A Review on Mechanical Behavior of Laminated Bamboo Lumber Connections

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ABSTRACT
Due to the transition of Architecture, Engineering and Construction (AEC) sector to a sustainable development, bamboo turned out to be a suitable option to conventional building materials due to its environmental friendliness and distinctive mechanical properties. Initially, it was impossible to use the original bamboo in flat applications due to its round cross-sectional shape, but engineered bamboo, in particular laminated bamboo lumber (LBL), solved this problem. Connections are one of the most important parts of building structures that are responsible for the distribution of loads and energy, ensuring the stability and safety of the structure by avoiding concentration of localized stress that can cause failures at the joints. Over the past decade, a series of experimental studies of connection performance of LBL have been conducted. In order to stimulate the use of laminated bamboo in construction industry, this article reviewed the existing published literature and described the behavior of LBL connections in terms of failure mechanisms and factors affecting the bearing capacity considering three connections categories, namely, LBL sheathing-to-framing connections, LBL dowel-type connections, and glued-in rods (GIROD) in LBL connections. According to the reviewed studies, LBL has great potential and can serve as a worthy alternative for conventional building materials. This work can provide a reference for engineering applications and future research.

KEYWORDS
Laminated bamboo lumber; connections; mechanical properties; composites

1 Introduction
Bamboo has got worldwide attention in the architecture, engineering, and construction (AEC) industry due to its sustainable characteristics [1-6]. It has a short life cycle and a high yield and can reach 30 m in height in 4 months and maximum strength in 3–8 years [7-11]. Its high carbon sequestration and low energy manufacturing help to reduce the impact on the environment compared to conventional building materials [9,12]. According to previous studies, bamboo copes well with bending and seismic loads, and its mechanical behaviour is comparable to mild steel, cast iron, aluminium alloys, and wood [9,13–20]. For instance, the tensile strength and modulus of elasticity (MOE) parallel to grain of Moso bamboo (Phyllostachys pubescens) can reach up to 309 MPa and 27.397 GPa in tension, 48–114 MPa and 3.6–11 GPa in compression, 50–132 MPa and 7.1–18.2 GPa in bending, and 15–20 MPa in shear, respectively [21–23]. It should be noted that the strength values of bamboo vary depending on the species type and moisture content [22,24–26]. Fig. 1 shows the selected mechanical properties of giant timber bamboo (Phyllostachys bambusoides) compared with conventional building materials. The data for giant timber bamboo, cast iron, aluminium alloy and structural steel are from reference [9], the data for Douglas-fir, eastern white pine, and
northern red oak are from reference [27], and the data for concrete from reference [28].

Figure 1: Selected mechanical properties of giant timber bamboo compared to conventional building materials

Due to the circular cross-section, bamboo was difficult to use in flat applications, so engineered bamboo was developed, such as laminated bamboo lumber (LBL), parallel strand bamboo (PSB), cross-laminated bamboo (CLB), glued laminated bamboo (glubam), etc. which can be utilized in various shapes and sizes, and its physical and mechanical properties are comparable to timber and glue-laminated timber products [29–36] (Fig. 2, Table 1).

Figure 2: Examples of engineered bamboo: (a) LBL; (b) PSB; (c) glubam.

Table 1: Selected mechanical properties of LBL material compared to similar wood and wood-based materials

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Species type</td>
<td><em>Phyllostachys</em></td>
<td><em>P. pubescens</em>,</td>
<td>Douglas-fir</td>
<td>Pine</td>
<td></td>
<td></td>
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<tr>
<td><em>D. strictus</em></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Bending strength parallel to grain (MPa)</td>
<td>63.87–128.4</td>
<td>54.2–71.7</td>
<td>48.74</td>
<td>26.1</td>
<td>85</td>
<td>80</td>
</tr>
<tr>
<td>Property</td>
<td>Range</td>
<td>LVL (MPa)</td>
<td>Glulam (MPa)</td>
<td>WPS (MPa)</td>
<td>LVL (MPa)</td>
<td></td>
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<tr>
<td>MOE in bending (MPa)</td>
<td>8320–10912</td>
<td>15400–19300</td>
<td>15370</td>
<td>4100</td>
<td>13400</td>
<td></td>
</tr>
<tr>
<td>Tensile strength parallel to grain (MPa)</td>
<td>90–124</td>
<td>88.5</td>
<td>16.5–26</td>
<td>11.6</td>
<td>107.6</td>
<td></td>
</tr>
<tr>
<td>MOE in tension parallel to grain (MPa)</td>
<td>10700</td>
<td>13790</td>
<td>9400–11900</td>
<td>3000</td>
<td>11600–14800</td>
<td></td>
</tr>
<tr>
<td>Compressive strength parallel to grain (MPa)</td>
<td>29.55–72.60</td>
<td>36</td>
<td>24–31</td>
<td>28.1</td>
<td>49.9</td>
<td></td>
</tr>
<tr>
<td>MOE in compression parallel to grain (MPa)</td>
<td>8396–11022</td>
<td>-</td>
<td>8600</td>
<td>3700</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Shear strength parallel to grain (MPa)</td>
<td>7.15–17.5</td>
<td>7.34</td>
<td>2.7–4.3</td>
<td>8.1</td>
<td>7.8</td>
<td></td>
</tr>
</tbody>
</table>


As can be seen from Table 1, the strength of LBL parallel to grain was 90–124 MPa with MOE of 10700 MPa in tension, 29.55–72.60 MPa with MOE of 8396–11022 MPa in compression, 63.87–128.4 MPa with MOE of 8320–10912 MPa in bending, and 7.15–17.5 MPa in shear [49] with the coefficient of variation (COV) within 10%. The variability in strength values of LBL can be explained by the effect of density and thickness of bamboo strips, location in culm, growth portion, type of treatment, and strips arrangements on the mechanical properties [49,50].

Over the past decade, extensive research has been done on the mechanical and physical properties of engineered bamboo. A series of studies were conducted on engineered bamboo sheathing-to-framing connections [51,52], bolted joints [53–60], roof trusses [61], and even furniture connections [62], with the results indicating that the loadcarrying capacity was comparable to timber connections. To summarize the state of the art, reviews on the existing knowledge about engineered bamboo, in particular LBL, were conducted to demonstrate its practical and potential use, as well as to increase its application in construction. Dauletbek et al. [63] reviewed the mechanical performance of structural LBL elements. Ramage et al. [64] reviewed the mechanical behaviour of bamboo scrimber and LBL and compared it to structural timber and LVL. Gatoo et al. [65] made a review of currently operating national and international timber codes and considered the possibility of developing similar comprehensive standards for LBL. Disen and Clouston [66] and Hong et al. [67] summarized the current state of the art in full culm bamboo connections.

An appropriate design of structures is a requirement of great importance, which ensures the safety of structures and the optimization of material resource consumption. According to previous studies, failure of connections is responsible for 25% of recent collapses of timber structures [68–71]. The reliability of connections is a key to stable structures, and a better understanding of the performance of the LBL connections is inevitable. This study aims to review the recent investigations on the behaviour of the LBL connections in terms of failure mechanisms and factors affecting the bearing capacity considering three connections categories, namely, LBL sheathing-to-framing connections, LBL dowel-type connections, and glued-in rods (GIROD) in LBL connections. The “Science Direct” database was used for full-text search, and 22 papers published between 2012 and 2021 were adopted for review.
2 Review on the mechanical behaviour of LBL connections

2.1 Sheathing-to-framing connections

Wooden frame buildings have always been distinguished by their high level of comfort, and resistance to extreme climatic conditions and earthquake damage. These advantages are explained by the ability of lateral systems of frame buildings to distribute energy without significant loss of lateral capacity. The lateral systems are usually wooden frames lined with wooden panels, such as oriented strand board (OSB) and plywood.

The behaviour of wood-based sheathing-to-framing connections has been thoroughly studied over the past decade. According to the studies, the material of the sheathing panel, wall aspect ratio (AR), and edge nail spacing were found to be the main influencing factors of wooden sheathing-to-framing connections’ performance under lateral forces [72–79]. With the invention of LBL, recent studies have been conducted to understand the embedding strength of its connections, their mechanisms of failure, as well as factors affecting their behaviour under lateral loads. Studies were conducted both on small-size connections to understand their basic mechanical characteristics and on full-size structural shear walls and house modules to understand their potential in structural applications. Table 2 provides a summary of selected papers on small-size LBL sheathing-to-framing connections.

<table>
<thead>
<tr>
<th>Nails</th>
<th>Size, mm</th>
<th>Frame</th>
<th>Species</th>
<th>Size, mm</th>
<th>Sheathing Species</th>
<th>Dens, g.cm³</th>
<th>Size, mm</th>
<th>Test</th>
<th>Edge distance, mm</th>
<th>Sampling number</th>
<th>COV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-drilling screw</td>
<td>D 3.8, L 70</td>
<td>LBL</td>
<td><em>Dendrocalamus giganteus</em> Munro</td>
<td>38x8 9x12 0</td>
<td>BOSB</td>
<td>0.73</td>
<td>12x5 0x30 0</td>
<td>Mono</td>
<td>50</td>
<td>6 mono tonic, 4 cyclic</td>
<td>10.54 33.09</td>
</tr>
<tr>
<td>Wire nail [80]</td>
<td>D 3, 3.4; L 70, 80</td>
<td>LBL</td>
<td><em>Dendrocalamus giganteus</em> Munro</td>
<td>38x8 9x12 0</td>
<td>BOSB</td>
<td>0.73, 0.63</td>
<td>12x5 0x30 0</td>
<td>Mono</td>
<td>10, 25, 50</td>
<td>6 mono tonic, 4 cyclic</td>
<td>5.54 – 33.76</td>
</tr>
<tr>
<td>Wire nail [81]</td>
<td>D 3.2; L 75</td>
<td>LBL</td>
<td><em>Phyllostachys pubescens</em> Moso</td>
<td>38x142.5x246 4</td>
<td>OSB</td>
<td>Douglas Fir</td>
<td>11.9x 50x50 0</td>
<td>Mono</td>
<td>19</td>
<td>11 for each geometry</td>
<td>32–35</td>
</tr>
<tr>
<td>Staple nail [82]</td>
<td>D 1.98; L 51</td>
<td>Wood lumber</td>
<td>SPF 38x8 9</td>
<td>Plybamboo</td>
<td><em>Guadua angustifolia</em> Kunth</td>
<td>0.847</td>
<td>-</td>
<td>Mono</td>
<td>60, 50</td>
<td>10 mono tonic, 1 cyclic</td>
<td>9.97–40.94</td>
</tr>
<tr>
<td>Wire nail [82]</td>
<td>D 2.10; L 51</td>
<td>Wood lumber</td>
<td>SPF 38x8 9</td>
<td>Plybamboo</td>
<td><em>Guadua angustifolia</em> Kunth</td>
<td>0.847</td>
<td>-</td>
<td>Mono</td>
<td>60, 50</td>
<td>10 mono tonic, 1 cyclic</td>
<td>8.05–30.91</td>
</tr>
<tr>
<td>Wire nail [83]</td>
<td>D 3.8, 4.19; L 76.2, 88.9</td>
<td>LBL</td>
<td><em>Guadua angustifolia</em> Kunth</td>
<td>40x9 0x15 0</td>
<td>Plybamboo</td>
<td>-</td>
<td>16x2 0x4 0</td>
<td>Mono</td>
<td>19</td>
<td>5 mono tonic tests, 10 cyclic</td>
<td>9.6–48.0</td>
</tr>
</tbody>
</table>


Sun et al. [80] investigated the behaviour of bamboo-oriented strand board (BOSB) and LBL connection with different nail types and compared it to conventional OSB-LBL and plywood-LBL connections. The monotonic tests were conducted according to the ASTM D1761 [84] and 6 replicates were...
tested, while cyclic tests were conducted based on ISO 16670 and 4 replicates were tested [85]. According to the results, the BOSB-LBL connection showed the following failure modes: brittle failure for hex head self-tapping screw; nail yielding followed by withdrawal and partial nail head pulling trough framing member for wire nails. It was obvious, that the nail type affected the failure pattern of the BOSB-LBL connection. The specimens with an edge distance of 10 mm failed in sheathing edge-tear, while 25 and 50 mm specimens were characterized by nail withdrawal and partial nail head pulling through the framing member. Considering the effect of nails type, and edge distances, the hex-head self-tapping screw had lower deforming ability but stronger lateral resistance and stiffness than that of wire nails, and an increase in edge distances appeared to enhance the strength and ultimate displacement of specimens. However, this conclusion needs further investigation, because the size and number of the specimens were small which led to high COV values constituting 15–30%. The authors mentioned, that the tests were conducted to obtain preliminary parameters of the bamboo-based sheathing-to-framing connection. Therefore, it is necessary to conduct more tests on at least 10 replications for each variable to obtain statistically significant results. Considering the sheathing type, the BOSB-LBL connections failed by nail withdrawal and nail head pulling through BOSB, while OSB/plywood-LBL connections – by nail head pulling through the framing member and nail bending [80,82]. The authors concluded that the behaviour of the BOSB-LBL connections had better lateral load-carrying capacity and energy dissipation compared to those of wood-based connections [81].

Based on test methods used for wood products, Echeverry and Correal [83] evaluated the monotonic and cyclic performance of a nailed lateral system consisting of LBL framing members and sheathing panels made of Laminated Guadua Mats (LGM) both parallel and perpendicular to the fibre direction [86] (Fig. 3).

![Test setup for LGM sheathing-to-framing connection (reproduced from [86])](image)

The study adopted 5 monotonic tests and 10 cyclic tests for each combination of sheathing orientation and nail size to obtain preliminary but adequate results to access the variability of the experimental outcomes. According to the test results, in both monotonic and cyclic tests, the most frequent failure mode was the nail yielding in bending despite the nail size and the orientation of the sheathing panel, except for specimens with 16D nails and perpendicularly oriented panels, which failed due to partial pulling out of the nail head through the panels. In contrast to the previous study with BOSB-LBL connection, no failures due to nail withdrawal from the framing member or fatigue occurred. The authors concluded, that the orientation of panels didn’t affect the cyclic behaviour of the connection, and maximum load and displacement significantly increased with an increase in nail size. The authors found, that general cyclic behaviour and the capacity of wood-framed connections made of wood framing members (Pinus radiata D. Don) and plywood sheathing with an equivalent thickness was similar to LGM connections, showing the same failure mode as nail yielding in bending, regardless of the panel orientation or nail size. Wood connections
appeared to be more ductile since the monotonic load–displacement values were 20–35% higher than those of LGM connections. The lower stiffness of LGM connections can be explained by the nonuniform density of the material caused by voids and imperfections of the split Guadua mats. Therefore, the optimization of manufacturing LGM panels should ensure the improvement of its connection capacity. In addition, further research should be done to investigate the behaviour of propersize LGM shear walls following the recommendation of international standards.

Sinha and Miyamoto [81] compared plate (PG) and edge (EG) geometries of LBL-OSB connections loaded perpendicular and parallel to LBL (Fig. 4).

![Figure 4: Schematic of connection geometries: (a) edge connection; (b) plate connection [81]](image)

A total of 22 connections were tested, 11 for each geometry. According to the results, no statistically significant differences were observed in the strength of both geometries. The authors used National Design Specification (NDS) Yield Model [87] for the design of nailed connections and concluded that it could reasonably predict capacity and yielding mode for EG if the dowel-bearing capacity of the material was known. However, the model overestimated the values for PG. In addition, the observed COV for EG and PG connections were 35% and 32%, respectively, and the number of samples tested in this study statistically confirmed the obtained results only at an 80% confidence level. Therefore, further investigation is necessary for the estimation of PG and LBL-OSB connections of different sizes.

The behaviour of bamboo-based sheathing-to-framing connections has also been studied in view of the structural applications, where members have been used in real dimensions. Table 3 provides the details from selected studies on sheathing-to-framing connections with structural dimensions. The material of sheathing panels was represented by Glued Laminated Guadua (GLG) connected to framing members made of wood or LBL.

<table>
<thead>
<tr>
<th>Nails</th>
<th>D, mm</th>
<th>Length, mm</th>
<th>Frame Specie s</th>
<th>Size, mm</th>
<th>Sheathing Specie s</th>
<th>Size, mm</th>
<th>AR</th>
<th>Loading Type</th>
<th>Edge distance, mm</th>
<th>Sampling number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire nail [88]</td>
<td>3.0</td>
<td>63.5</td>
<td>Wood, solid Chilean Radiata pine</td>
<td>41×90</td>
<td>GLG</td>
<td>9×120, 0×240</td>
<td>1:1, 2:1 Monotonic, cyclic</td>
<td>152</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>
Correal and Varela [89] examined and compared 3 building modules as one-story module, a two-story module, and a two-story module with a wall finish, the shear walls of which were made of GLG, OSB, and plywood. Under the shake table test, the modules exhibited light damage on the wall and the wooden frame structure without finishing, and significant cracking appeared on the corners of the windows and at the joints between the structural and non-structural walls of the exterior and interior finishing (Fig. 5).

Varela et al. [88] compared the cyclic performance of shear walls made of LBL, OSB, and Plywood with different edge nail spacing of 50 mm, 76 mm, and 152 mm and AR of 1:1 and 2:1. A total of 24 shear wall racking tests was conducted. The failure modes were associated with the removal of nails from the panels, although the punching of the panels with nails also took place. It is worth noting that the nail driving schedule for walls with AR 2:1 was performed in a staggered order and the nails were driven into both double end studs instead of one to improve load transfer to the end posts since monotonic and cyclic tests of shear wall with a distance between the edges of the nails 76 mm and 50 mm and AR 1:1 showed localized failure in the form of tension in the two end studs to which the clamps were attached. All cyclic tests demonstrated localized fatigue failures of sheathing nails regardless of the type of wall. At the same time, for OSB and plywood walls, tearing and punching with nails with further damage to the panel itself was observed more than for GLG walls. This was explained by a higher density of the GLG panels compared to OSB and plywood, constituting 0.72 g.cm$^{-3}$, 0.63 g.cm$^{-3}$, and 0.48 g.cm$^{-3}$, respectively. This, in turn, prevented the breaks and slippage in the GLG panels that were observed in wood-based panels. Based on the results of studies made by Correal and Varela [89] and Varela et al. [88], it can be concluded that shear wall sheathing with GLG has similar load–displacement behaviour to shear walls sheathing with OSB and plywood panels. Shear walls with the GLG panels were affected by the edge nail spacing in the same manner as OSB and plywood. According to the results, increasing the number of nails improved the wall
strength, but AR showed no effect on the peak shear strength and energy dissipation of the GLG walls. The authors recommended using adequate anchorage and force transfer details for walls with AR 1:1 and closely spaced nails due to the low capacity of the framing members. A decrease in nail spacing decreased the displacement ductility capacity and the dissipation of energy by walls, while the stiffness and maximum load-carrying capacity of the wall increased. The peak shear strength values for all panels were found to be comparable, and it is worth noting that the higher density of GLG panels allowed them to dissipate more energy and save themselves from significant damages compared to OSB and plywood. The results of the shake table test showed limited damages on shear wall sheathing with GLG panels after a strong earthquake simulation. Summing up, stiffness, maximum load capacity, and ductility of bamboo-based lateral systems were significantly affected by a number of nails, nail spacing, and sheathing panel materials, while AR of the wall didn’t show any impact.

Luna and Takeuchi [90] investigated the behaviour of GLG frames with K-bracing and stiffened with GLG panels under lateral load (Fig. 6). According to load–displacement curves obtained from the tests, frames with K-bracing exhibited elastoplastic behaviour, while the elastic behaviour of frames with panels was divided into two zones such as accommodation of frames and elastic region. Both structures showed that the frames had great ductility. The maximum lateral drift allowed in Colombia by the earthquake-resistant building code is 1%, the value for which, the two types of structures tested were still in the elastic behaviour area.

![Figure 6](image)

**Figure 6:** Composition of GLG frames: a) frames with K-bracing; b) frames with panels [90]

The reviewed connections were subjected to monotonic and cyclic loads. Regardless of size, the number of nails and edge distance, the connection exhibited similar behaviour. The typical hysteretic curves for bamboo sheathing-to-framing connections were practically similar to those made of OSB and plywood. As can be seen from Fig. 7 a, the typical hysteretic loops of sheathing-to-framing connections made of bamboo were characterized by pinched unloading response [80,82,83]. The initial loading stiffness was similar to that of monotonic tests (Fig. 7 b) [82]. With an increase in displacement between cycles in the reloading phase, the reduction of the elastic stiffness and ultimate load was observed and constituted half of those in the loading condition [80,82,83].
Figure 7: Typical cyclic and monotonic curves for bamboo sheathing-to-framing connections: (a) cyclic load-displacement curves; (b) monotonic load-displacement curves (taken with permission from Echeverry and Correal [83]).

The typical backbone curves observed from the cyclic test showed similar general behaviour as positive curves from the monotonic test and were characterized by the high nonlinear response when the peak load was reached [80,82] (Fig. 7 b). The connection capacity also decreased by 50–80% of the peak load in the reverse direction. It was observed, that full-scale shear walls exhibited similar behaviour, which can be explained by the mechanical properties of used nails [82,91].
### 2.2 Dowel-type connections

Many studies have been done to understand the behaviour of the LBL dowel-type connections and determine factors affecting their stability and strength. Table 4 provides a summary of selected papers on the mechanical behaviour of the LBL dowel-type connections.

**Table 4: Selected data on LBL dowel-type connections**

<table>
<thead>
<tr>
<th>Species</th>
<th>Size, mm</th>
<th>Direction</th>
<th>Dowel type</th>
<th>D, mm</th>
<th>Standard</th>
<th>Sampling number</th>
<th>COV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moso [92]</td>
<td>20–40×90×168</td>
<td>Radial</td>
<td>Steel dowel</td>
<td>9.92, 11.86, 13.95, 15.75</td>
<td>ASTM D 5764</td>
<td>3</td>
<td>2–16</td>
</tr>
<tr>
<td>Moso [93]</td>
<td>30×90×168</td>
<td>Radial</td>
<td>Steel dowel</td>
<td>12</td>
<td>ASTM D 5764</td>
<td>5</td>
<td>3–15</td>
</tr>
<tr>
<td>Moso [94]</td>
<td>38×50×50</td>
<td>Radial</td>
<td>Groove</td>
<td>6, 8, 10, 12</td>
<td>ASTM D 5764</td>
<td>12</td>
<td>15–30</td>
</tr>
<tr>
<td>Moso [94]</td>
<td>60×80×170</td>
<td>Radial</td>
<td>LBL dowel</td>
<td>6, 8, 10, 12</td>
<td>ASTM D 5652</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Guadua [95]</td>
<td>20.2–30.2×40×50</td>
<td>Radial</td>
<td>Wire nail</td>
<td>3.05, 3.76, 4.19</td>
<td>ASTM D 5764</td>
<td>5–6</td>
<td>8–23</td>
</tr>
<tr>
<td>Moso [96]</td>
<td>-</td>
<td>Tangential</td>
<td>Steel bolt</td>
<td>15.9</td>
<td>ASTM D 5764</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Moso [97]</td>
<td>38×72×350</td>
<td>Radial</td>
<td>Steel dowel</td>
<td>12</td>
<td>EN 383</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Moso [98]</td>
<td>20×40×50</td>
<td>-</td>
<td>Wire nail</td>
<td>2.5</td>
<td>ASTM D 5764</td>
<td>5–8</td>
<td>-</td>
</tr>
<tr>
<td>Moso [99]</td>
<td>20×40×150</td>
<td>-</td>
<td>Wire nail</td>
<td>2.1, 2.5, 2.8</td>
<td>ASTM D 1761</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Moso [100]</td>
<td>30–120×120×900</td>
<td>Radial</td>
<td>Dowel</td>
<td>10, 12, 14, 16</td>
<td>ASTM D 5652</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>Moso [101]</td>
<td>30×120×250</td>
<td>-</td>
<td>Bolt</td>
<td>8, 10, 12, 14, 16</td>
<td>ASTM D 5764</td>
<td>3</td>
<td>11.84</td>
</tr>
<tr>
<td>Moso [102]</td>
<td>Beams 100×250×900, Columns 180×250×1000</td>
<td>-</td>
<td>Bolt</td>
<td>14, 18, L-, L-, T-shapes</td>
<td>ASTM D 1761</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Guadua [103]</td>
<td>200×300×2440</td>
<td>-</td>
<td>Bolt</td>
<td>10</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

According to the literature, most of the tests on the dowel-bearing strength of LBL connections were conducted based on the ASTM D5764 standard [104], which suggests two types of test configurations – half-hole and full-hole (Fig. 8).
Cui et al. [92] conducted a full-hole test on the dowel-bearing capacity of LBL parallel to grain considering the impact of specimen size, the loaded length, and the bamboo strip arrangements. A total of 13 groups were adopted for the tests, each group has been repeated 3 times. The COV of obtained dowel-bearing properties ranged between 2 and 16%. There were 2 failure modes: crushing of fibres under the dowel hole and propagating of 1–2 shear cracks at the edge of the hole or internal buckling and peeling with light cracks (Fig. 9 a,b). According to the results, the strip arrangements had no significant effect, while with an increase in thickness and loading length, the embedding strength of the LBL connection decreased.

In the next investigation, Cui et al. [93] studied the behaviour of dowelled connections of LBL under elevated temperatures from 20°C to 250°C. Two types of grain directions of the laminated bamboo were studied, perpendicular to grain and parallel to grain. The target temperatures were 20°C, 50°C, 80°C, 100°C, 120°C, 150°C, 180°C, 200°C, 220°C, and 250°C, each test was repeated 5 times. The COV of mechanical
parameters parallel and perpendicular to grain ranged between about 3–6% and 3–15%, respectively. The specimens parallel to grain exhibited 2 failure modes characterized by the fibre crushing beneath the dowel hole without a visible crack in the range of 20°C–180°C, and the appearance of 1–2 shear-splitting cracks on the hole edge. The specimens perpendicular to grain showed expansion of 2 cracks at an angle of 45˚ along the loading direction with bamboo fibres crushing under tensile and shear stresses, and shear fracture parallel to grain from one side of the dowel to the other with densification beneath the dowel caused by compression in the range of 20°C–100°C (Fig. 10).

![Figure 10: Failure modes of specimens perpendicular to grain: a) Mode 1; b) Mode 2 (reproduced from Cui et al. [93])](image)

All the specimens showed brittle failure regardless of the increase in temperature. The load–displacement curves for the parallel direction remained linear and reached the yielding phase after the proportional limit and showed the long plastic displacement before failure in the temperature range of 20°C–180°C. The curves of transverse specimens kept growing after the yielding phase, showing plastic displacement in the temperature range of 20°C–250°C. The turning points for both grain directions were 100°C and 150°C, where the load–displacement curves changed and the embedding strength increased.

Reynolds et al. [97] investigated the behaviour of dowelled connections of LBL treated by caramelization and bleaching. The test procedure was based on EN 383 [105], 10 specimens for each type of LBL were adopted. According to the results, the ductility of bleached bamboo was twice of the caramelized one. In addition to the failure modes 1 and 2 mentioned in previous studies, LBL also failed by shear plug formation (Fig. 9 c). Khoshbakht et al. [96] tested 15 replications of the LBL dowel connection as determined by ASTM D2915 [106] and gave a better understanding of the failure mechanism by finite element modelling (FEM). No glue failure was observed in the specimens. According to the results, in-plane shear stress was the primary cause of LBL failure which typically occurred off-hole centre at 1/6 of the hole perimeter left or right of the centre. Tension perpendicular to grain appeared to be the secondary reason for failure which occurred 7.4 mm beneath the hole, at the centre of the contact region. The FEM matched the experimental results within reasonable limits of statistical variability. High sensitivity to friction forces was observed during simulations, therefore, the effect of the coefficient of friction between the steel bolt and the LBL material on the destruction of LBL should be investigated.

When comparing load–displacement diagrams, the LBL parallel to grain showed an explicit transition from linear stage to plastic followed by cracks propagation from the dowel parallel to the loading direction. At the same time, caramelized bamboo exhibited brittle behaviour and short plastic region before fracture, compared to bleached bamboo (Fig. 11 a, b). To compare, Sitka spruce had a weakly expressed transition to a lower-stiffness plastic region (Fig. 11 c). The specimens loaded in a perpendicular direction showed a steady increase after reaching the yielding stage, the failure occurred suddenly and the load decreased quickly (Fig. 11 d).
Figure 11: Load-displacement graphs: a) Sitka spruce parallel to grain; b) bleached LBL parallel to grain; c) caramelized LBL parallel to grain; d) LBL parallel to grain under elevated temperature; e) LBL perpendicular to grain under elevated temperature (taken with permission from Reynolds et al. [91] and Cui et al. [87])

Li and Zhou [94] conducted a half-hole embedment test of LBL connection according to ASTM D5764 [104], and 12 specimens for each dowel diameter (6, 8, 10, and 12 mm) were considered. Similar to fullhole test specimens, a brittle behaviour, crushing failure around the pressure head, and splitting along the fibre grain of the specimens were observed. In general, the COV from embedment tests ranged from 15 to 30% and in some cases exceeded 30%. According to Ramirez et al. [95], the dowel-bearing strength of the LBL connection depended on the diameter of the nail and threaded bar fastener and the specimen width-to-diameter ratio, since with an increase in the diameter the dowel-bearing strength decreased due to the volume effect under the fastener hole. The dowel-bearing strength of the LBL connection was higher in the parallel direction than in the perpendicular direction. The authors compared the behavior of LBL connections considering embedding load directions (longitudinal, tangential, and radial), 45 and 115 tests were conducted on groups of nails and threaded bars, respectively. Each group contained from 3 to 6 specimens. The results showed that tangential and radial directions were similar and could follow the same design rules. Curves for loading parallel to the grain showed a linear increase up to the LBL bearing yielding (5% offset), and the stresses remain almost constant beyond this point. Curves for loading perpendicular to the grain showed a linear increase up to the LBL bearing yielding, followed by a continuous stress increase until the end of the tests. The COV values of bearing strength for each dowel diameter and load case were in the range of 3 and 23% which complies with the general experience mentioned in ASTM D5764 [104]. The authors developed a three-dimensional FEM and determined the depth of the bearing zone which depended on the fastener diameter of 1.6D, and local material properties under the fastener which were obtained as a function of the LBL bulk properties. The expressions for calculating the LBL dowel-bearing strength as a function of the fastener diameter and the specimen width-to-fastener diameter ratio were
presented, however, they were valid only for the range of diameters considered in the study. Li and Zhou [94] investigated the load-carrying capacity of the LBL connection under lateral load according to ASTM D5652 [107]. The test dowel diameters were 6, 8, 10, and 12 mm, 5 specimens were adopted for each group. The specimen was made of the main member and side members assembled by the LBL dowel and there was no adhesive on the interface. According to the results, the failure mode of the connection test under lateral load was the dowel yielding with two plastic hinges which was similar to Mode IV of the European Yielding Model (EYM) [94] (Fig. 12).

Chen et al. [98] investigated the LBL-to-LBL connection consisting of LBL main member nailed between two LBL plates (Fig. 13).

The test procedure followed the ASTM D1761 standard [84], 23 groups of nailed LBL joints were tested under monotonic loads, with 5–8 replicates tested for each series. According to the results, the connection had three failure modes characterized by bearing failure, splitting failure, and row shear failure. To prevent brittle failure in nailed connections, the authors provided limiting ranges for end distance, edge distance, row spacing, and centre-to-centre spacing as 6D, 2–3D, 3D, and 6D, respectively. With an increase in centre-to-centre and end distances, the capacity of nailed joints also increased until the spacing was exceeded. Chen, Yang [99] conducted push-out tests to study the effect of nail arrangements on the strength, stiffness characteristics and load-displacement response of LBL nailed connections (Fig. 14).
A total of 125 specimens were tested, with 5 replicates for each group: nail diameter (2.1, 2.5, and 2.8 mm), number of nail rows (1, 2, and 3), and number of nail lines (1, 2, 3, 4 and 5). The tests were conducted following the requirements of ASTM D1761 [84]. According to the results, the arrangement of nails has a significant impact on failure modes. Both embedding and splitting failures were observed in LBL nailed connections. An increase in the diameter and number of nails in a row led to a better capacity of connections and lower ductility.

Cui et al. [100] studied the behaviour of steel-to-laminated bamboo dowel connections with a slotted-in steel plate under tension based on the ASTM D5652 [107] (Fig. 15), 4 groups were prepared corresponding to the end distances of the connections (5D, 6D, 7D, and 8D), each test was repeated 3 times. All the dowels showed 3 types of failure modes described in the EYM (Fig. 16).
Mode I was characterized by the crushing of wood fibres under the dowel, no fasteners bending and through cracks were observed. This type of failure happened when the thickness of the side members and the thickness-to-diameter ratio were small while the bending strength of the dowel was big and the shear strength parallel to grain of LBL was low. In Mode II, fasteners were deformed in bending at one plastic hinge point per shear plane, with a predominant bearing yield of wood fibres in contact with the fasteners in side members. In Mode III, wood fibres locally crushed near the shear planes with fasteners yield in bending at two plastic hinge points per shear plane. Mode III occurred in specimens, where the thickness-to-diameter ratio was large enough because the bearing zones became larger and dowel bending was restrained. The connection members mainly failed in shear or splitting failure, while the dowel showed the one-hinge yield mode (Mode II).

The yield, ultimate load, and initial stiffness significantly increased and the ductility ratio decreased with an increase in the diameter from 10 mm to 16 mm. It should be noted that the bearing area between the dowel and bamboo material was defined by the dowel diameter and its increase could change the failure mode of the connection from embedding or splitting failure to shear failure. According to the results, the change in thickness didn’t affect yield load but a decrease in the thickness of the dowel diameter led to a larger load-carrying capacity. Various end distances insignificantly affected the yield load. Specimens with an end distance of 6D–8D exhibited better ductility and embedding failure.

In the connections with the LBL dowel, the load-displacement curves were in the linear elastic stage before brittle failure occurred in a sudden manner [94]. To compare, the LBL nailed connections exhibited similar load-slip responses regardless of the number and arrangement of nails [99, 101]. The brittle failure of LBL nailed connections was characterized by the elastic stage, nonlinear stage, and descending stage (Fig. 17).

![Figure 17: Typical load-slip response of LBL nailed connection: a) 2.1-R1L1; b) 2.5-R1L1; c) 2.8-R1L1; d) 2.1-R1L3; e) 2.5-R3L3; f) 2.5-R3L5 (taken with permission from Chen et al. [99])](image)

At the beginning of loading, the load displayed linear characteristics with the increase in the relative slip between the side and main members, and then a nonlinear increase until the ultimate load was reached.
Before the failure was reached, the splits which occurred in the members, led to sporadic decreases in load in most specimens. Afterwards, the load started to decline very slowly up to the final failure, representing the occurrence of splits in the middle or side members. Nevertheless, the specimens didn’t completely lose the capacity of withstanding load.

Similar to the LBL nailed connections, the typical load-displacement curves of steel-to-laminated bamboo dowel connections with a slotted-in steel plate under tension were also divided into a linear stage, a nonlinear stage within and beyond the proportional limit, and descending stage.

### 2.3 Bolted connections

Leng et al. [102] compared the moment-rotation behaviour of 3 types of LBL beam-to-column connections: 1) conventional bolted connections with clotted-in steel plates (I-connection), 2) T-shaped extended end plate connections with side plates that confine the beam, 3) L-shaped end bracket connection which partially confines both the beam and column (Fig. 18).

![Figure 18](image)

**Figure 18:** Three types of bolted beam-to-column connections: a) bolted connections with slotted-in steel plates (I-connection); b) bolted connections encased with T-shape steel plates (T-connection); c) bolted connections encased with double L-shape steel plates (double L-connection) (reproduced from Leng et al. [102])

A total of 13 specimens were adopted for tests (7 monotonic, 6 cyclic). A monotonic test was carried out following ASTM D1761 [84] and cyclic test – Test Method B of ASTM E2126 [108]. According to the results, failure of the specimens under monotonic and cyclic loads was characterized by brittle behaviour and caused by splitting parallel to grain direction, which started at the bolt line. However, the monotonic specimens with the cross-laminated arrangement in the connection region failed due to delamination between laminas, and the splitting was effectively reduced. Based on test results, T- and L-connections increased elastic stiffness, plastic stiffness, load-carrying capacity, and ductility by 215% and 169%, 153% and 53%, 58% and 50%, 15%, and 13% compared to I-connections, respectively. For T-connections, the influence of bolt arrangement was negligible compared to I-connections, which showed a lower elastic stiffness when more bolts with smaller diameters were used. The authors stated, that EC5 conservatively estimated the bearing capacities of the T- and L-connections. For the I-connections, the safety margin was significantly smaller.

Castaneda and Bjarnadottir [103] concluded, that improving the stiffness is of great importance in the design of the I-shaped beam. The authors tested three different configurations of bolted connections to create an optimal composite bamboo I-shaped beam which was stiffer and safer in structural applications. The configurations were: beam bolted at each support and midspan with steel angle at the bolts (B1), beam bolted at each support and quarter points along the full span of the beam with steel angle at the bolts (B2), and beam bolted at each support and every 30.5 cm across the full span of the beam with steel angle along the entire span of the beam (B3). The authors developed a three-dimensional model based on the bilinear stress-strain relationship, shear modulus of elasticity determined by the model of Saliklis and Falk [109], and orthotropic behaviours of the beam obtained from experimental results with transversal isotropic in the radial-tangential plane [95]. According to the results, B3 was the most optimal configuration of bolts since deflection and maximum stress concentration were reduced by 48% and 72% compared to B1 and B2,
respectively. In addition, better contact between bodies was observed in B3 which led to a stiffer I-shaped beam. To compare, B1 had the highest maximum stress concentration and deflection, while B2 showed a slight improvement over B1.

Tang et al. [101] investigated the behaviour of single-bolted and multiple-bolted connections using LBL and steel plates (Fig. 19).

Figure 19: Test setup for single-bolted and multiple-bolted connection: a) profile and front view of single-bolted joint; b) dimensions of single-bolted and double-bolted joints; c) dimensions of multiple-bolted joints; (reproduced from Tang et al. [101])

A total of 14 groups of bolted LBL connections with 3 specimens for each group (edge distance, bamboo thickness, and bolt size) were tested with reference to the bolted connection tests on timber and bamboo in the literature. The variations of load-carrying capacities for single-bolted connections were within 11.81%. Meanwhile, the COV values of load-carrying capacities of multiple-bolted connections were within 9%, showing good consistency. For both single-bolted and multiple-bolted connections, the failure modes were characterized by longitudinal splitting, shear out, and combined longitudinal splitting and bamboo crushing (Fig. 20).
Figure 20: Failure modes of single-bolted and multiple-bolted connection: a) single-bolted; b) two-bolted; c) multiple-bolted connection (reproduced from Tang et al. [101])

For single-bolted connections, the capacity increased with an increase in bolted diameter and edge distance. When the edge distance in a single-bolted connection and the spacing in a multiple-bolted connection were bigger than 5D, the connection capacity was stable. In addition, the stagger arrangement of the bolts led to a better capacity of multiple-bolted joints. The authors established parameters of the constitutive relation and Hill’s failure criterion and used them for computational models of the connection. The computational results were in good agreement with the test results. ASTM D5764–97a used for timber connection appeared to be unsuitable for strength prediction of the bolted LBL connections.

2.4 Glued-in rods (GIROD) connections

Glued-in rod (GIROD) connection is one of the most promising and highly effective methods of connection that are currently being investigated and used in wood and bamboo engineering. Typically, GIROD consists of one or more rods glued to solid wood or wood- and bamboo-based construction material. Over the past decade, an extensive study of GIROD in timber has been conducted [110-117]. There are few investigations on GIROD-LBL connections in the existing literature. Yan et al. [118] carried out both-ends pullout test on GIROD-LBL (Fig. 21) according to ASTM D1761–88 [119], 8 samples were adopted for each group corresponding to rod diameter (8, 12 am 16 mm) and rod embedded depth (40, 80, 120 and 160 mm). The specimens showed 2 failure modes, which were threaded rod rupture and adhesive interface failure. According to the results, an increase in the diameter and depth of the threaded rods increased the pullout peak load of both-end GIROD-LBL. The normal shear strength of threaded rods glued-in LBL was
governed by interfacial shear strength between glue and base materials, so increasing the contacting area was suggested to improve the strength of the connection. The authors suggested using 4.8 rods with a slenderness ratio of 10 or over to satisfy interface stability and a tensile load of the metal used in the connections.

Zhang et al. [120] evaluated the pull-out capacity of threaded steel glued with two-component epoxy resin into LBL under axial load. The test procedures followed ASTM D1761–88 [119], the total number of all test specimens was 125 considering the edge distances, the glue thicknesses, the rod diameters, and the slenderness ratios. The COV values of the obtained failure loads were within 10%. Similar to previous studies, the anchorage length and rod diameters affected the failure load, which increased with an increase in the slenderness ratio until the critical value was achieved. Based on the analysis of variance, the effects of glue thickness, edge distances, and rod diameters were statistically significant since the corresponding p-values were less than 0.05. To avoid splitting behaviour and ensure better load-carrying capacity, the edge distance should be more than 3D and the thickness of a glue line should be 2 mm. The shear failure at the bamboo and adhesive interface was the main failure mode, therefore the interfacial shear stress between these layers determined the normal shear stress (Fig. 22).

The authors compared several design equations and models established for GIROD-wood connections and concluded that the Riberholt design equation [121] was consistent with the experimental test results, the EC5 [122] and Feligioni design methods [123] predicted unreliable estimates, whereas the DIN 1052 [124] design equation showed conservative results.

3 Numerical models

3.1 Numerical models for sheathing-to-framing connections

Several attempts have been done to describe the load-displacement relationship and predict the yield strength and bearing capacity of bamboo-based sheathing-to-framing connections (Table 5).
Table 5: Numerical models for LBL sheathing-to-framing connections

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
<th>Predicted parameter</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDS [83]</td>
<td>$k_3 = -1 + \sqrt{\frac{2(1 + R_e)}{R_e} + \frac{2F_{sh}(2 + R_e)D^2}{3F_{em}l_x^2}}$</td>
<td>Yield Strength</td>
<td>28-30</td>
</tr>
<tr>
<td></td>
<td>$R_e = F_{em} / F_{ex}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F_{fr} = f_{h,b}d_1 + F_{ax,R} \frac{10(b_1 + b_2) + 0.5(b_1 + b_2)^2}{100 + (b_1 + b_2)^2} \frac{l - t_2 - b_1}{l - t_2}$</td>
<td>Bearing capacity</td>
<td>15</td>
</tr>
<tr>
<td>EYM [82]</td>
<td>$f_{h,b} = \frac{1}{86} \rho^{1.331}d^{-0.257}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F_{ax,R} = 54.12 \cdot L \cdot d \cdot S_G^{2.5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echeverry and Correal</td>
<td>Governing equations can be found in [120]</td>
<td>Bearing capacity</td>
<td>N/a</td>
</tr>
<tr>
<td>[83]</td>
<td></td>
<td>Load–displacement</td>
<td>N/a</td>
</tr>
<tr>
<td></td>
<td>Governing equations can be found in [120]</td>
<td>Load–displacement</td>
<td></td>
</tr>
<tr>
<td>Modified Foschi model</td>
<td>$P = \begin{cases} \left( P_0 + K_3 \Delta \right) \left( 1 - \exp \left( -\frac{k_2\Delta}{P_0} \right) \right), &amp; \text{if } \Delta \leq \Delta_{\text{peak}} \ P_{\text{peak}} + K_3 \left( \Delta - \Delta_{\text{peak}} \right), &amp; \text{if } \Delta_{\text{peak}} &lt; \Delta \leq \Delta_{\text{fail}} \end{cases}$</td>
<td>Load–displacement</td>
<td>22.02-34.41</td>
</tr>
</tbody>
</table>

Note: $Z$ – reference lateral design value; $D$ – diameter of the dowel, in (see NDS Table 12.3.7 [87]); $l$ – side member dowel bearing strength, in; $F_{em}$ – main member dowel bearing strength, psi (see NDS Table 12.3.3 [87]); $F_{es}$ – main member dowel bearing strength, psi (see NDS Table 12.3.3 [121]); $R_d$ – reduction term (see NDS Table 12.3.1B [87]); $F_{sh}$ – dowel bending yield strength, psi; $F_{fr}$ – bearing capacity of timber-bamboo connectors; $f_{h,b}$ – embedment strength, MPa; $\rho$ – wood or bamboo material density, kg/m$^3$; $d$ – diameter of the nail, mm; $F_{ax,R}$ – nail withdrawal capacity; $L$ – the penetration depth; $S_G$ – specific gravity of wood or bamboo materials; $P_{\text{peak}}$ – peak load, N; $\Delta_{\text{peak}}$ – corresponding displacement of peak load, mm; $P_u$ – ultimate load, N; $\Delta_u$ – ultimate displacement, mm.

As can be seen, American code NDS used by Sinha et al. [81] overestimated the yield strength of LBL sheathing-to-framing connections, and the relative difference between experimental and predicted results constituted 28–30%. The EYM model used by Li et al. [82] relatively accurately predicted the bearing capacity of the connections, with an error lower than 15%. Echeverry and Correal [83] developed a numerical model in the software CASHEW to obtain the typical load-displacement response and cyclic behaviour of LGM shear walls (Fig. 23).
Figure 23: Typical models of load-displacement relationship and cyclic behaviour of LGM shear walls: a) load-displacement response model; b) estimated cyclic behaviour (taken with permission from Echeverry and Correal [83])

The model provided a preliminary comparison with wood-framed shear walls, showing that bamboo-based shear walls can be an alternative to conventional wood-framed construction, considering the similar shear capacities expected. Sun et al. [80] proposed the exponential prediction equation to describe the shape of the load-displacement curves. As can be seen, the difference between tested and fitted values constituted up to 34.41%, calling for further research for a complete experimental characterization of bamboo-based shear wall behaviour, considering a wider range of nail diameters and sample sizes.

3.2 Numerical models for dowel-type connections

The design rules from Europe, the United States, Canada, and China, including EC5 [126], NDS [87], CSA O86 [127], and GB 50005 [128], were collected and proposed by scholars to predict the load-carrying capacity, embedment strength and the effective number of nails of bamboo-based dowel-type connections. Fig. 24 shows the accuracy of predicted load-carrying capacity using existing calculation models.

Figure 24: Error analysis of the load-carrying capacity of LBL connections: a) smaller dowel diameters; b) bigger dowel diameters (data is taken from the reviewed literature in Table 4)

According to errors analysis, the EYM established in EC5 can accurately predict the capacity of the LBL nailed connections with smaller diameters (Fig. 24 a). It was found that the relative difference between the experimental and calculated values by Blass et al. [99] and Whale et al.[99] increased with the increase
in the diameter of nails. Fig. 24 b shows, that EC5, EYM, and CSA showed conservative results for bigger dowel diameters with a relative difference of 20–90%. Among national standards, the results calculated with NDS and GB5005 were the closest to experimental results; and the relative difference was less than 15%. Cui et al. [100] proposed a set of equations to predict the behaviour of the steel-to-laminated bamboo dowel connection with a slotted-in steel plate. Although the predicted failure modes were accurate, the calculated results were conservative. The authors introduced the modified coefficient $C_g$ to accurately predict the load-carrying capacity of the connections. However, considering the limited number of connections, the modified coefficient suggested in the paper needs to be further verified.

### Table 6: Numerical models for bearing capacity of LBL dowel-type connections

<table>
<thead>
<tr>
<th>Model name</th>
<th>Dowel diameter, mm</th>
<th>Equation</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU5 [99]</td>
<td>2.1–2.8</td>
<td>Governing equations can be found in [93]</td>
<td>4.05</td>
</tr>
<tr>
<td>NDS [100]</td>
<td>6–12</td>
<td>Governing equations can be found in [94]</td>
<td>11.61</td>
</tr>
<tr>
<td>GB5005 [100]</td>
<td>6–12</td>
<td>Governing equations can be found in [94]</td>
<td>13.01</td>
</tr>
</tbody>
</table>

**Note:** $f_{c_0}$ – embedding strength of the LBL parallel to grain, MPa; $f_{c_0}$ – compressive strength of the LBL parallel to grain, MPa; $t$ – is the thickness of side member, mm; $d$ – is the dowel diameter, mm.

The scholars used and compared two general methods for embedding strength of LBL connection based on compression strength, density, and dowel diameter as major influencing factors adopted in different national standards [87,126,129–132]. However, the calculated results were smaller than the experimental ones since the moisture content (MOC) of LBL was smaller than the 12% specified in some formulas, and the strength-to-weight ratio of LBL was larger than that of conventional wood materials [93].

Cui et al. [93] proposed a tri-linear model for both grain directions to evaluate the embedding strength reduction of LBL connection at elevated temperature ($T$), where $\eta_T$ was defined as the ratio of embedding strength at elevated temperatures to that at ambient temperature, and 0.50 was used in the temperature range of 100–180°C to simplify the calculation:

$$
\eta_T = \begin{cases} 
-0.0063T + 1.125 & 20°C \leq T \leq 100°C \\
0.50 & 100°C \leq T \leq 180°C (1) \\
-0.005T + 1.400 & 180°C \leq T \leq 280°C 
\end{cases}
$$

To calculate the embedding strength of LBL connection considering the effect of the different factors, Cui et al. [92] adopted a fitting model based on dowel diameter and compressive strength as major influencing factors expressed as:
\[ f_c = (-0.0236D + 1.471) f_{c,0} R^2 = 0.8935 \quad (2) \]

The parameter ranges of \(2D \leq T \leq 3D\), \(H = 7D\), \(6D \leq B \leq 9D\), where \(D\), \(H\), \(B\) are the dowel diameter, loading length, and thickness of the specimen in mm. \(f_{c,0}\) is the compressive strength in MPa. The calculating results were in good agreement with the experimental results.

Many countries evaluate the load-carrying capacity of the entire connection by multiplying the capacity of a single nail by the effective number of nails, and the calculated results appeared to be higher than the actual results obtained from the experiment [99]. According to previous studies on timber, this happens due to unequal distribution of loads in a connection with multiple fasteners, and due to failure of the first and last fasteners since they receive the highest load level [133–136]. Calculation methods based on EC5, SIA 265 [132], and Jorissen [137] provided overestimated or conservative predictions of the effective number of nails in a row [98], while the formula proposed by Hossain et al. [138] can adequately predict the effective number of nails [99] (Fig. 25).

![Figure 25: Effective number of nails (taken with permission from [99])]  
For LBL-nailed connections, Chen et al. [98] proposed the formula to predict the bearing capacity of the LBL connection with multiple nails in a row by multiplying the lateral load capacity of the single-nail joint by the effective number of nails in the row:

\[
    n_{ef} = \min \left\{ \frac{n}{0.9 \left( \frac{s}{6D} \right)^{0.25}} \right\} \quad (3)
\]

Where, \(n_{ef}\) is \(f\) is the effective number of nails in a row parallel to the grain, \(n\) – is the number of rows.

In addition, Foschi’s formula [139] accurately described the load-slip of LBL nailed connections with different configurations [98], and Folz formula [125] was suitable for the description of the load-slip relationship of the LBL nailed connection loaded laterally [99].

4 Discussion

4.1 LBL and wooden sheathing-to-framing connections

For LBL sheathing-to-framing connections, the material type and nail spacing appeared to be the main influencing factors of load-carrying capacity. However, in wood connections, wall AR also significantly affected lateral behaviour. In general, both LBL and wood sheathing-to-framing connections shared similar behaviour. In the reviewed studies, BOSB and GLG panels were used as sheathing materials, and LBL was used as framing members. The type of nail appeared to affect the failure mechanism of the connections; for wire nails, the failure mode was characterized by nail yielding and pulling through framing member, while
for self-tapping screws – by brittle failure. Edge distances also affected the failure behaviour of nails since
increased edge distance led to nail withdrawal and partial nail head pulling through the framing member,
while small distances caused sheathing edge-tear. At the same time, the LGM panel didn’t show any nail
withdrawal from the framing member or fatigue. The energy dissipation capability of the LGM panels was
lower compared to that of BOSB or wood panels. This was due to the different strip configurations in the
LGM panels and the presence of voids and imperfections, which in turn calls for optimization of the
processing method of LGM.

Among reviewed sheathing materials, the strength and energy dissipation of BOSB and GLG were
higher than those of wood and the LGM panels due to a higher density of the former which led to more
bending on the sheathing nails instead of wood crushing. Therefore, steel nails could contribute more to
energy dissipation on walls sheathed with bamboo panels than OSB and plywood panels where more wood
crushing was observed. However, the high density of bamboo materials caused a lower ductility of the
connection itself, which in turn caused earlier nail fatigue. Nonetheless, the ductility demand at 2% of the
drift for GLG-sheathed walls was still comparable with the plywood and OSB-sheathed walls.

Finally, the ultimate displacement capacity of the plywood and OSB walls and their BOSB/GLG
counterpart was almost the same, suggesting that bamboo walls would be able to withstand similar
earthquake displacement demands than those for walls sheathed with OSB and plywood. In full-size shake
purpose tests, shear walls and frames with GLG panels and K-bracings were subjected to a sequence of ground
motions with increasing intensity that was representative of those expected in a high seismic hazard zone
in Colombia, and earthquake records of El Centro (California, 1940), Quindío (Colombia, 1999),
Northridge (California, 1994) and Kobe (Japan, 1994) were the selected. The structures showed slight
damage, and both frames with panels and K-bracings were at the elastic stage when the maximum allowed
displacement reached 1% based on Colombian standard, which allowed the frames to return to their initial
condition.

4.2 Dowel-type and bolted LBL and wood connections

The studies were conducted on the embedding strength of dowel-type LBL connections. According to
the results, dowel-type LBL joints exhibited three failure modes: fibres crushing beneath the dowel hole,
1–2 shear splitting cracks on the hole edge, or internal buckling and peeling with insignificant cracks, and
shear plug formation. It is worth noting that there were no failures along the glue line, therefore the failures
were caused by in-plane shear stress and tension perpendicular-to-grain. All dowel-type LBL connections
loaded in parallel directions exhibited an elastic-plastic behaviour with a pronounced yielding phase before
a constant stress increase until the end of the test or brittle failure.

Connection tests on dowel-type LBL showed three failure modes such as bearing failure, splitting
failure, and row shear failure. The brittle behaviour of the LBL nailed connections included the elastic stage,
nonlinear stage, and descending stage. Similar behaviour was observed in wooden joints, in which failure
modes included splitting, row shear, block shear, and net tension. The yield modes of dowel-type fasteners
in the LBL connections were similar to those in timber connections described in EC 5 [126].

Similar to wood, the mechanical behaviour of dowel-type and bolted connections was governed by
several geometric, material, and loading parameters like material density, fastener slenderness, end and
distance, spacing and number of fasteners, and loading configuration. However, LBL joints turned
out to be stiff and brittle compared to wood connections. Dowel-type wood connections can show both
ductile and brittle behaviour. Since timber is prone to brittle failure when bent and stretched, joints are the
key to the ductility of timber structures. Brittle behaviour is not desirable in buildings, since sudden
destruction of the structure can lead to human and material damage. Therefore, ductile behaviour is
considered the most desirable, especially in areas of increased seismic hazard due to the consistent
deforation of the structure, which helps to identify and eliminate possible destruction in time and ensures
proper structural strength. To avoid brittle behaviour in the LBL connections, the scholars provided limiting
values for end distance, edge distance, row spacing, and centre-to-centre spacing which were 6D, 2–3D,
3D, and 6D, respectively. The edge distance limits appeared to be the same for Douglas-fir and spruce [140], while the minimum end distance for wood-nailed connections loaded parallel to grain with and without pre-bored holes was 15D and 10D [141].

Many models have been developed to predict the brittle behaviour of wood connections. Taking into account the similarity of bamboo with wood, the reviewed articles analyzed the existing models of national standards EC5 [126], Jorissen [137], CSA [127], NDS [87], GB 50005 [128], as well as models developed by Hossain et al. [138], Folz and Filiatrault [125], and Foschi [139], and proposed modified calculation methods suitable for describing the behaviour of the LBL connections. According to the calculated results, there was a trend of conservative predictions based on models of EC5, Jorissen, and SIA 25 [132], while models based on GB 50005 and NDS, Hossain, Folz, and Foschi showed the most accurate results. In many studies of wood connections, the ductile model included in EC5 also proved to be conservative, demonstrating a mode of brittle failure instead of ductile, which could lead to risky situations especially in earthquake-prone regions due to the wrong estimation of the failure mode [68]. Yurrita and Cabrero [68] proposed an optimized method in which the ductile failure mode was based on EC5 without the parameter of the effective number of nails, and brittle failure modes based on the model of Yurrita et al. [142] were considered separately. According to the results, the optimized method reached a total of 90.0% of correct predictions compared to EC5 with 65.0% of positive matches, which in turn calls for the validation of this method for the LBL connections.

4.3 Rods glued-in LBL and wood connections

GIROD-LBL connections have not yet been fully investigated. According to review studies, GIROD-LBL connections have demonstrated 2 failure modes, which were threaded rod fracture and adhesive interface failure. To compare, GIROD-timber connections have the following failure modes: rod tension failure, adhesive failure and cohesive failure of the adhesive, localized timber shear failure, splitting of the timber, and failure of the timber member. Pull-out tests were conducted in the reviewed studies on the behaviour of GIROD-LBL connections, while GIROD-timber connections were experimentally studied through pull-out loading at one or both ends, pull-compression, pull-beam, and pull-pile foundation [143]. The variety of loading configurations calls for further investigation of the capacity of GIROD-LBL connections.

GIROD is a hybrid system that comprises at least three materials such as adhesive, wood or bamboo, and rods, therefore, it is necessary to study the influence of these factors on the mechanical properties of GIROD-LBL connections. For GIROD-LBL connections, two-component epoxy resin was used in the reviewed studies, while commonly used adhesives for GIROD-timber connections were epoxies, polyurethanes, and phenol-resorcinol based adhesives [114]. The impact of glue-line thickness should be studied in terms of GIROD-LBL applications, although, some studies stated that in terms of GIROD-timber applications, it was an important parameter [123], while others reported no significant effect [144,145]. Considering the influence of types of adhesives and species of bamboo on the basic mechanical properties of LBL, it is necessary to conduct further research on their impact in a view of GIROD-LBL applications. Thus, the influence of such factors on the behaviour of GIROD-LBL as different types of rods, adhesives, bamboo species, and environmental conditions remain relevant.

5 Conclusion

Similar to timber connections, it was concluded, that the bearing strength of LBL connections had a strong correlation with material properties, fastener geometries, end and edge distances, spacing and number of fasteners, and loading configuration. However, LBL joints turned out to be stiff and brittle compared to wood connections. Since LBL connections fail in a brittle manner, the ductility of LBL structures should be provided by the proper design of connections.

Considering the sheathing-to-framing connections, LBL panels have similar behaviour to traditional OSB panels and plywood under lateral loads. Due to its density, LBL copes with energy distribution better...
than conventional materials, which makes it the best for use in seismically hazardous areas. According to the results, the diameter of the screw and the distance between the screws and the nails significantly affected the behaviour of the panels, while the influence of the wall aspect ratio was not observed. In addition to the effect of the thickness, direction, and shape of the lamina, previous studies have noted the influence of the species, glue type, growth portion, and type of processing on the basic physical and mechanical properties of the material. From this, it follows that it is necessary to confirm the influence of these factors on the behaviour of LBL connections.

Similar to wood, bamboo is also an anisotropic material; its connection failure is characterized by splitting caused by the formation of cracks at the location of maximum shear stress. In contrast, failure in timber is generally caused by the formation of a crack at the location of maximum tensile strength perpendicular to grain. According to different failure mechanisms, it is impossible to directly apply timber design rules for splitting prevention in bamboo structures. Therefore, the need for methods predicting the behaviour of bamboo connections is still important. Moreover, the differences in connection performance of caramelized and bleached bamboo call for further investigation of treatment and processing methods' effects on LBL connections.

According to the reviewed studies, LBL has great potential and can serve as a worthy alternative to conventional building materials. Nowadays, the number of tests on LBL connections is far from enough compared with timber structures, so modern practitioners are not fully aware of the structural applications of LBL connections. Some of the studies adopted an insufficient number of samples in order to obtain a preliminary characterization of bamboo-based connections, which led to high COV values, and 95% of reliability could not be achieved. Therefore, it is inevitable to carry out more comprehensive experiments to explore unique bamboo-based factors affecting the behaviour of LBL connections and establish design standards similar to those in use for timber. According to studies, most of the connections failure occurred in LBL itself instead of the connection area, thus, more studies should be held to improve the load-carrying capacity and splitting resistance of LBL.

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