

Perpendicular-to-Grain Behaviour of Bolted Steel-to-Timber Connections: A State-of-the-Art Review

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Abstract

This paper reviews the perpendicular-to-grain mechanical behaviour of bolted steel-to-timber connections, focusing on embedment strength, slip modulus, ductility, and splitting failure. The review synthesizes experimental and theoretical studies from major design codes (Eurocode 5, NDS, GB 50005) and recent research. Key findings indicate that embedment strength depends on density, fastener diameter, moisture content, and loading angle; the bending-specimen test method better reflects actual joint conditions. Slip modulus and group effect lack unified models, and ductility evaluation standards are inconsistent. Fracture-mechanics-based models for splitting resistance show improved accuracy but need further validation for multi-bolt configurations. Finally, the paper outlines four research tasks: (1) perpendicular embedment tests using bending specimens, (2) an initial slip modulus formula based on beam-on-elastic-foundation theory, (3) a group reduction factor for multiple bolts, and (4) an optimised design method for perpendicular load capacity. This review highlights research gaps and provides a basis for future code improvements.

Keywords

Timber Connections; Bolted Joints; Perpendicular-to-Grain; Embedment Strength; Splitting Failure; Ductility; Group Effect

1. Introduction

Timber has regained prominence in civil engineering owing to global sustainability goals. Each cubic metre of timber sequesters 1.0 tonne CO₂ and produces 730 kg O₂. Since 2016, China has promoted wood-based construction materials. Modern timber structures, using engineered wood products (glulam, CLT), offer superior seismic performance and prefabrication efficiency. However, their connections—critical for load transfer—often adopt dowel-type fasteners (bolts, pins, nails) due to good ductility. Architectural demands inevitably impose loads perpendicular to grain, exploiting wood's weakness in that direction. Two failure modes govern: ductile

embedment (European yield mode) and brittle splitting. Since connection failures account for most timber structure damages, research on perpendicular-to-grain behaviour of bolted steel-to-timber joints is essential.

2. State of the Art

2.1. Embedment Strength Perpendicular to Grain

Johansen's yield theory, originally for parallel-to-grain loading, has been extended to perpendicular cases. Embedment strength is influenced by density, moisture content (MC), fastener diameter, temperature, and test method (half-hole, full-hole, or bending-specimen). Ehlbeck & Werner [4] established density-dependent formulas adopted in Eurocode 5. Comparative studies (Molina et al. [6,7], Santos et al. [11]) show significant discrepancies among Brazilian, European, and US standards. Feng et al. [12] recommended the 5% offset strength from bending specimens as a reliable indicator for perpendicular embedment. Moisture content negatively affects strength (Fahlbusch [17], Winistorfer [18], Koponen [19]), while temperature causes softening (Schneid & Poliana[23]). Resin impregnation improves stiffness but reduces ductility (Ogawa et al. [38]). Numerical models (Hong & Barrett [40], Karagiannis et al. [20]) have been developed, but most focus on parallel grain; perpendicular studies are sparse, especially using bending specimens that better replicate actual joint behaviour. Therefore, further perpendicular embedment tests with bending specimens are needed.

2.2. Ductility and Slip Modulus

Research on slip modulus, group effect, and ductility is less mature. Gattesco [41] found lateral restraint increases embedment strength by 40% perpendicular to grain. Schweigler et al. [42] observed displacement hardening for angles above 60°. Jockwer et al. [43] showed fastener diameter affects slip modulus via a power law, stronger than Eurocode 5's linear assumption. Jorissen & Fragiaco [44] proposed ductility criteria for seismic design, while Malo et al. [45] developed energy-based ductility indices. Xu et al. [46] found densified wood dowels have no group reduction. Patel & Hindman [48] verified NDS and TR-12 models for LVL. However, systematic studies on slip modulus (beyond loading angle) and group reduction factors are lacking; ductility evaluation standards remain inconsistent.

2.3. Splitting Failure

Van der Put & Leijten [49] applied linear elastic fracture mechanics (LEFM) to predict splitting capacity, forming the basis of Eurocode 5. Schoenmakers et al. [50,51] calibrated fracture parameters for several species. Zarnani & Quenneville [52] proposed a riveted-joint model considering width and end distance. Franke & Quenneville [53,54] developed a nonlinear fracture model incorporating joint geometry, reducing errors by ~40% compared to Eurocode 5. Jensen et al. [55–62]

used beam-on-elastic-foundation theory with tensile strength as a criterion, introducing fracture energy as a key parameter. Chinese researchers (Fan [64–66], Xu et al. [67–70], Zhu et al. [71,72], Wang et al. [73], Song et al. [74], Cui et al. [75]) conducted extensive tests, proposing design formulas and verifying yield modes. Nonetheless, current models often ignore multi-bolt interaction and complex geometric configurations; brittle splitting remains a critical design concern.

3. Research Gaps and Objectives

Based on the review, key gaps include:

- Limited perpendicular embedment studies using bending-specimen tests.
- Lack of unified slip modulus formulas accounting for density, diameter, and geometry.
- No consensus on group effect reduction factors for multiple bolts.
- Inconsistent ductility evaluation criteria.

This study aims to:

1. Conduct perpendicular embedment tests using bending specimens to investigate density and bolt diameter effects, and propose a calculation model validated with literature data.
2. Derive an initial slip modulus formula based on beam-on-elastic-foundation theory.
3. Propose a group reduction factor from experimental results.
4. Develop an optimised design method for perpendicular load capacity of bolted steel-to-timber connections.

4. Conclusions (Optional)

This review summarises the current knowledge on perpendicular-to-grain behaviour of bolted timber connections. While embedment strength and splitting models are relatively advanced, ductility, slip modulus, and group effects require further investigation. The proposed research tasks will address these gaps and contribute to more rational design provisions.

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