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# EFFECT OF CONNECTION GEOMETRY ON THE JOINT CAPACITY OF AN LVL LOADED PERPENDICULAR TO THE GRAIN

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**ABSTRACT:** The load-carrying capacity of bolted timber connections loaded perpendicular to the grain is governed not only by fastener size and minimum spacing rules, but also by the overall geometry of the joint. Australian Standard AS 1720.1-2010, however, provides no explicit allowance for this geometric effect and contains no characteristic perpendicular-to-grain tensile strength for Laminated Veneer Lumber (LVL). This paper presents an experimental study on Australian-sourced radiata-pine LVL in which 54 two-bolt connections were tested under monotonic tension. Eighteen joint geometries were created by combining three bolt diameters (10, 12 and 16 mm) with systematic variations in row spacing parallel to the grain (2D–4D) and column spacing perpendicular to the grain (3D–5D). Companion tests measured the LVL tensile strength perpendicular to the grain ($f_{t,90}$ = 0.49 MPa). The results show that AS 1720.1 over-predicts capacity by up to 34 % for medium-to-large bolts placed parallel to the grain, yet is highly conservative, by as much as 108 %, for bolts placed perpendicular to the grain. The paper quantifies the influence of bolt diameter and spacing, documents failure modes, and identifies priority areas where AS 1720.1 could be recalibrated to achieve uniform reliability while removing unnecessary conservatism in LVL connection design.

**KEYWORDS:** Laminated Veneer Lumber; bolted connections; perpendicular-to-grain tension; connection geometry; AS 1720.1

## 1 – INTRODUCTION

Timber remains a vital construction material globally, prized for its sustainability and structural efficiency. Engineered Wood Products (EWPs), particularly Laminated Veneer Lumber (LVL), have significantly expanded the applications of timber. LVL, produced by bonding thin wood veneers—often from fast-growing species like Australian radiata pine—with their grain parallel, offers enhanced dimensional stability and more consistent mechanical properties than traditional timber. The Meyer Timber LVL used in this study, conforming to AS/NZS 1604.1, exemplifies the advantages of LVL, including superior material uniformity and reduced natural defects (Franke et al. – insert specific reference), which lead to greater strength and lower performance variability. Li et al. [1] also note LVL's potential for superior bending strength compared to some traditional timber products. These qualities support its increasing use in diverse Australian structural applications.

However, the performance of a timber structure is often dictated by its connections. Mechanical fasteners, such as bolts, create critical points that govern overall strength and stiffness. A significant challenge arises when loads act perpendicular to the grain of the wood. Wood's orthotropic nature means that its tensile strength is markedly lower perpendicular to the grain than parallel to it, rendering members susceptible to brittle splitting failures. For LVL, this issue is acute; its perpendicular-to-grain bearing strength can be as low as 3–10 MPa, compared to over 20 MPa in tension parallel to the grain, because load is resisted by veneer crushing and glue lines rather than direct fibre strength. This can lead to failure modes like plug shear, bearing failure, or splitting if fastener spacing is inadequate, alongside serviceability issues like "crush creep" under sustained loads.

Practical examples in Australian construction illustrate these concerns: LVL ridge beams in roofs may crush under notched rafters; LVL ledgers supporting floor joists can deform under hanger pins; and LVL truss chords can experience crushing around bolts. These issues necessitate careful design, often involving increased bearing areas through steel plates or larger washers, and diligent serviceability checks. This study selected LVL due to a recognised lack of comprehensive research into its connection behaviour under perpendicular-to-grain loading, especially for Australian-sourced material.

In Australia, timber connection design is primarily governed by AS 1720.1-2010, Timber Structures Part 1: Design methods [2]. This standard, alongside AS 1649, has evolved towards probabilistic methodologies [3], with

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these authors also noting that changes in material supply and fastener technology require fresh approaches to connection design. For perpendicular-to-grain loading, AS 1720.1 [2] specifies minimum edge/end distances and bolt spacing, alongside characteristic single-bolt capacities. However, a critical limitation is its silence on the broader influence of connection geometry beyond these minimums, particularly for tension perpendicular to grain. The standard lacks explicit models for predicting splitting failure, a dominant mode. Instead, capacity estimations rely on fastener values and spacing rules that may not adequately capture the complex stress interactions leading to splitting. This is significant, as research by Pavković et al. [4] demonstrated that minimum distances alone are insufficient to ensure joint capacity; overall connection geometry is crucial.

These limitations are amplified for LVL. AS 1720.1 [2] does not provide an explicit characteristic tensile strength perpendicular to the grain for LVL, creating uncertainty for designers and often necessitating reliance on the manufacturer's data, which may not be suitable for specific connection configurations or Australian conditions. The general scarcity of research and guidance for Australian LVLS loaded perpendicular to the grain means that designs may be unduly conservative, or, more critically, may not achieve the intended performance. The experimental work underpinning this paper addresses a clear gap in AS 1720.1 [2].

While this study focuses on AS 1720.1 [2], international research and other codes like Eurocode 5 acknowledge the importance of connection geometry more comprehensively. Jockwer & Dietsch [5] emphasised that a holistic evaluation of member dimensions, fastener configuration, and load proximity is essential for predicting splitting resistance. Research has yielded predictive equations based on two main theories: strength-based approaches (e.g., Ehlbeck et al[6].), focusing on tensile strength perpendicular to grain, and fracture mechanics (e.g., Van der Put, Jensen JL et al.[7]), considering energy for Mode I crack propagation. Ehlbeck et al [6]. highlighted non-linear geometric effects. Despite this international work, Jockwer & Dietsch [5] also point to the partial validation of many geometric factors, indicating a continued need for empirical data. Furthermore, Jensen et al. [8] found potential discrepancies in code predictions for LVL, stressing the need for material-specific studies. The limited Australian research on LVL connections loaded perpendicular to the grain further underscores the necessity of the current investigation.

Given LVL's growing use in Australia and the identified shortcomings of AS 1720.1-2010 [2] regarding connection geometry and specific LVL provisions, this study provides crucial experimental data. The overall aim of this research is to experimentally investigate and quantify the effect of connection geometry on the joint capacity, defined as the ultimate load-carrying capacity before failure, and associated failure modes of bolted LVL connections subjected to loads applied perpendicular to the grain.

The specific objectives of this paper are, therefore, to experimentally determine the ultimate load-carrying capacity of bolted connections in Australian-sourced Meyer Timber LVL under perpendicular-to-grain tensile loading, considering variations in bolt diameter and systematic changes in bolt spacing both parallel and perpendicular to the grain. Concurrently, this research aims to meticulously observe, document, and categorise the predominant failure modes exhibited by these LVL connections under the different geometric configurations tested. Furthermore, the study seeks to compare the experimentally obtained joint capacities from our new experimental results with the characteristic joint capacities predicted using the current design provisions of AS 1720.1[2]. Through these comparisons, this paper will critically assess the adequacy and potential conservatism or unconservatism of AS 1720.1[2] provisions for designing bolted LVL connections loaded perpendicular to the grain, thereby identifying areas where the standard could be improved to reflect actual observed behaviour better.

This research addresses key questions regarding how connection geometry influences the ultimate capacity and failure of Australian LVL loaded perpendicular to the grain, whether current AS 1720.1 [2] provisions are adequate, and how experimental capacities compare to code predictions. The findings are expected to provide valuable data for Australian engineers, deepen the understanding of LVL connection behaviour, and offer insights that could inform future revisions to AS 1720.1 [2], ultimately fostering safer and more efficient timber structures.

## 2 – EXPERIMENTAL PROGRAM

### 2.1 OVERVIEW

The experimental program was designed to investigate the influence of connection geometry on the ultimate load-carrying capacity of bolted connections in Australian-sourced Laminated Veneer Lumber (LVL) when subjected to tensile loading perpendicular to the grain. The program encompassed two principal components: firstly, the characterisation of relevant LVL material properties, with a specific focus on its tensile strength perpendicular to the grain; and secondly, a comprehensive series of tests to determine the capacity of bolted LVL connections under various geometric configurations.

### 2.2 MATERIAL PROPERTY CHARACTERISATION

To accurately interpret the behaviour of the bolted connections, it was essential first to determine the fundamental mechanical properties of the LVL utilised in the study. The primary property of interest was the tensile strength perpendicular to the grain ($f_{t,90}$).

#### 2.2.1 Test Method and Standard

The determination of the LVL's tensile strength perpendicular to the grain was conducted in accordance with AS/NZS 4063.1-2010 [9]. This standard specifies a three-point bending test configuration, as illustrated notionally in Figure 1 of the standard, to induce tensile failure perpendicular to the grain. This method was selected due to the adaptability of available universal

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testing equipment to the three-point bending methodology, ensuring compatibility and facilitating precise measurement. Furthermore, this standardised approach is known to produce consistent and uniform results, particularly when specimens of specific, prescribed dimensions are tested, thereby enhancing the reliability and reproducibility of the obtained data.

In this test, the specimen maintains its full cross-sectional dimensions (b × d) throughout the portion under evaluation, with an additional extension of length $l_h$ at each end, where $l_h$ is defined as one-third of the specimen depth (d/3). A uniformly distributed load (F) is applied at the mid-span and incrementally increased at a controlled rate until failure occurs. The test setup employs pin supports and a rocker slider to ensure proper load distribution and minimise unintended stress concentrations.

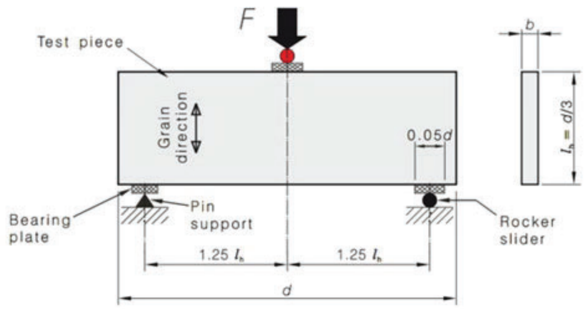


*Figure 1. Test specimen and test setting for tension perpendicular to grain by AS/NZS 4063.1-2010 [9].*

#### 2.2.2 Specimen Preparation

Specimen preparation for the material property tests adhered strictly to the guidelines outlined in AS/NZS 4063.1-2010 [9]. The LVL was sourced from Meyer Timber, a local Australian supplier. The technical specifications of this LVL, as provided by the manufacturer, include the nominal density of 550 kg/m³ and the moisture content of 8%.

A total of 6 specimens, representative of the bulk LVL material, were prepared for the material property tests. The length of these specimens was 80 mm. All material property specimens were carefully extracted from remnants of the larger LVL members previously used for the bolted connection tests (specifically, from sections that had been subjected to loading perpendicular to the grain), as notionally illustrated in Figure 2. The precise dimensions for these specimens were determined in accordance with AS/NZS 4063.1-2010 [9].

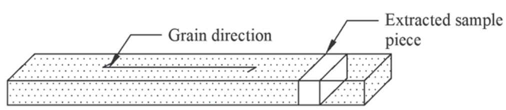


*Figure 2. Test sample extraction from timber bolted connection sample.*

#### 2.2.3 Experimental Setup And Procedure

The prepared LVL specimens were tested using a 50 kN capacity Universal Testing Machine (UTM). Each specimen was securely positioned on two cylindrical roller supports within the UTM, as depicted in Figure 3, ensuring stability during the three-point bending test. The loading head of the UTM, fitted with a metallic indenter, was carefully aligned above the mid-span of the specimen. The load was applied in a displacement-controlled manner at a constant rate of 1 mm/min, which remained constant throughout the controlled loading phase. This controlled displacement ensured that the force was uniformly transferred to the specimen, minimising uneven stress distribution.

To capture the failure progression and deformation behaviour, a high-resolution digital camera was synchronised with the testing apparatus. The camera was programmed to record images at a rate of one frame every five seconds throughout the duration of each test. These sequential images were subsequently used for post-experimental visual analysis, allowing for a detailed examination of crack initiation, propagation, and the overall failure mechanism.

#### 2.2.4 Experimental Setup And Procedure

During each material property test, the ultimate load (F) at failure was systematically recorded by the UTM. This critical parameter was then used to calculate the tensile strength of the LVL perpendicular to the grain ($f_{t,90}$) using the calculation described in AS/NZS 4063.1-2010 [9]. This standardised calculation provided an accurate assessment of the LVL's resistance to perpendicular tensile forces.

### 2.3 BOLTED CONNECTION CAPACITY TESTS

The second, and principal, phase of the experimental program focused on determining the ultimate load-carrying capacity of bolted LVL connections loaded in tension perpendicular to the grain, with systematic variations in connection geometry.

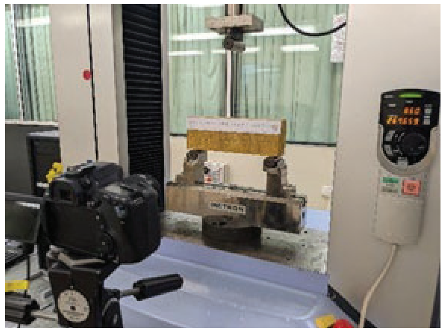

*Figure 3. Assembly for testing according to AS/NZS 4063.1:2010 [9].*

### 2.3.1 Test Matrix And Specimen Configuration

The connection test specimens were fabricated from the same batch of Meyer Timber LVL, with a consistent cross-section of 200 mm (depth) x 45 mm (thickness). The overall length of these specimens was maintained at 1200 mm. Each specimen had two bolts. The experimental matrix involved three distinct nominal bolt diameters: 10 mm (M10), 12 mm (M12), and 16 mm (M16). For each bolt diameter, the spacing between bolts was varied in two directions:

• Spacing parallel to the grain (SC): 2D, 3D, and 4D.

• Spacing perpendicular to the grain (SR): 3D, 4D, and 5D.

Here, ‘D’ represents the nominal bolt diameter.

This systematic variation in bolt diameter and spacing resulted in a total of 18 unique connection configurations. To ensure statistical reliability, each unique connection type was tested three times, leading to a total of 54 bolted connection tests.

### 2.3.2 Specimen Preparation

Prior to testing, each LVL specimen underwent a standardised preparation procedure. This involved the precision drilling of bolt holes through the 45 mm thickness of the LVL specimen and through corresponding 20 mm thick Plexiglas plates, which served as part of the loading mechanism. An illustration of a prepared specimen assembly is shown in Figure 4. To facilitate smooth bolt insertion during assembly and to accommodate minor potential misalignments, all bolt holes in both the LVL and the Plexiglas were drilled 1 mm larger than the nominal bolt diameter.

### 2.3.3 Experimental Setup And Procedure

The experimental procedure for investigating the splitting strength of the bolted timber connections loaded perpendicular to the grain was generally conducted in accordance with the principles outlined in European Standard EN 26891:1991 [10]. A three-point bending configuration was employed, with loading applied under displacement control.

In this setup, the 1200 mm long LVL specimen was positioned horizontally, with its ends resting on two roller supports, providing a clear span typically around 1100 mm. The load was applied centrally at the mid-span of the specimen. Instead of a conventional steel loading plate, the aforementioned 20 mm-thick Plexiglas plates were utilised. These plates were firmly attached to the LVL specimen at its mid-section using the test bolts. The load from the testing machine was then applied to this Plexiglas assembly, effectively transferring the force into the LVL specimen perpendicular to its grain via the bolts. The transparency of the Plexiglas, a technique used by Franke et al. [11] for enhanced visualisation, provided unobstructed visual access to the critical connection zone on the LVL surface.

Two Linear Variable Differential Transformers (LVDTs) were strategically installed. One LVDT was positioned above the loading point to monitor and assist in controlling the displacement input from the testing machine. A second LVDT was placed below the specimen at its mid-span to accurately record the actual mid-span deflection of the LVL member during loading. A detailed schematic of the complete test setup is provided in Figure 4.

The mechanical behaviour of the bolted connections under perpendicular-to-grain loading was evaluated using a flexural testing machine, applying load at a constant rate of displacement of 1 mm/min until complete failure of the connection occurred. To document the deformation, crack development, and failure process, a high-resolution digital camera was positioned directly in front of the specimen, aligned with its centreline. This camera was configured to capture images at 10-second intervals throughout each test.


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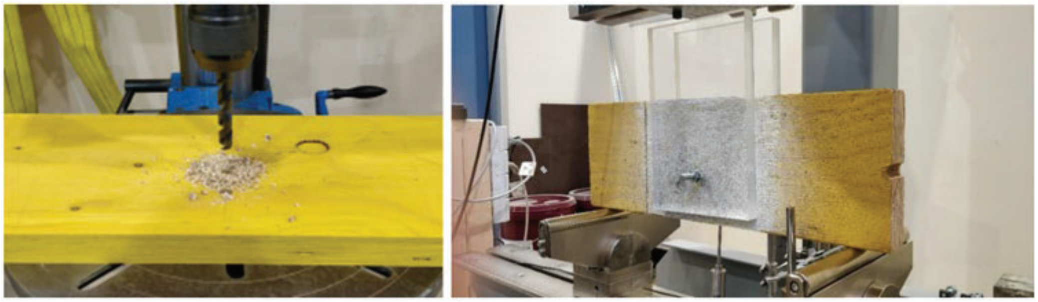

*Figure 4. Experimental arrangement and specimen preparation.*

### 2.3.4 Experimental Setup And Procedure

Throughout the connection testing program, the LVDTs continuously recorded the applied load versus the displacement (deflection) behaviour of the connection. This data provided critical information on stiffness, yield points (if any), and the ultimate load capacity, reflecting the overall connection deformation, which implicitly included any bolt deformation. The initiation and propagation of cracks were carefully monitored and documented through visual analysis of the time-lapse images captured by the high-resolution digital camera. This allowed for a detailed qualitative assessment of the splitting failure mechanisms characteristic of timber connections subjected to perpendicular-to-grain loading. The primary outcome for each test was the ultimate load-carrying capacity of the bolted connection.

## 3 – RESULTS AND DISCUSSION

This section presents and discusses the experimental findings from both the material characterisation tests conducted on the Laminated Veneer Lumber (LVL) and the main series of bolted connection tests. The results are analysed in the context of existing knowledge and the provisions of the Australian Standard AS 1720.1-2010.

### 3.1 MATERIAL PROPERTIES OF LVL

The characterisation of the LVL's mechanical properties, particularly its tensile strength perpendicular to the grain ($f_{t,90}$), was crucial for understanding the subsequent behaviour of the bolted connections.

### 3.1.1 Tensile Strength Perpendicular To Grain ($f_{t,90}$)

From the six primary test specimens subjected to three-point bending tests as per AS/NZS 4063.1-2010, the measured values for tensile strength perpendicular to the grain ($f_{t,90}$) were 0.49 MPa, 0.40 MPa, 0.46 MPa, 0.48 MPa, 0.50 MPa, and 0.50 MPa. The mean $f_{t,90}$ value was calculated to be 0.49 MPa, with a standard deviation of 0.016 MPa. This mean value provides a baseline material property for the Australian-sourced Meyer Timber LVL used in this study.

### 3.1.2 Failure Mode Of LVL Specimens

The typical load-deflection curve obtained from the material property tests distinctly illustrated that no visible cracks developed within the elastic region during the initial loading phase. However, as the material response transitioned from the elastic region into the softening region, the emergence of microcracks was detected. These microcracks typically initiate at the weakest points within the material structure, often influenced by the inherent variability of the wood veneers. With continued loading, these microcracks progressively evolved into larger, more discernible fractures, ultimately leading to the failure of the specimen.

In general, crack propagation was predominantly vertical, aligning with the grain direction of the veneers. This resulted in a brittle failure mode, which is a characteristic response of timber, including LVL, when subjected to tensile loading perpendicular to the grain. The initial crack formation was typically observed at or near the midpoint of the specimen, corresponding to the location of maximum bending moment and tensile stress, as indicated in illustrative failure patterns (Figure 5). However, it was noted that due to natural imperfections inherent in wood products, such as minor grain deviations or variations in veneer density, even in engineered products like LVL, crack initiation in certain specimens occurred away from the central region.

The cross-sectional view of failed specimens (Figure 5) further revealed that cracks propagated through the layered structure of the LVL. This often demonstrated delamination and interlaminar separation between the individual veneers. This type of failure is indicative of the material's layered composite nature and its susceptibility to tension-induced splitting along and between veneer interfaces. The overall failure mode observed was sudden and brittle, with minimal plastic deformation preceding the final fracture. This behaviour reinforces the inherent anisotropic nature of LVL under perpendicular-to-grain tensile loading, where the material's capacity is significantly lower and its response is less ductile compared to loading parallel to the grain.

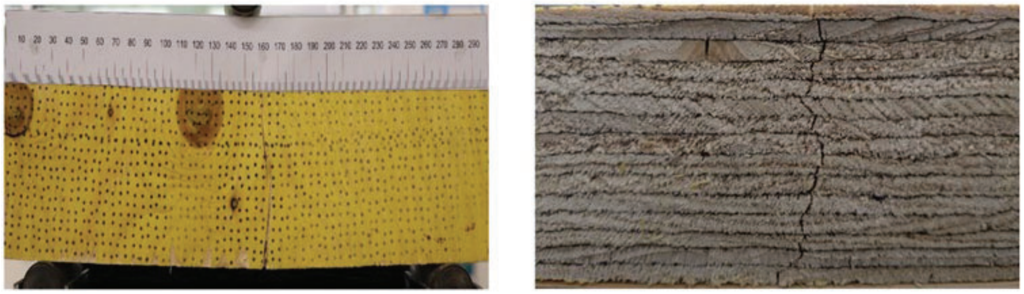

*Figure 5. Typical crack pattern in the sample (left); Cross section of the sample for interlaminar separation (right).*

## 3.2 BOLTED CONNECTION BEHAVIOUR

The primary focus of this study was the experimental evaluation of bolted LVL connections under load, with results compared against AS 1720.1 [2]. The experimental failure loads for the eighteen distinct timber-to-timber bolted connection configurations are summarised in Table 1, alongside their corresponding characteristic design capacities calculated according to AS 1720.1. Illustrative load-deflection curves and failure modes for connections with bolts spaced parallel to the grain are presented in Figure 6, and for connections with bolts spaced perpendicular to the grain in Figure 7.

*Table 1: Results of the connection tests*

| connection type | Bolt dia, D (mm) | SC | SR | Failure load (kN) | AS 1720.1 (kN) |
|---|---|---|---|---|---|
| type 1 | 10 | 4D | - | 15.89 | 15.32 |
| type 2 | 12 | 4D | - | 16.17 | 18.36 |
| type 3 | 16 | 4D | - | 16.86 | 24.48 |
| type 4 | 10 | 3D | - | 15.23 | 15.32 |
| type 5 | 12 | 3D | - | 17.43 | 18.36 |
| type 6 | 16 | 3D | - | 16.22 | 24.48 |
| type 7 | 10 | 2D | - | 16.92 | 15.32 |
| type 8 | 12 | 2D | - | 16.72 | 18.36 |
| type 9 | 16 | 2D | - | 16.23 | 24.48 |
| type 10 | 10 | _ | 5D | 31.84 | 15.32 |
| type 11 | 12 | _ | 5D | 32.84 | 18.36 |
| type 12 | 16 | _ | 5D | 32.74 | 24.48 |
| type 13 | 10 | _ | 4D | 31.42 | 15.32 |
| type 14 | 12 | _ | 4D | 31.35 | 18.36 |
| type 15 | 16 | _ | 4D | 29.71 | 24.48 |
| type 16 | 10 | _ | 3D | 28.33 | 15.32 |
| type 17 | 12 | _ | 3D | 28.01 | 18.36 |
| type 18 | 16 | _ | 3D | 27.2 | 24.48 |

### 3.2.1 Comparison With AS 1720.1 Design Capacities

The comparison between the experimental failure loads and the characteristic design capacities prescribed by AS 1720.1 reveals a marked imbalance in the Standard's predictive accuracy. Distinct zones of over- and under-prediction emerge, hinging primarily on the bolt spacing relative to the grain, bolt diameter and, to a lesser extent, bolt spacing.

*Bolt Spaced Parallel to the Grain (Types 1–9)*

When the bolts were spaced parallel to the grain (refer to Figure 6 for typical behaviour), AS 1720.1 was generally found to be unconservative, particularly for medium-to-large bolt diameters. For 10 mm bolts, a mixed response was observed: at the standard spacing of 4D (Type 1), their mean test-to-code (T/C) ratio was 1.04, indicating a slight reserve of capacity. However, reducing the spacing to 3D (Type 4) dropped this ratio to 0.99, effectively eliminating any safety margin. Further tightening the spacing to 2D (Type 7) surprisingly lifted the ratio to 1.10. The fact that such a modest change in spacing can cause the code prediction to oscillate between marginally safe and slightly unsafe suggests that the current parallel-to-grain design expressions in AS 1720.1 may underestimate the sensitivity of connection strength to secondary confinement effects and splitter-crack behaviour at short end distances or tight spacings.

For 12 mm bolts spaced parallel to the grain (Types 2, 5, 8), the deficiency in the Standard's prediction is more pronounced and consistent. Across 4D, 3D, and 2D spacings, the T/C ratios were between 0.88 and 0.95. This indicates a systematic shortfall of 5% to 12% in the predicted capacity, which must be absorbed by any inherent material overstrength or the nominal conversion factor from characteristic to mean strength, potentially rendering the effective reliability unacceptably low for serviceability-critical details.

The most significant over-prediction by AS 1720.1 for parallel-to-grain spacing occurred with 16 mm bolts (Types 3, 6, 9). Here, the code-predicted capacities exceeded the measured mean experimental values by 31% to 34% (T/C ratios of 0.66–0.69). This substantial discrepancy suggests that the diameter-squared term, which often underpins rope-effect and bearing-resistance components in timber


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connection design standards, scales too aggressively relative to the actual stiffness and plastic deformation reserve of the LVL substrate used in this study.

Collectively, these trends highlight that the parallel-to-grain formulae in AS 1720.1, while potentially calibrated historically for smaller bolts and larger end distances in sawn timber, do not appear to provide a uniform reliability index when designers employ larger dowel sizes or tighter joint geometries, which are increasingly common in modern engineered-timber frames to optimise member lengths.

*Bolts Spaced Perpendicular to the Grain (Types 10–18)*

In stark contrast to the parallel-to-grain results, the test series for bolts spaced perpendicular to the grain (Types 10–18; refer to Figure 7 for typical behaviour) showed AS 1720.1 to be overwhelmingly conservative. For 10 mm bolts (Types 10, 13, 16), the measured mean strengths exceeded the code-predicted capacities by 85% to 108% (T/C ratios from 1.85 to 2.08). This level of conservatism implies that designers could, in theory, significantly reduce the number of fasteners or adopt a smaller bolt diameter for such connections without impinging on the ultimate limit state capacity, based on these experimental findings.

This conservatism, while reducing with increasing bolt diameter, remained material. For 12 mm bolts spaced perpendicular to the grain (Types 11, 14, 17), the experimental results showed excess margins of 53% to 79% (T/C ratios from 1.53 to 1.79). Even for the largest 16 mm bolts (Types 12, 15, 18), a substantial safety buffer of 11% to 34% was retained (T/C ratios from 1.11 to 1.34). The observation that the code remains on the safe side for every perpendicular-to-grain spacing tested, from 5D down to 3D, suggests that the governing bearing-perpendicular-to-grain limit state within AS 1720.1 may be penalised excessively. This could be due to a combination of factors: potentially low characteristic bearing strength values that do not fully account for local tension relief provided by ductile steel dowels, and spacing requirements that might have been originally drafted to pre-empt brittle row-shear failures more typical in sawn timber rather than in a laminated veneer product like the LVL tested here. The data, therefore, point to a significant opportunity for rationalising the perpendicular-to-grain provisions in AS 1720.1, especially for the increasingly popular 10–12 mm bolts, where current oversizing appears to inflate material costs and potentially increase joint slip without delivering measurable gains in ultimate safety.

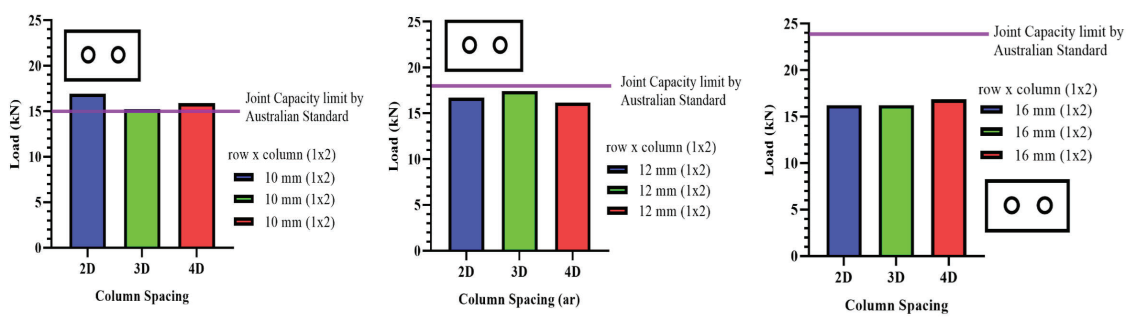


*Figure 6. Comparison of experimental results and the predictions by the Australian standard, bolts placed parallel to the grain.*

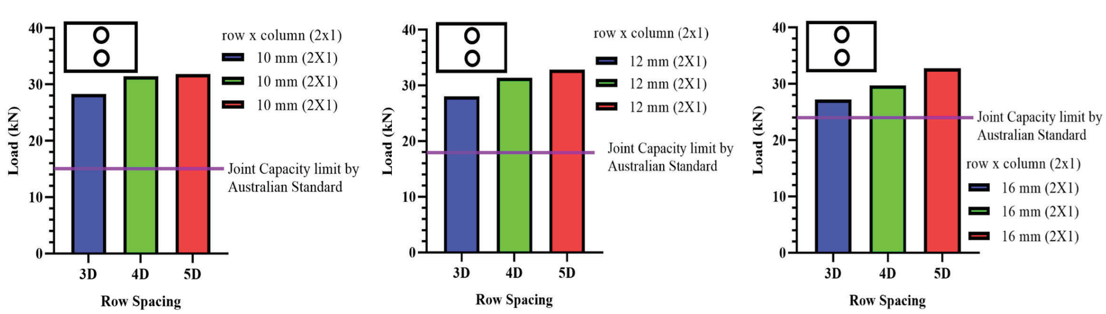


*Figure 7. Comparison of experimental results and the predictions by the Australian standard, bolts placed perpendicular to the grain.*

### 3.2.2 Influence Of Connection Parameters

*Effect of Bolt Diameter*

Bolt diameter emerges as the dominant parameter modulating the Standard's predictive bias. In parallel-to-grain spacing, increasing D from 10 mm to 16 mm swung the code from being marginally conservative (or slightly unconservative at 3D spacing) with T/C ratios around 1.0, to being distinctly unsafe with T/C ratios around 0.67.

Conversely, in perpendicular-to-grain spacing, the same increase in bolt diameter eroded the degree of conservatism but did not reverse it; the T/C ratios remained above 1.0 for all 16 mm bolt configurations. This asymmetric response indicates that a single diameter exponent or influence factor within the design equations cannot faithfully serve both grain directions. It suggests that the complex interaction between timber bearing strength, dowel bending capacity, and localised timber crushing varies significantly with the loading mode relative to the grain.

*Effect of Bolt Spacing*

Bolt spacing, while generally secondary to diameter in its impact on the T/C ratio, still exerted enough influence to alter the code's safety classification in isolated cases. The switch from slight over-prediction to slight under-prediction for 10 mm bolts spaced parallel to the grain when moving from 4D to 3D spacing, and then back to over-prediction at 2D spacing, underscores the need for a more nuanced understanding or modelling of spacing-dependent modification factors. This appears particularly relevant for small-diameter, parallel-to-grain joints where timber splitting, rather than dowel yielding, often governs the ultimate capacity. For perpendicular-to-grain spacing, varying the spacing from 5D down to 3D consistently reduced the experimental failure load and the T/C ratio, as expected, but the Standard remained conservative across all tested spacings.

## 3.3 IMPLICATIONS FOR DESIGN PRACTICE AND CODE DEVELOPMENT

The experimental findings from this study carry significant implications for both practising structural engineers using AS 1720.1 and for future development of the Standard itself.

### 3.3.1 Guidance For Designers

From a practical standpoint, designers relying on AS 1720.1 for bolted LVL connections should be alert to two divergent risks identified in this research. Firstly, for medium (12 mm) and large (16 mm) diameter bolts spaced parallel to the grain, the Standard can substantially over-predict capacity, in some cases by up to one-third. This erosion of the intended reliability margin could potentially precipitate premature serviceability problems, such as excessive slip, or even ultimate capacity issues under certain load conditions, like progressive splitting under cyclic wind loads. A prudent interim measure for designers might be to apply an additional bolt-size reduction factor or consider adopting the next higher deformation classification (implying lower capacity) for such connections until revised, validated design values are promulgated.

Secondly, at the opposite end of the spectrum, the Standard's significant conservative bias for bolts spaced perpendicular to the grain limits design efficiency. In applications where connection length, member size, or fabrication cost is critical, such as in truss shoe detailing, moment-resisting portal frame knee joints, or connections for Cross-Laminated Timber (CLT) floor-to-beam bearings, there appears to be considerable room to rationalise bolt numbers or trial smaller bolt diameters. However, designers choosing to optimise based on such findings should proceed with caution and verify ductility and deformation limits, potentially through specific testing or more detailed analysis, especially if serviceability is a key concern.

### 3.3.2 Recommendations For AS 1720.1 Revisions

The data presented also carries significant implications for the future development of AS 1720.1. A reliability-based recalibration that explicitly models the effects of bolt diameter and spacing, possibly through a piecewise or non-linear formulation, would be beneficial. Such an approach could bring the parallel-to-grain predictions back onto a target reliability index while simultaneously releasing unnecessary conservatism in the perpendicular-to-grain direction. Incorporating material properties like timber density and fastener slenderness as continuous variables, rather than relying on discrete tables or broad classifications, may further harmonise predictions across different timber species and engineered wood products like LVL.

# 4 – CONCLUSION

This study provides a comprehensive set of experimental data to date on the tensile capacity of bolted LVL connections loaded perpendicular to the grain within an Australian context. By systematically varying bolt diameter and spacing in both parallel and perpendicular directions to the grain, and by benchmarking the measured capacities against the provisions of AS 1720.1 2010, several important insights have been gained.

First, connection geometry matters. For bolts aligned parallel to the grain, the Standard's current equations are prone to overprediction once the bolt diameter exceeds 12 mm or the row spacing is reduced below 4D. In the present tests the mean test to code ratio fell to 0.66 for 16 mm bolts, indicating that the intended reliability index is not achieved and that brittle splitting failures may occur before the nominal design load is reached. Conversely, for bolts aligned perpendicular to the grain the Standard is demonstrably conservative, with capacities underestimated by up to a factor of two for 10 mm bolts and by at least 11 % even for the largest bolts examined. This conservatism inflates material use, increases fabrication time and, paradoxically, can exacerbate serviceability problems because oversized joints are generally more flexible.

Second, bolt diameter exerts a non linear influence on capacity that is not captured by the current diameter squared term implicit in AS 1720.1. The data reveal that stiffness and confinement effects provided by larger dowels are offset by stress concentrations and limited plastic deformation capacity in the thin LVL veneers, particularly when load is transferred primarily through bearing rather than dowel bending. This mismatch explains the Standard's loss of accuracy for larger bolts.

Third, the experimentally determined LVL tensile strength perpendicular to grain ($f_{t,90} \approx 0.49$ MPa) is an order of magnitude lower than the parallel to grain tensile strength normally assumed for sawn softwood.


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Notwithstanding the strength of the dataset, several limitations constrain direct generalisation.

• Only one LVL product of medium density ($\approx 550\,kg\,m^{-3}$) and a single veneer lay up was tested. Higher density LVLs, parallel strand lumber or hybrid lay ups could display different splitting behaviour.

• All specimens were loaded monotonically at a constant displacement rate; cyclic, impact or mixed mode loading was not assessed.

• Moisture content was tightly controlled (8 %), yet in service LVL may equilibrate at higher humidities that lower tensile strength perpendicular to grain.

• Connection detailing was limited to two bolt arrangements; rows of three or more bolts, common in portal frame knee joints, may introduce additional row shear or group tear out modes.

• Finally, the study did not measure serviceability attributes such as slip modulus or long term creep, both critical to deflection controlled members.

## 5 – REFERENCES

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