering group-dowel effects and multi-factor coupling, and supplement design codes for new connector types. Peridynamics should be extended to multi-dowel group connections, and coupled PD-FEM methods should be developed. Research on water resistance of rotationally welded joints and the potential of compressed wood dowels should be strengthened, along with durability studies under complex environmental conditions.

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