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BAMBOO SCRIMBER DOWEL-TYPE JOINTS FOR ENGINEERED WOOD AND BAMBOO STRUCTURES

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ABSTRACT: This research delves into dowel-type joints with bamboo scrimber as an innovative alternative to traditional wooden fasteners. The focus is on their application in connecting timber elements of medium density suitable for engineered wood or bamboo product assemblies and timber structures. The test results showed that bamboo scrimber can be ideal for dowel-type joint applications. The mechanical performances of such joints (such as the failure mode, carrying capacity, and slip modulus) are significantly dependent on the ratio of side laminate thickness to dowel diameter and the embedment strength of the laminate. A small ratio of side laminate thickness to dowel diameter is found to result in a ductile failure mode and high capacity, small joint slip.

KEYWORDS: bamboo scrimber; LBL; dowel-type joint; failure mode; carrying capacity

1 – INTRODUCTION

In traditional timber structures, wood-based dowel joints have recently gained popularity as an effective and durable joint for connecting timber-based structural members[1]. In contemporary timber (or engineered bamboo) structural systems, the hardwood (wood) dowel-type joint method has been investigated a lot, focused on the structural feasibility and the mechanical properties, and utilised in wide applications both for inter-component (such as beam-to-beam or beam-to-column joint)[2] and intra-component joints (such as Dowel Laminated Timber, DLT)[3]. Nonetheless, there are still some limitations when using hardwood as dowel material, such as the inherent natural variation of wood material, instability of their mechanical properties [4], and sensitivity to internal moisture content changes influenced by the surrounding environment [5]. Moreover, hardwoods have much longer growth cycles (e.g. compared with softwood or bamboo)[6]. In these contexts, bamboo scrimber, acknowledged for its high strength and renewable characteristics (thanks to the rapid growth of bamboo), is emerging as a potential alternative to hardwood for construction and structural applications. As such, it has recently gained considerable attention in the research community. However, research concerning using bamboo scrimber as a joint remains relatively underexplored.

This research investigates the feasibility of utilising bamboo scrimber as a viable alternative to hardwood in dowel-type fasteners, evaluates the applicability of the current theoretical method on timber-to-timber connection using dowel-type fasteners, and analyses the impact of slenderness ratio on joint. The mechanical behaviour of joints was experimentally studied in accordance with BS EN 26891:1991 [7], concurrently assessing the impact of different aspects. Finally, the experimental outcomes were analysed and compared with the calculated values in current codes, aiming to determine the feasibility of methodology governing the load-bearing capacity and stiffness of joints employing bamboo scrimber dowels.

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2 – BACKGROUND

2.1 DOWEL-TYPE JOINTS

In recent years, existing research has focused on the timber-to-timber joints with wooden dowel [8]. Frontini et al. [9] studied the load-carrying capacity and stiffness of softwood dowel joints. Utilising hardwood as dowel-type joints were also widely studied [10]. Riggio et al. [11] conducted experimental studies involving compressed beech wood dowels, with a compressing ratio of 60%, as a replacement for metallic fasteners in connecting two solid wood elements. High-speed welding rotation dowels utilising wood, compressed wood or Moso bamboo was also studied sufficiently [12], aiming to improve the joint effectiveness between the board and the dowel material.

As for the application in building and construction, dowel-type connection applied to the inter-element connection (e.g. DLT beam or floor) [13] and intra-element connection (e.g. beam-beam or beam-column) [2] were also studied a lot to evaluate the feasibility and mechanical properties of the connection. Ceraldi et al. [14] applied and experimentally evaluated the wooden dowel as the connection between the new timber elements and the standing structure for ancient timber building restoration.

Various aspects that influenced the connection's mechanical properties were also researched, such as dowel-bearing capacity, fibre orientation and original crack [15]. However, these mainly studied the impact on steel dowel joints, and the influence parameters on wood- or bamboo-based dowel connections were rarely experimentally evaluated. Furthermore, the effect of the dowel's properties and configuration on connections was often ignored as the previous studies paid more attention to the wood member instead. Moreover, the slenderness ratio (ratio between sideboard thickness and dowel diameter) is a significant parameter to determine the failure mode and capacity of the dowel-type connection. However, it has not been studied sufficiently and not considered to predict the failure mode and calculate the load-carrying capacity of dowel-type connection in the design method and codes.

2.2 THEORETICAL APPROACHES

To determine the failure mode and the load-carrying capacity of a dowelled timber joint, the European Yield Model (EYM) theory and prediction formulas corresponding to four failure modes (Mode I, II, III, IV), as shown in Figure 1 (a, b, c, d), were first introduced by Johansen [16] in 1949. Based on the EYM, European standard Eurocode 5)[17] and American standard (National Design Specification for wood construction, NDS)[18] provide design formulae to estimate the ultimate load-carrying capacity of timber-to-timber joints in double shear in which the capacity value is related to the ultimate embedment strength of wood and the bending moment of the fastener. The two design codes and methods are mainly proposed depending on steel fasteners. Especially for wooden (or bamboo-based) fasteners, a novel failure mode (Mode V) is adopted by the Standard for Design of Timber Frame Structures and Commentary (TFEC 1-2019) [19], which is a supplemental clause to NDS. This mode considers the dowel "effective shear" failure, a combination of dowel bearing, bending, and shear failure. According to the EYM theory, timber members and steel fasteners are considered perfectly plastic materials. However, as for the timber dowel that failed in Mode V, flexural plastic hinges rarely develop in the dowel, as they occur only exceptionally as a secondary effect after the dowel effective shear fails. Therefore, in this study, the experimental results will be evaluated and analysed in accordance with the theoretical method of TFEC 1-2019 [19].

3 – PROJECT DESCRIPTION

3.1 MATERIALS

LBL, spruce and bamboo scrimber in the connection experimental test were oriented toward those more commonly used or emerging in timber structures. To reduce the coefficient of variation (CoV) of material properties, the LBL members were supplied by the Zhenghe Nanzhu Bamboo Product Co., Ltd., China, bamboo scrimber materials were provided by Hangzhou Dasso Bamboo Technology Co., Ltd., China and softwood (spruce) were supplied by Dongguan Huiteng Wood Product Co., Ltd, China. LBL with an average 770 kg/m3 density at 12±1% moisture content (MC) was used to manufacture the connection members. Bamboo scrimber with an average 1195 kg/m3 density at 12±1% moisture content was used to manufacture the connection dowel. For comparison evaluation purposes, spruce with an average 435 kg/m3 density at 8±1% moisture content was also used to manufacture the connection members.

3.2 PUSH-OUT TESTS OF JOINTS

Thirty-five double shear tests of joints (Figure 1) have been conducted with various nominal dowel diameters d = {6, 8, 12, 18, 30} mm. The impact of the slenderness ratio on connection mechanical behaviour was experimentally studied and critically analysed. In push-out tests, the

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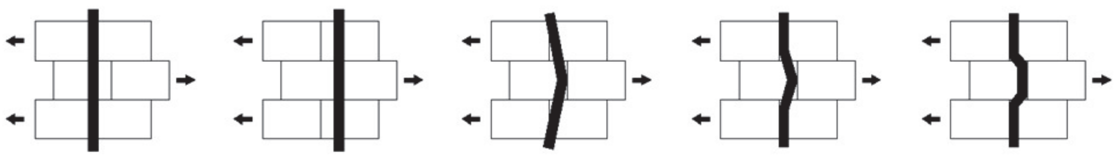
thickness of the sideboards was 20 mm, and that of the middle board was 40 mm. The specimen's dimensions are reported in Table 3, and the test setup can be seen in Figure 2. The load was applied on the middle member through a displacement control process at a constant 2 mm/min loading rate. The load force was measured by the load sensor. The slips between the middle and side members were measured using the displacement sensor. Then, the initial slip, modified initial slip, elastic slip, initial slip modulus and slip modulus were calculated and analysed.



a) Mode I b) Mode II c) Mode III d) Mode IV e) Mode V

Figure 1. Different failure modes of double shear joint

4 – EXPERIMENTAL SETUP

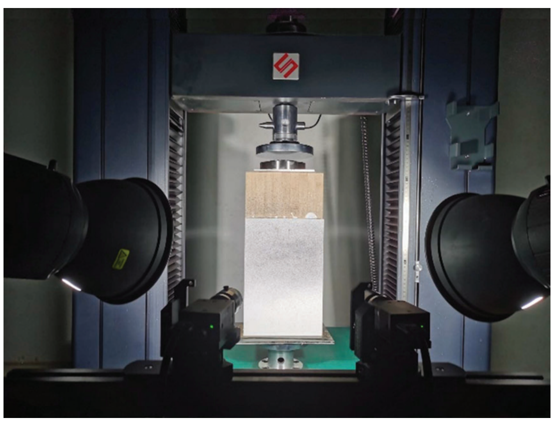


Figure 2. Double shear tests of the joints

Thirty-five double shear tests of joints (Figure 2) have been conducted with various nominal dowel diameters d = {6, 8, 12, 18, 30} mm. The initial slip, modified initial slip, elastic slip, initial slip modulus and slip modulus is calculated in accordance with BS EN 26891:1991 [7] as the following equation (1)-(4):

Initial slip: $v_i = v_{04}$ (1)

Modified initial slip: $v_{i,mod} = \frac{4}{3}v_{04} - v_{01}$ (2)

Initial slip modulus: $k_i = \frac{0.4F_{est}}{v_i}$ (3)

Slip modulus: $k_s = \frac{0.4F_{est}}{v_{i,mod}}$ (4)

The terms in Eqs. (1) to (5) are as follows: "F_{est}" is the estimated ultimate load force in N, $v_{i,mod}$ is modified initial slip,v_{04} is the slip value at 40% estimated highest loading force in mm, and v_{01} is the slip value at 10% estimated highest loading force in mm.

5 – RESULTS

As the diameter enlarged, as shown in Figure 3, there was a discernible transition in the failure mode from Mode V (at 6, 8, 12 and 18 mm) to Mode III (at 30 mm). The ultimate load capacity, corresponding slip, initial slip, modified initial slip, elastic slip, initial slip modulus, and slip modulus are demonstrated in Table 8. Evidently, with the diameter augmentation, there was a marked increment in capacity (by 186%, 119%, 109% and 48.35%, respectively), accompanied by a notable escalation in the corresponding slip (by 83.10%, 22.31%, 103.14% and 32.51%, respectively). The hardening effect induced by the dowel diameter was readily apparent, but the rate of growth, both the capacity and deformation, decreased when the diameter reached 12 mm and 30 mm.

a) CS-LBL-6(Mode V) b) CS-LBL-8(Mode V) c) CS-LBL-12(Mode V)

d) CS-LBL-18(Mode V) e) CS-LBL-30(Mode III)

Figure 3. Failure modes of joints

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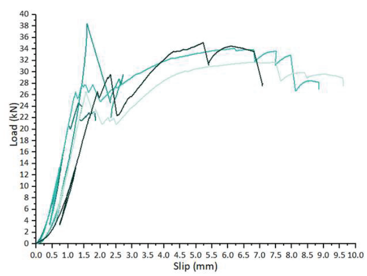
Table 8: Joints Push-out Test Results

Sample	Slender Ratio	Failure Mode	Capacity (kN)	Slip (mm)	v_i (mm)	$v_{i,mod}$ (mm)	k_i ($N \cdot mm^{-1}$)	k_s ($N \cdot mm^{-1}$)
CS-LBL-6	3.33	Mode V	1.68	0.71	0.33	0.33	2196	2125
CS-LBL-8	2.5	Mode V	4.82	1.30	0.41	0.44	4862	4412
CS-LBL-12	1.67	Mode V	10.56	1.59	0.42	0.47	10290	8740
CS-LBL-18	1.1	Mode V	22.11	3.23	0.51	0.52	17608	17136
CS-LBL-30	0.67	Mode III	32.80	4.28	0.71	0.53	18532	25080
CS-Spruce-8	2.5	Mode V	2.96	2.19	0.40	0.43	3895	3369
CS-Spruce-12	1.67	Mode V	5.18	2.21	0.53	0.53	4608	4272

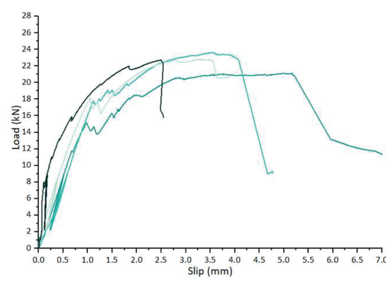
Note: "v_i" donates initial slip, "$v_{i,mod}$" donates modified initial slip, "v_e" donates elastic slip, "k_i" donates initial slip modulus, and "k_s" donates slip modulus.

Table 11: Capacity comparison between experimental and calculated values (unit is kN)

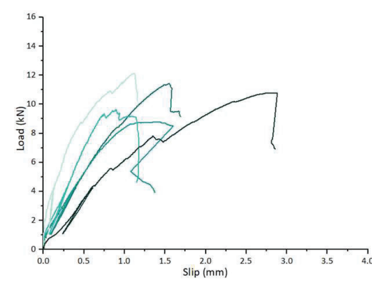
Sample	Slender ratio	Failure Mode	Experiment Capacity (kN)	Calculating Capacity in TFEC 1-2019 (kN)
CS-LBL-6	3.33	Mode V	1.68	0.50
CS-LBL-8	2.5	Mode V	4.82	1.71
CS-LBL-12	1.67	Mode V	10.56	2.42
CS-LBL-18	1.1	Mode V	22.11	4.79
CS-LBL-30	0.67	Mode III	32.80	19.34
CS-Spruce-8	2.5	Mode V	2.96	1.17
CS-Spruce-12	1.67	Mode V	5.19	2.41



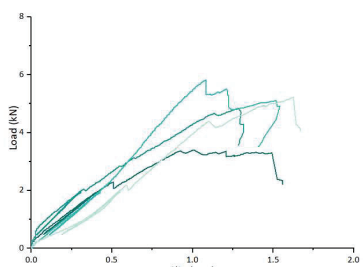
a) CS-LBL-30



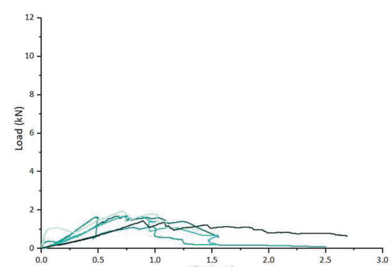
b) CS-LBL-18



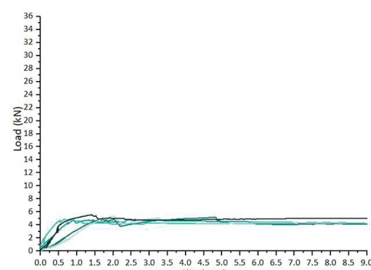
c) CS-LBL-12



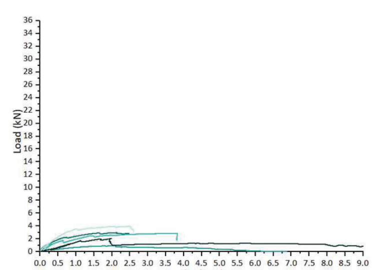
d) CS-LBL-8



e) CS-LBL-6



f) CS-spruce-12



g) CS-spruce-8

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Figure 4 Load-slip curve of connection double shear test

The fastener with a low slenderness ratio remains relatively unyielding during joint loading, leading to complete joint failure when the load-carrying capacity of the connected elements is surpassed. This failure mode is characterized as "brittle". Conversely, the fastener with a high slenderness ratio undergoes bending deformation, thereby reducing the propensity of the joint components to split. Consequently, total joint failure occurs when the load-carrying capacity of the fastener itself is exceeded. However, the bending deformation of the fastener is restricted by the embedment strength of the joint components in the contact zone between the fastener and the joint components. Hence, a ductile failure mode can be expected.

This phenomenon can be attributed to the utilization of a larger diameter. Following the initial occurrence of a crack within a limited cross-sectional area of the dowel, a significant proportion, if not the entirety, of the fibres and adhesive material can continue to bear the load. Consequently, the load experiences repeated increments, leading to the occurrence of multiple cracks either within the dowel or the board embedding or in some instances, within both. Conversely, in the case of a relatively smaller diameter, as exemplified by the 6 mm diameter in this study, a majority of the fibres tend to fracture when subjected to a peak load, resulting in failure.

This underscores the significance of selecting an appropriate diameter and slenderness, as it enables the connection to exhibit enhanced performance by effectively harnessing the mechanical properties of both the dowel and the board (the range of 12 to 18 mm for dowel diameter and 1.67 to 1.1 for slenderness in this study).

As the diameter expands, the degree of slippage can be effectively managed under identical loading conditions (as depicted in Figure 4). This phenomenon will notably enhance the structural element's rigidity during its operational phase within the structure.

When comparing various baseboard materials with identical dowel sizes (CS-LBL-12 and CS-Spruce-12, CS-LBL-8 and CS-Spruce-8, respectively), it becomes apparent that the LBL samples with relatively small-diameter dowels exhibited a brittle failure characterized by dowel breakage. In contrast, the Spruce samples displayed a more ductile behaviour, demonstrating significantly greater plastic deformation before joint failure. This behaviour is clearly illustrated in Figure 4 (c), (f), (d), and (g). Moreover, it is noteworthy that the LBL baseboard samples exhibited significantly higher load-carrying capacity (an increase of 99.63% and 62.84%, respectively) while experiencing considerably less deformation (a decrease of -28.05% and -40.64%, respectively). Furthermore, it is discerned that the LBL samples exhibit superior performance in terms of both the initial slip modulus and the slip modulus, with specific details provided in Table 1.

In the context of the spruce board, the noteworthy factors are the considerably lower values of both the initial embedment and elastic foundation moduli, resulting in a notably heightened embedment deformation within the connection. Additionally, the pronounced slippage occurring between the sideboards and the central board leads to a relatively substantial displacement load. Furthermore, when the deformation of the dowel surpasses its bending elastic modulus, it enters a phase of plastic deformation, during which the tension side of the dowel's fibres undergoes fracture, resulting in dowel cracking. Consequently, the spruce sample exhibits a relatively diminished load-bearing capacity and an elevated propensity for slippage.

Bamboo-based materials, exemplified by Laminated Bamboo Lumber (LBL), manifest greater embedment strength and rigidity when juxtaposed with their wood-based counterparts. Consequently, LBL-to-LBL connections showcase distinct failure modes in contrast to wood-to-wood joints. The former exhibits a damage pattern that leans more toward shear and a composite of shear-induced damage modes, while the latter inclines more toward board embedding or a composite of board embedding-induced damage modes. Also, the LBL board is more trend to splitting while the wood board intend to be embedded. Furthermore, LBL boards are prone to splitting due to their relatively low-tension strength perpendicular to the grain when the dowel diameter exceeds a certain threshold (≥30mm in this study), whereas wood boards tend to favour embedding.

Excessively large perforations can also lead to a reduction in the overall structural integrity of the board, resulting in increased stress and decreased strength. Hence, it is advisable to restrict the diameter to a specific value (less than 30mm in this study) when employing it as a connection method for LBL (engineered bamboo) boards or elements.

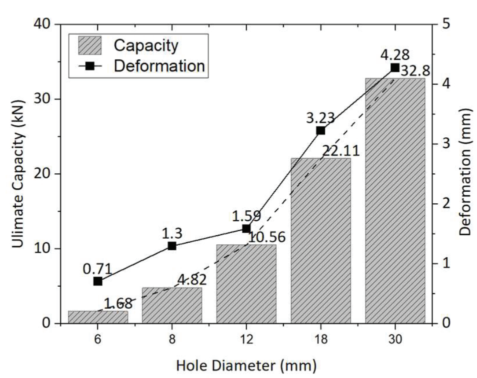

Figure 5. Capacity and corresponding slip of joint push-out test

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From Figure 5, with the increase in diameter, the initial slip gradually increased (by 24.24%, 2.44%, 21.43%, and 39.22%). The modified initial slip similarly demonstrated a progressive rise (by 33.33%, 6.82%, 10.64%, and 1.92%), as shown in Table 1. Further, the elastic slip demonstrated an increasing trend, a drop in the 12-mm and 18-mm samples. Specifically, the elastic slip changed by 35.48%, -7.14%, -2.21% and 15.38%. Moreover, the initial slip modulus exhibited a gradual increase (by 121.4%, 111.7%, 71.11%, and 5.25%), and the slip modulus displayed a corresponding incremental pattern of growth (by 108%, 98.10%, 96.06%, and 46.36%).

For the spruce board, lower initial embedment and elastic foundation moduli values resulted in a notably heightened embedment deformation. A significant slip between the sideboards and the middle board occurred. Furthermore, when plastic deformation increased, the tension side of the dowel's fibres exhibited fracture, resulting in dowel cracking. Consequently, the spruce sample exhibited a relatively low load-bearing capacity and a significant slip.

Engineered bamboo materials, such as LBL, exhibited greater embedment strength and stiffness when compared with wood-based materials (e.g. spruce). Consequently, LBL-to-LBL connections showed distinct failure modes in contrast to wood-to-wood joints. The former exhibited a damage pattern that tended more toward shear and a combination of shear-induced damage modes. In contrast, the latter inclined more toward board embedding or a combination of board embedding-induced damage modes. Furthermore, LBL boards are prone to splitting due to their relatively low-tension strength perpendicular to the grain when the dowel diameter exceeds a specific value (⩾30mm in this study). In contrast, wood boards tend to be embedding failure.

The connection specimens with a large diameter and low slenderness (diameter ⩾ 8 mm and slenderness ratio ⩽ 2.5) exhibited more excellent ductility. In contrast, the connection with a smaller diameter and high slenderness (diameter = 6 mm and slenderness ratio = 3.3) showed a more brittle behaviour, as given in Figure 4.

Compared to various baseboard materials (from Figure 4 c, f, d, g), LBL samples with relatively small diameters exhibited a brittle failure caused by dowel break. In contrast, the spruce displayed more ductility, demonstrating more significant plastic deformation before joint failure. Moreover, the LBL baseboard exhibited significantly higher load-carrying capacity (an increase of 99.63% and 62.84%) while experiencing less deformation (a decrease of 28.05% and 40.64%). Furthermore, the LBL exhibited superior performance in the initial slip modulus and the slip modulus, see Table 1.

The results showed that the bamboo scrimber can be suitable for dowel-type joint applications with considerable load-carrying capacity and stiffness. The mechanical performances of such joints (such as the failure mode, carrying capacity, and slip modulus) are significantly dependent on the ratio of the side thickness to the dowel diameter and the embedment strength of the laminates. A relatively small ratio of side laminate thickness to dowel diameter results in a ductile failure mode, high capacity and small joint slip.

6 – CONCLUSION

In conclusion, bamboo scrimber can be feasible and effective in dowel-type joint applications. The slenderness ratio significantly influenced connection mechanical properties, and the slenderness ratio should be more widely considered to predict the failure mode and load-carrying capacity depending on further studies. A design formula confidently defining the slenderness ratio value associated with failure mode (e.g. whether the joint can achieve the effective shear) for the double shear plane joint is necessary. From the result, the slenderness ratio ranging from 1.1 to 1.67 is recommended, in which failure mode behaves ductile (Mode IV) with superior bearing capacity and stiffness.

In accordance with TFEC 1-2019, when utilising the bamboo scrimber as the dowel material, all failure modes (I, II, III and V) are underestimated the joints carrying capacity, which is just about 30% to 25% the value of the experimental capacity. In the connections with relatively medium slenderness values (slender ratio value = 1.1 and 1.67), predicted values with the equations in the Eurocode 5 can be well-estimated for load-bearing capacity. In contrast, these predicted values significantly overestimated the capacity both for connections with smaller (0.67) and larger (2.5 and 3.3) slenderness. On the other hand, stiffness was relatively accurately estimated in the connections with relatively medium and smaller slenderness but tended to be overestimated for connections with larger slenderness.

For further research, calculating methods for bamboo or wooden dowel-type joints, the inserting angle of the dowel, the slip prediction, and the mechanical performance of the multiple-dowel joint should be researched experimentally and theoretically to expand the development and application of wooden or bamboo dowel-type joint.

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