buildings

Article

Bending Behaviour and Failure Modes of Non-Glue-Laminated Timber Beams Composed of Wooden Dowels and Self-Tapping Screws

Yu-Hsiang Yeh * and Yi-Chi Yeh

Department of Architecture, National Cheng Kung University, Tainan City 701, Taiwan; n78081098@gs.ncku.edu.tw
* Correspondence: yeh1212@ncku.edu.tw

Abstract: The purpose of this research is to compare the bending behaviour of non-glue-laminated timber beams and glulams by full-scale four-point bending tests. The focus is on the non-glue beams laminated by different materials or techniques and then to determine their bending stiffness and failure modes. The laminating efficiency of various materials or techniques is underlined. The manufacturing process concerning non-glue-laminated timber beams has to be determined. As structural elements with large dimensions, such components require adaptable laminating and producing techniques. While the beams composed of wooden dowels refer to the dowel-laminated timber (DLT), those made of self-tapping screws (STSs) can be simply related to nail-laminated timber (NLT) products. Then, a full-scale four-point bending test was carried out to appraise 26 laminated beams, including non-glue- and glue-laminated timber. The results of the test demonstrated that the material, the spacing and the angle of the transversal fasteners significantly influence bending behaviour. The bending stiffness of the beams laminated by STSs was about 7.86% higher than the value of the beams with wooden dowels, although the tendency of each pair of beams did not remain convergent. Reducing the interval of the fasteners can considerably increase the bending stiffness of the beams. Fasteners inserted at 45 degrees, or in a so-called V-type pattern, contribute to improving bending stiffness, and both wooden dowels and STSs reveal the same tendency. At this angle, STSs demonstrate better laminating efficiency than wooden dowels. The STS beams' bending stiffness was about 48.6% of that determined for glulams. On the contrary, in beams with 135-degree fasteners, or, namely, an A-type pattern, inserted fasteners possessed lower bending stiffness than in those with 90-degree fasteners. In addition to the considerable bending stiffness, the STS beams revealed a stable response as far as their load-deflection curves were concerned. A comparison of experimental and theoretical results contributes to verifying the feasibility as well as the weakness of two analytic methods. The predicting capacity of the associated equations needs to be improved, particularly for the withdrawal resistance and connecting effect of inclined STSs.

Keywords: non-glue-laminated timber beam; DLT; NLT; bending behaviour; wooden dowel; self-tapping screw

Citation: Yeh, Y.-H.; Yeh, Y.-C. Bending Behaviour and Failure Modes of Non-Glue-Laminated Timber Beams Composed of Wooden Dowels and Self-Tapping Screws. *Buildings* **2024**, *14*, 394. https://doi.org/10.3390/buildings14020394

Academic Editor: Hassan Karampour

Received: 30 September 2023
Revised: 24 November 2023
Accepted: 14 December 2023
Published: 1 February 2024

1. Introduction

Timber buildings have arisen as viable and compatible constructions in recent decades. In order to fulfil the growing requirement for wooden structures, there is a soaring demand in building sectors for laminated timber elements with larger dimensions or greater capacity. Currently, glulam or cross-laminated timber (CLT), which are glue-based products, are generally applied in diverse wooden constructions. Owing to their capacity, rigidity and reliability, glue-based wooden components account for the majority of various engineered timber materials.

Although rarely produced, non-glue-laminated timber elements are the subject of soaring interest not only from academic groups but also in industrial circles. Without glue or adhesives, non-glue-laminated timber generates less environmental impacts and hazardous substances for the human body. Since it is easy to dismantle the laminae and associated fasteners, non-glued wooden products exhibit a greater possibility to be substantially reused. This feature underlines the ecological efficiency of timber construction, particularly its carbon-sequestrating and energy-saving effects. Despite the scarcity of experience producing it, the manufacturing process for non-glue-laminated timber only requires simple techniques and common assembly facilities. Normal manufacturers or carpenters are capable of producing such materials, and its manufacturing process poses few obstacles for local or small-scale sawmills. As a result, these advantages may lead to its increased use and potential in the domestic manufacturing chain and circular economy.

Due to limited experience with its production and market share, local manufacturers or sawmills encounter considerable difficulty in producing, evaluating and using non-glue-laminated timber elements. Despite the few obstacles to its prefabrication, manufacturing processes must be regulated to ensure their reliability. In addition, the database concerning the structural behaviour of non-glue-laminated timber remains insufficient. Among various applications of non-glued timber, structural beams are less studied, and their bending behaviour needs to be determined. Diverse laminating techniques, profiles or materials may lead to different bending stiffness, and their outcomes should be quantified. Meanwhile, the efficiency of different analytic models for the composite effect of non-glue-laminated beams must be verified by comparing the experimental and theoretical results. Different models or equations may exhibit a certain prediction capability for specific laminated timber beams with diverse transversal fasteners.

To investigate these issues, this study attempts to carry out a series of full-scale bending tests and to compare the results to analytical evaluations.

2. Literature Review

While glue-based composite beams account for the majority of contemporary engineered timber, non-glue-laminated elements are gaining increasing attention. The laminating processes mainly apply metallic or wooden fasteners to compose the laminae. The function of these transversal fasteners is to provide shear resistance between laminae or adjacent components, restricting relative displacement. In recent decades, in Europe, non-glue-laminated timber has been used in diverse buildings. The main areas of application comprise the floor, roof and wall [1,2]. Along with building practice, some scientific studies have focused on the mechanical properties of various non-glued timber elements. In these studies, structural beams have been tested and analysed to estimate the composite efficiency of different laminating materials and techniques.

O'Loinsigh et al. appraised the structural behaviour of non-glued timber beams by means of a four-point bending test [3]. This study applied wooden dowels as transversal fasteners to laminate the wooden planks. All dowels were inserted at a 60-degree angle to the fibre's direction of the laminae. The research group found that the numbers of the wooden dowels, i.e., the spacing distance of the fasteners, influenced the bending stiffness of the non-glued beams. As shown by their tests, the enhancement of beams' bending stiffness may exhibit certain limits. Increasing the number of the wooden dowels cannot always improve the bending behaviour of non-glued timber beams. By means of an experiment, Jelušič and Kravanja estimated the bending behaviour of timber beams composed of a self-tapping screw (STS) [4].

Their screws were drilled in at a 90-degree and 45-degree angle to the grain of the planks, and the screws were spaced 50 and 100 mm apart. With the same spacing, beams with screws inserted at a 45-degree angle demonstrated greater rigidity than those with screws inserted at a 90-degree angle. The influence of STSs' spacing is relatively small. Sotayo et al. extended the application potential and evaluation scope of non-glue components [5]. Named adhesive-free laminated timber, their specimens consisted of beams and CLT panels. As far as the beams were concerned, the specimens were laminated with wooden dowels of a 10 and 15 mm diameter. These wooden dowels were inserted into the beams at a 90- or 45-degree angle and with 100 or 150 mm spacing. According to the test, the flexural modulus of adhesive-free beams is about 12% to 32% of the outcome for glulams. The greater diameter and reduced spacing between wooden dowels resulted in higher bending rigidity. As indicated by Sotayo et al., beams with a larger cross-section exhibit lower bending stiffness compared to specimens with a smaller dimension. This phenomenon can be attributed to the size effect. Bui et al. assessed the mechanical properties of adhesive-free timber beams and CLT panels [6]. Their specimens were laminated with wooden dowels as well. While the planks were sawn from oak, their wooden dowels were made of the spruce. Originally, spruce's density is lower than that of oak. After compression, spruce dowels reached a density of 1200 kg/m^3, on average, which is higher than oak's mean density value of 625 kg/m^3. Laminated by means of wooden dowels, the composite wooden products in [5,6] are widely named dowel-laminated timber (DLT).

As a sustainable and reversible technique, the use of a transversal fastener is applied not only in contemporary buildings but also in cultural heritage buildings. Gubana reviewed various profiles regarding the assurance of the in-plane structural performance of wooden floors [7]. These composite floors were reinforced by means of wooden dowels or self-tapping screws. Associated studies quantified the structural efficiency of diverse reinforcing techniques and proved that these flooring systems possess sufficient structural capacity against earthquakes. With regard to a general assessing method, however, Gubana's conclusion recalled that diverse studies comprise divergent prerequisites, specimens and boundary conditions, posing a challenge for determining a convergent method for estimating composite elements' in-plane behaviour. Li et al. applied simple methods to laminate flooring components using nails [8]. The research group investigated the failure modes and bending stiffness of the floors by four-point bending tests. The bending strength corresponding to specific failure modes was determined according to two failure criteria. The strength associated with failure due to lamination was about 88% of the ultimate strength. In addition to horizontal elements like beams and floors, non-glue-laminated timber can be used as a structural wall. Zhang et al. evaluated the lateral behaviour of a non-glued timber wall by full-scale testing [9]. Like the flooring specimens of Li et al., i.e., in [8], Zhang et al. applied nails to laminate a series of wooden planks to build the massive timber wall. The testing demonstrated that nail-laminated timber (NLT) walls demonstrate significant ductility against lateral force.

As shown in the studies of non-glue-laminated timber elements, the transversal fasteners for joining wooden planks influence the structural behaviour of components. Some studies apprised the mechanical properties of various transversal fasteners, particularly, their shear performance [10–16]. The shear resistance and stiffness of fasteners constrain the relative movement of adjacent wooden elements or laminae, forming the rigidity or capacity of the whole component. As far as laminated timber beams are concerned, different fasteners, as well as diverse profiles for their use, lead to discrepant composite efficiencies of these horizontal elements against the bending moment. Schiro et al. carried out a series of shear test to appraise the shear properties of a variety of joints possessing not only different screws but also diverse profiles [17]. Compared to a conventional bolt, the screws exhibited increased potential to constrain the relative movement of wooden components. This effect results from the thread of the screw, named rope effect. The tight embedment between screws and wood reduces the initial slippage of the constructions. Two comparable research groups have carried out experimental and numerical inspections to evaluate the structural behaviour of dowel-type joints composed of wood, slot-in steel plate and metallic fasteners [18,19]. While Fonesca et al. focused on steel dowels based on Eurocode 5 [18], Geiser et al. added some threaded screws to enhance the ductility of similar joints according to the ongoing Eurocode 8 [19].

On the other hand, wooden dowels have been tested or analysed to determine their shear behaviour. Derikvand et al. estimated the mechanical properties of dowel connectors made of salvaged wooden materials [20]. Focusing on species of wood in tropical or subtropical areas, Pereira et al. appraised the structural behaviour of CLT panels laminated by wooden dowels [21]. Their specimens can be referred to as DCLT panels. They integrated a shear test of wooden dowels' mechanical properties and analytical assessment of CLT panels' bending behaviour. Their evaluation verified the capability of this type of CLT for residential constructions. Giordano et al. used salvaged plywood tenon to produce DLT panels and estimated the panels' bending stiffness [22]. Their plywood tenons contributed to the use of short wooden planks, solving the issue of using wood with limited length. By applying the plywood tenon, the DLT panels do not need end-to-end gluing.

In addition to conventional wood, some studies investigated the mechanical properties of densified or treated wooden dowels. The greater density may lead to higher resistance of the dowels and restrict the relative movement of laminae. El-Houjeyri et al. appraised the material properties and compositing efficiency of thermo-mechanically compressed wooden dowels [23]. By densifying the wood and increasing its density by 2.6 times, the wooden dowels can provide acceptable bending stiffness for three-layer timber beams. Although the wooden dowel beams exhibit only half the bending stiffness of glulam, the result is considerable compared to other studies which applied a conventional wooden dowel. As shown by testing, compressed wooden dowels lead to ductility, in terms of the bending behaviour of the adhesive-free timber beams. Owing to the interest in the properties and potential of densified wooden dowels, Dourado et al. determined the bending stiffness of non-glue-laminated timber beams and compared the results of the experimental and finite element method [24]. Their test demonstrated that the stiffness of timber beams composed of densified wooden dowels is about half of the value of glued specimens. Among four inclinations of dowels, beams with 45-degree inclined densified wooden pins possess about 80% of the strength of glue-bonded elements. Sotayo et al. reviewed the state of the art in DLT products [25]. The associated studies of various research groups demonstrated the adaptability and capability of this engineered timber.

Regarding the requirements of theoretical models for bending behaviour, Tomasi et al. evaluated and compared different methods to predict the effective EI of mechanically laminated elements [26]. The focus of Tomasi's research was not only the method of Eurocode 5 (EC5) but also the theoretical model for inclined connectors or fasteners. By verification with experimental results and EC5 data, the research group proposed a robust method for predicting effective EI. To determine the efficiency of composite, Gutkowski et al. applied an equation to quantify the performance of various composite techniques within a specific spectrum [27]. They use a normalised indicator, i.e., μ, to demonstrate the percentage between maximum and minimum EI.

According to current research, the structural behaviour of non-glue-laminated beam is influenced by the material, spacing and inserted angle of the transversal fasteners. When the dimension and span of the beams increase, quantitative study is required to appraise the structural performance of the new composite.

3. Manufacturing

Since experience manufacturing dowel- or screw-laminated beams with such a large dimension is rare, it is worth introducing the production processes of these non-glue-laminated timber components. Due to a lack of well-developed machines and knowledge about making these components, the providers and carpenters in this research must carry the research out using a trial-and-error strategy. Even well-experienced conventional producers or carpenters must work outside of their usual cognition or mindset.

The manufacturing consists of the following steps:

(i) Evaluating the MoE of each plank of domestic wood by non-destructive testing (NDT) and then arranging these laminae into heterogeneous-graded elements.

(ii) Carrying out the lofting on the plank according to the position of the transversal fasteners.

(iii-a) Pre-drilling for STSs while clamping the planks at the same time. The pre-drilled holes are 4 mm in diameter, which is smaller than 70% of the diameter of STSs. The holes perpendicular to the shear face can be drilled directly using an electric drill. For precise orientation, however, carpenters should use an angler for inclined STSs. Due to the limitation in the channel's length, the angler can support a penetration stroke up to 100 mm. Based on carpenters' experience, this depth is considerable for further drilling.

(iii-b) Regulating the order of pre-drilling. After positioning the points of STSs, carpenters should pre-drill from mid-point to both ends and side-over-side, alternatively, in both ends. This strategy contributes to controlling deviation or error.

(iv-a) Pre-drilling for wooden dowels (WD) and, simultaneously, constraining the planks during drilling. Carpenters should pre-drill some 19 mm-diameter holes penetrating the entire depth of the beam. For a 90-degree dowel, it is possible to pre-drill manually, while the inclined holes require an angler to ensure the accuracy of the angle. Since the angler can only regulate the initial 100 mm stroke, the remaining depth must be accomplished by hand, as shown in Figure 1a).

(**a**) (**b**) (**c**)

Figure 1. Manufacturing processes of DLT and NLT beams. (**a**) Pre-drilling for wooden dowel (WD). (**b**) Beams with WD (**left**) and STS (**right**). (**c**) Beams laminated by 45-degree STS.

(iv-b) Managing the order of pre-drilling. After lofting, the holes are pre-drilled from centre to both ends and one-over-one, alternatively, in both ends, the same as for STSs.

(v) Inserting the transversal fasteners. Like in pre-drilling, it is necessary to clamp the planks during inserting, and the processes are carried out side-over-side, alternatively, in both ends. Figure 1b) depicts the dowel- and STS-laminated beams. As far as STSs are concerned, drilling can be carried out quite similar to pre-drilling. Owing to the limitation of the angler's stroke, the drilling procedure beyond 100 cm can only be accomplished by hand. Regarding the insertion of wooden dowels, however, the procedure is complicated. Theoretically, to provide friction, the dowels' diameter should be slightly larger than the holes' dimension. In an extraordinarily deep cross-section, however, wooden dowels are produced with the same diameter as the pre-drilled holes, i.e., 19 mm, in order to mitigate the risk of fracture. When inserted into holes near the ends of the beams, wooden dowels may break in the last 150 mm depth. This issue could be due to the increasing displacement between planks in the end of the beams. Inevitably, the dowels have to be ablated somewhat to fit the pre-drilled holes. The abrasion of the dowels may cause reduction in the shear behaviour of the dowel and, consequently, in the rigidity of the beam.

Some steps in the manufacturing processes are depicted in Figure 1. One phenomenon in manufacturing has to be underlined: after insertion, beams with 45-degree inclined fasteners, i.e., in a V-type pattern, reveal slightly arching profiles. The curvature deformation is illustrated in Figure 2a), indicating a sort of pre-stressed effect. STSs may cause more significant deformation after insertion compared to wooden dowels. This effect demonstrates that the materials and techniques for laminating chosen in this study contribute considerably to constraining the planks. On the contrary, beams with 135-degree inclined fasteners, i.e., in an A-type pattern, show inverse arching layouts, as delineated as Figure 2b).

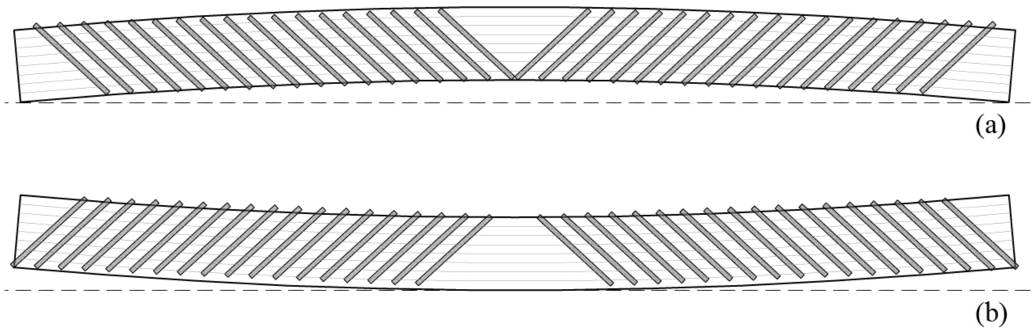


Figure 2. Beam deformation after insertion. While (**a**) refers to V-type, (**b**) is named A-type.

4. Testing Setup

4.1. Testing Rig

This study applied four-point bending tests to estimate and compare the bending behaviour of various glue- and non-glue-laminated beams. The testing rig is illustrated in Figure 3. The span was 3600 mm, which is a general modular for timber buildings, as demonstrated in a case study by Malo et al. [28]. In order to spare sufficient margins for a large deformation of the beams, the total length of the specimen was 4200 mm, allowing a 300 mm redundancy at each end. The hydraulic jack pushed a W-shaped steel beam, generally named an H-section, to homogeneously impose two points of load over the specimens. The distance between the two loading points was 1200 mm. The hydraulic jack possessed the loading capacity of 10 tons and pushed the steel beam at the rate of 5–9 mm/min. The total testing duration was from 25 to 40 min. A load cell equipped on the jack recorded the load during the entire testing procedures. The load cell was a Type LCX-100 kN produced by the NTS Technology Co., Ltd., in Zhunan Town, Miaoli County, Taiwan. Two LVDTs were placed under the middle point of the beams to track the deflection. The dimension of the specimen in this study were greater than that in former tests carried out in [3,5,6,23,24], leading to somewhat out-of-plane deformation during testing. Regarding the probable torsion or out-of-plane bending of the specimens, applying two LVDTs contributes to monitoring unexpected deformations and obtaining the mean value of two sets of deflections. The LVDT located at the mid-span of the beam was an SDP-200D, which possesses a 200 mm measuring capacity and is produced by Tokyo Measuring Instruments Lab. In addition to the sensors at mid-span, alternative LVDTs were placed in the end of the beam in order to measure the relative displacement between the laminae. The magnitude of this displacement indicates whether the cross-section remains on one plane and how sufficient the laminating technique is. The LVDT placed in the end of the beam was an SDP-100CT. Its measuring capacity is 100 mm, and its producer is also Tokyo Measuring Instruments Lab. The mechanism and one specimen are depicted in Figure 4.

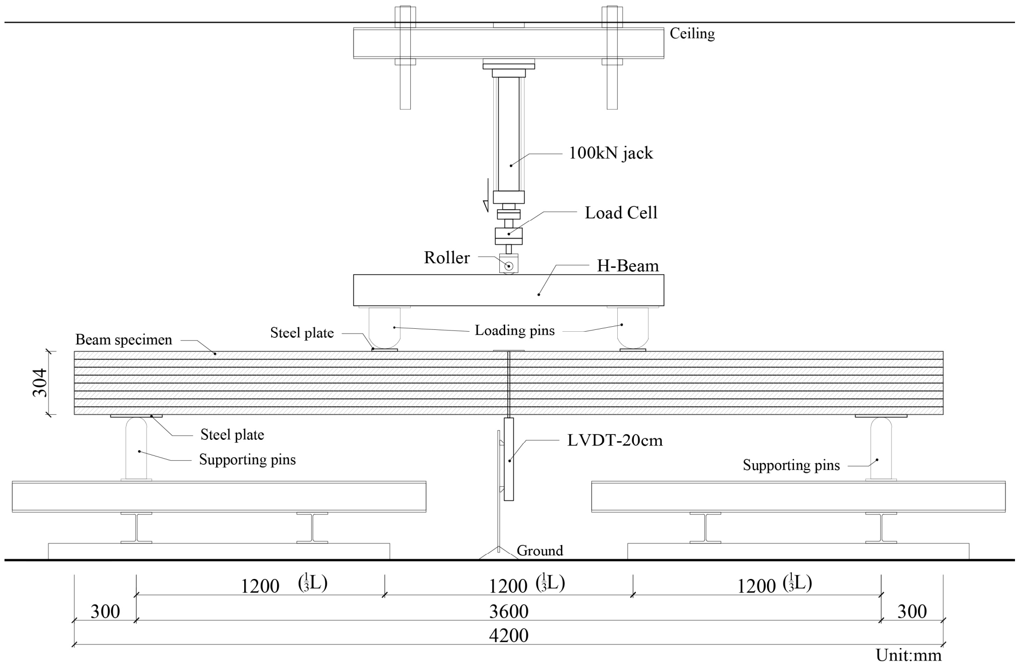
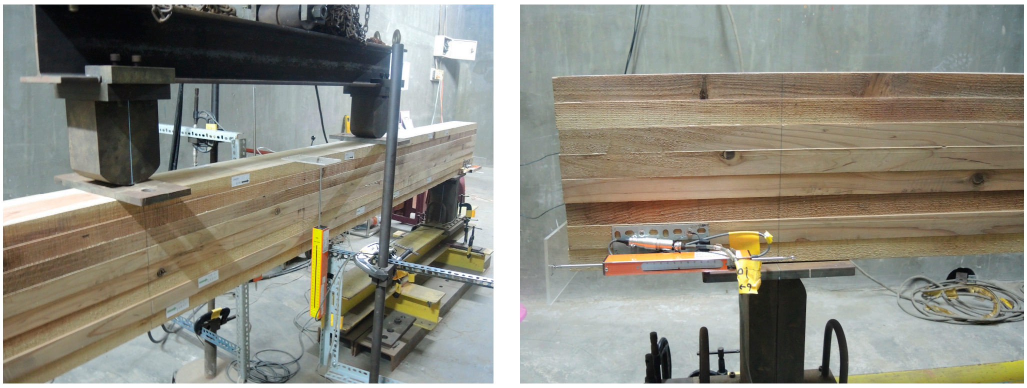


Figure 3. Testing rig of four-point bending test.



(**a**) (**b**)

Figure 4. Detail of the sensors and specimens. (**a**) W-shape steel beam and loading points. (**b**) LVDT in the end of the beam.

4.2. Material and Specimens

The planks of the specimens were domestic wood, *Cryptomeria japonica*, from Taiwan. Due to limited supply, this study used domestic wood from two sources: 35- and 42-year-old planted forests. Although the quality of the purchased wood varied somewhat, the mechanical properties of each plank can be defined, and the MoE of the laminated beam can achieve a certain class by means of appropriate arrangement. According to the National Standards in Taiwan [29], the specimens can be designated as classes from E55-F200 to E95-F270. Here, E55-F200 refers to a laminated timber element with a bending MoE of 5.5 GPa and bending strength of 20 MPa. E95-F270 means that the laminated timber demonstrates a bending MoE of 9.5 GPa and bending strength of 27 MPa. The specifications for bending MoE, i.e., E55, E75 and E95, etc., are denoted in specimens' coding. As instructed in Section 4.1, the length of the beam as well as the plank was 4200 mm. Laminated with 838 mm-thick, 150 mm-wide planks, the cross-section of the beam was thus 308 mm in depth and 150 mm in width.

The planning of the specimens emphasized the transversal fasteners for non-glue-laminated timber. As indicated in previous research, the material, spacing and inserted angle of the fasteners determine the bending behaviour of the laminated beams. Thus, this study employed a variety of specimens to evaluate these factors.

As far as the materials are concerned, the most broadly used fasteners are wooden dowels and metallic pegs. Among various metallic fasteners, the self-tapping screw (STS) is an emerging product that combines advantageous elements owing to its capacity, feasibility and efficiency. With regard to the beam's width and depth, this study used an STS of 8 mm diameter. The STS was made of carbon steel with chrome plating and possessed a 100 mm-long thread in the pointing end. The testing used a wooden dowel made of *Shorea* spp., which is a hardwood widely available in subtropical areas in Taiwan. The specimens laminated with wooden dowels were DLT beams. Prior to inserting the dowels, it was necessary to pre-drill a series of round holes. Regarding the dimensions of the beams and dowels, this study used a drilling hole with a 19 mm diameter. As far as normal bolts or pegs are concerned, the fasteners should be slightly larger than the holes. Because of the great depth of the beam, i.e., the extreme length of the fastener, however, the diameter of the wooden dowel was 19 mm, which is equivalent to that of the pre-drilled holes. Otherwise, the wooden dowels tend to break during the insertion process, particularly for those holes close to the ends of the beams. Both STSs and wooden dowels possess two specifications regarding their length. One is 300 mm in length and the other is 420 mm long. These profiles allow the transversal fasteners to penetrate the entire depth of the beam at 90 and 45 degrees, respectively. One particular scheme concerning the STSs has to be underlined: some 420 mm-long STSs were used as 90-degree fasteners. This arrangement leaves about 120 mm of the shank protruding over the specimens. The shank contributes to investigating whether the STS rotates along with the beam's cross-section or remains globally vertical.

The second factor is the spacing of the fasteners. As demonstrated in the previous literature, a smaller interval between fasteners, i.e., a larger number of inserted fasteners, results in greater bending stiffness for the beam. During manufacturing, however, extremely small spacing may cause cracks along the line of fasteners. On the other hand, an increase in the number of fasteners may not always enhance the bending stiffness [3]. Composite efficiency demonstrates certain limitations. In order to utilize a moderate interval between fasteners in these specimens, this study set three magnitudes of spacing, i.e., 100, 150 and 200 mm. These magnitudes of spacing refer to about 5, 7.5 and 10 times a wooden dowel's diameter, respectively. For the beams laminated by an STS, we only used 100 and 150 mm spacing, or 12.5 and 19 times the screw's diameter, respectively.

Finally, the insertion angle of transversal fasteners is analysed in this study. Normally, the dowels are inserted perpendicular to the grain of the planks, which is referred to as 90-degree in this study. In order to improve the composite efficiency and, therefore, the rigidity, some studies applied inclined fasteners. From the side elevation, the layout of the fasteners demonstrates a V-type array. In this study, this type of angle is defined as a 45-degree inclination. Rarely can the fasteners be inserted at an alternative 45-degree angle. From the side point of view, the fasteners in both ends present an A-type pattern. Unlike the previously mentioned method of inclination, the A-type pattern is defined as 135 degree. The three layouts of fasteners are depicted in Figure 5. The materials used in this test are listed in Table 1.

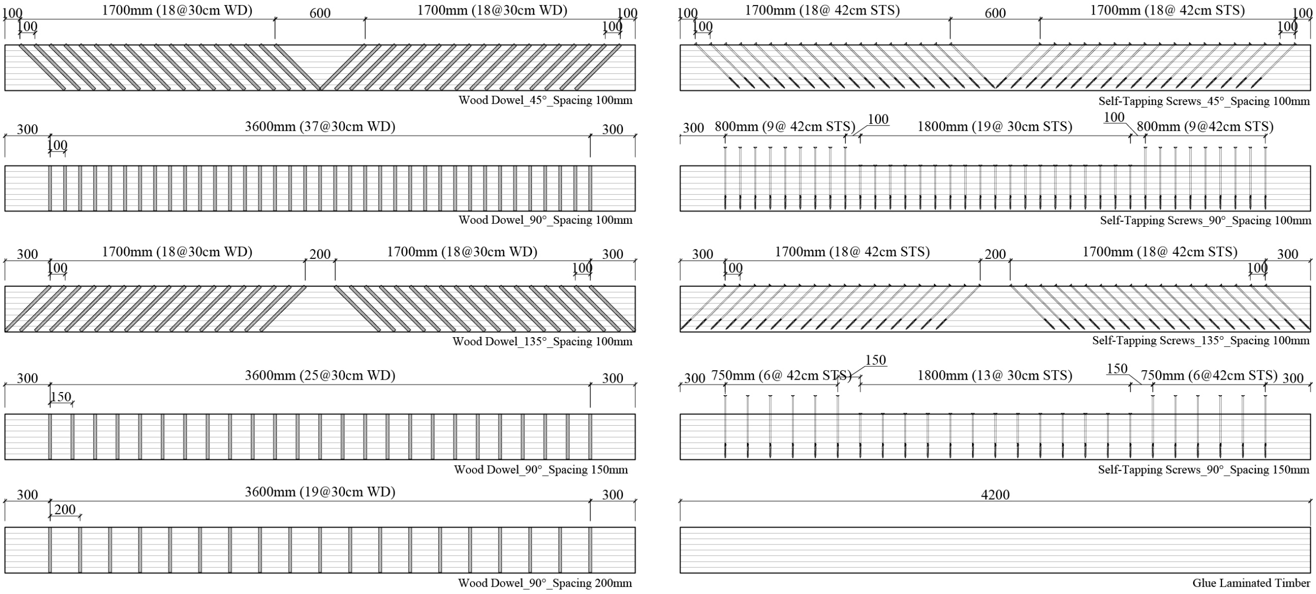


Figure 5. Eight types of specimens.

Table 1. Materials used in non-glued timber beams.

Element	Material	Density kg/m^3	Moisture Content	Length mm	Diameter mm	Thread mm	Treatment	Note
Wooden plank	*Cryptomeria japonica*	412	16.1%	4200			None	
Wooden dowel	*Shorea* spp.	547	13.6%	300 420	19 19	10 10	None	For different depths
STS	Carbon steel	7650		300 420	8 8	10 10	Chrome plating	For different depths

In order to include and indicate the associated factors, the coding of the 26 specimens basically comprises four sets of coordinates, such as AA_BB_CC_DD. The first coordinate represents the fasteners' materials. While WD means a wooden dowel, STS is a self-tapping screw. GLT refers to glulam. The second coordinate indicates the class of the beam, which derives from the MoE of the laminae. Five classes, from E55-F200 to E95-F270, are labelled based on the National Standards in Taiwan [29]. Although the classes of beams can be defined scientifically no matter where the wood is harvested, the coding of this study indicates the different sources of the wood in the coordinates. The second coordinate consists of an a or b in brackets to show that the planks come from 42-year-old or 35-year-old planted forests, respectively. The third coordinate indicates the spacing in centimetres. Here, S10, S15 and S20 represent 100 mm, 150 mm and 200 mm spacing, respectively. The fourth coordinate refers to the inserted angle of the fasteners. The number 90 means that the fasteners were inserted in the basic manner, in which fasteners are inserted perpendicular to the grain; 45 indicates the commonly applied V-type allocation, whereas 135 implies the contrary A-type array for transversal fasteners.

All specimens are listed in Table 2. Twenty-two non-glue-laminated timber products comprise four coordinates, while the four glulam products consist of only two labels.

Table 2. Specimens for bending test.

No.	Code	Fastener's Material	Fastener's Diameter	Fastener's Spacing	Inserted Angle	Fastener's Pattern
1	GLT_E95(a)	Glue	-	-	-	-
2	GLT_E85(a)	Glue	-	-	-	-
3	GLT_E85(b)	Glue	-	-	-	-
4	GLT_E75(b)	Glue	-	-	-	-
5	WD_E85(b)_S10_45	WD [1]	19 mm	100 mm	45°	V-type
6	WD_E55(b)_S10_45	WD [1]	19 mm	100 mm	45°	V-type
7	WD_E95(a)_S10_90	WD [1]	19 mm	100 mm	90°	
8	WD_E85(a)_S10_90	WD [1]	19 mm	100 mm	90°	
9	WD_E75(b)_S10_90	WD [1]	19 mm	100 mm	90°	
10	WD_E65(b)_S10_90	WD [1]	19 mm	100 mm	90°	
11	WD_E85(b)_S10_135	WD [1]	19 mm	100 mm	135°	A-type
12	WD_E55(b)_S10_135	WD [1]	19 mm	100 mm	135°	A-type
13	WD_E95(a)_S15_90	WD [1]	19 mm	150 mm	90°	
14	WD_E85(a)_S15_90	WD [1]	19 mm	150 mm	90°	
15	WD_E95(a)_S20_90	WD [1]	19 mm	200 mm	90°	
16	WD_E85(a)_S20_90	WD [1]	19 mm	200 mm	90°	
17	STS_E85(b)_S10_45	STS [2]	8 mm	100 mm	45°	V-type
18	STS_E55(b)_S10_45	STS [2]	8 mm	100 mm	45°	V-type
19	STS_E95(a)_S10_90	STS [2]	8 mm	100 mm	90°	
20	STS_E85(a)_S10_90	STS [2]	8 mm	100 mm	90°	
21	STS_E75(b)_S10_90	STS [2]	8 mm	100 mm	90°	
22	STS_E65(b)_S10_90	STS [2]	8 mm	100 mm	90°	
23	STS_E85(b)_S10_135	STS [2]	8 mm	100 mm	135°	A-type
24	STS_E55(b)_S10_135	STS [2]	8 mm	100 mm	135°	A-type
25	STS_E95(a)_S15_90	STS [2]	8 mm	150 mm	90°	
26	STS_E85(b)_S15_90	STS [2]	8 mm	150 mm	90°	

[1] WD refers to wooden dowel made of *Shorea* spp. [2] STS indicates self-tapping screw made of carbon steel with chrome plating.

5. Results

The testing results of 26 total specimens, including glue- and non-glue-laminated beams, are shown in Table 3. In this table, Δp is the increased loading within the linear elastic stage, and $\Delta\delta$ is the corresponding deflection in the same range. The stiffness, K, is the value of Δp over $\Delta\delta$. The bending MoE is calculated based on Equation (1). The ultimate bending resistance is not analysed in this study, because the specimens may not have reached their capacity yet. During testing, the beams deformed tremendously, and it was necessary to cease loading. Without a significant crack in the beam and a sudden reduction in terms of resistance, the specimens were not described as having failed.

$$\mathrm{EI} = \frac{23l^3}{1296} \times \frac{\Delta P}{\Delta\delta_{center}} \tag{1}$$

where l is the span between two supports.

The materials of the fasteners influence the bending stiffness of non-glue-laminated timber. Overall, beams with STSs demonstrate 7.86% greater bending stiffness than the specimens composed of wooden dowel. Table 4 shows the values, percentages and associated specimens. Regarding particular pairs of beams, however, the tendency does not remain convergent. Figure 6 shows the specimens with fasteners inserted at 90-degree angles and with 100 mm spacing. Among them, beams with a wooden dowel exhibit a 75% higher bending stiffness than those with an STS. Figure 7 shows the specimens with fasteners inserted perpendicularly to the grain and 150 mm spacing. In this profile, wooden dowel beams possess 23.5% greater bending stiffness than STS beams. As far as the beams with 45-degree/V-type fasteners are concerned, the STS beams exhibit significantly higher stiffness than the wooden dowel specimens do, as shown in Figure 8. STS beams' bending stiffness is almost 100% higher than beams using wooden dowels. This extreme discrepancy reveals the overall performance of wooden dowel and STS. The different magnitudes of bending stiffness led by diverse laminating profiles are shown in Figure 9. The chart underlines the significant advantages in bending stiffness of 45-degree STS beams. Figure 10 depicts the behaviour of beams with 135-degree inclined/A-type pattern fasteners with 100 mm spacing. With this pattern, wooden dowel beams possess about 46.7% greater bending stiffness than STS specimens.

Table 3. Bending stiffness K and MoE of 26 beams.

	Code	Load Δp	Deflection Δδ	Stiffness K	MoE
		kN	mm	kN/mm	GPa
1	GLT_E95(a)	25.06	12.92	1.940	4.575
2	GLT_E85(a)	17.79	10.96	1.624	3.828
3	GLT_E85(b)	25.60	14.69	1.743	4.109
4	GLT_E75(b)	25.05	13.69	1.830	4.314
5	WD_E85(b)_S10_45	13.09	27.56	0.475	1.120
6	WD_E55(b)_S10_45	16.99	43.50	0.391	0.921
7	WD_E95(a)_S10_90	14.32	55.00	0.260	0.614
8	WD_E85(a)_S10_90	16.75	79.00	0.212	0.500
9	WD_E75(b)_S10_90	13.48	35.32	0.382	0.900
10	WD_E65(b)_S10_90	11.26	31.87	0.353	0.833
11	WD_E85(b)_S10_135	13.21	49.12	0.269	0.634
12	WD_E55(b)_S10_135	15.53	76.93	0.202	0.476
13	WD_E95(a)_S15_90	11.42	60.01	0.190	0.449
14	WD_E85(a)_S15_90	12.65	73.54	0.172	0.405
15	WD_E95(a)_S20_90	11.63	78.64	0.148	0.350
16	WD_E85(a)_S20_90	12.59	83.93	0.150	0.354
17	STS_E85(b)_S10_45	15.57	17.40	0.895	2.110
18	STS_E55(b)_S10_45	10.38	12.37	0.839	1.978
19	STS_E95(a)_S10_90	12.22	60.03	0.204	0.480
20	STS_E85(a)_S10_90	10.64	60.01	0.177	0.418
21	STS_E75(b)_S10_90	16.39	100.33	0.163	0.385
22	STS_E65(b)_S10_90	16.32	112.24	0.145	0.343
23	STS_E85(b)_S10_135	15.86	86.73	0.183	0.431
24	STS_E55(b)_S10_135	10.76	77.79	0.138	0.326
25	STS_E95(a)_S15_90	10.92	69.48	0.157	0.371
26	STS_E85(a)_S15_90	10.02	73.46	0.136	0.322

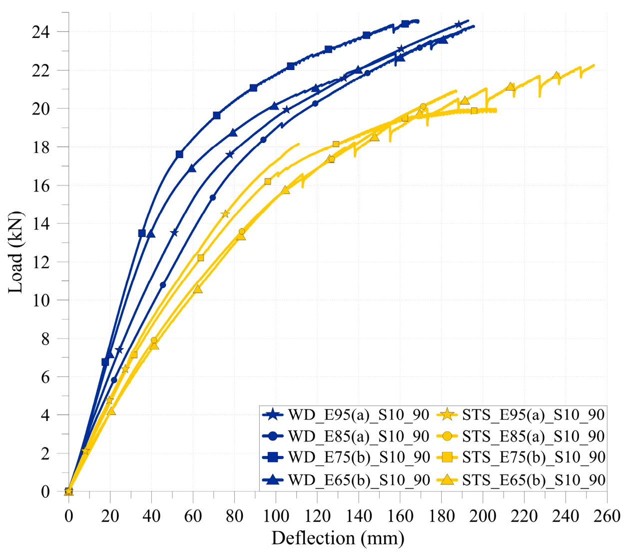


Figure 6. Testing curves of beams with fasteners spaced 10 mm apart.

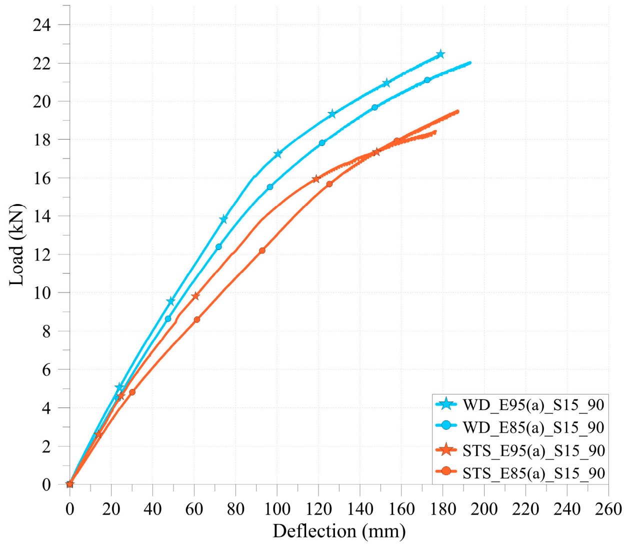


Figure 7. Testing curves of beams with fasteners spaced 15 mm apart.

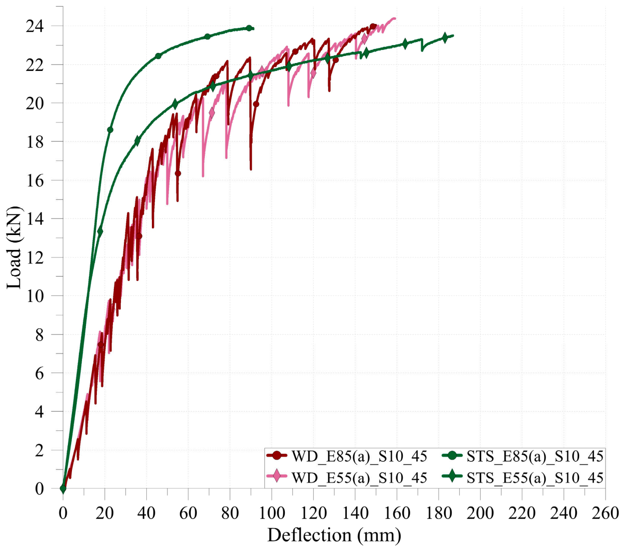


Figure 8. Testing curves of beams with 45-degree fasteners (V-type).

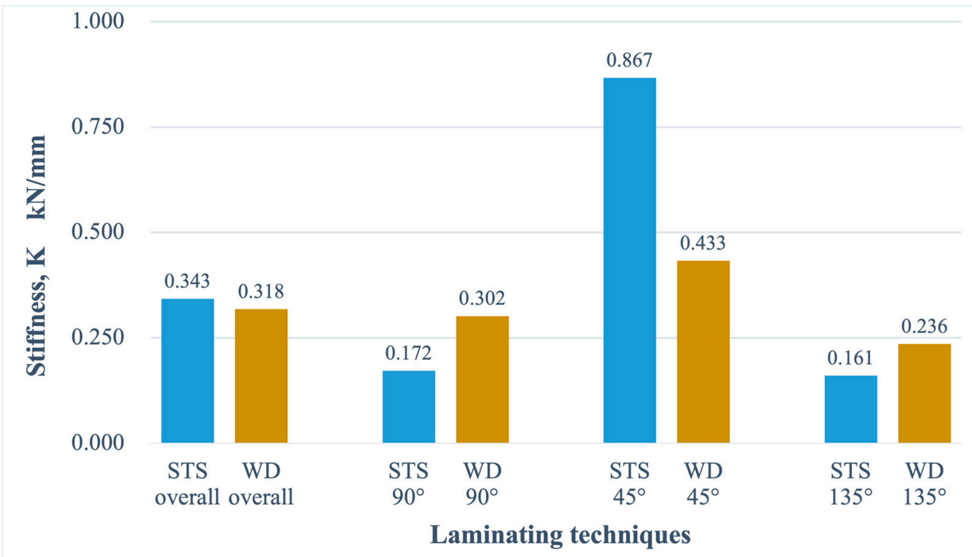


Figure 9. Bending stiffness for different angles of fasteners.

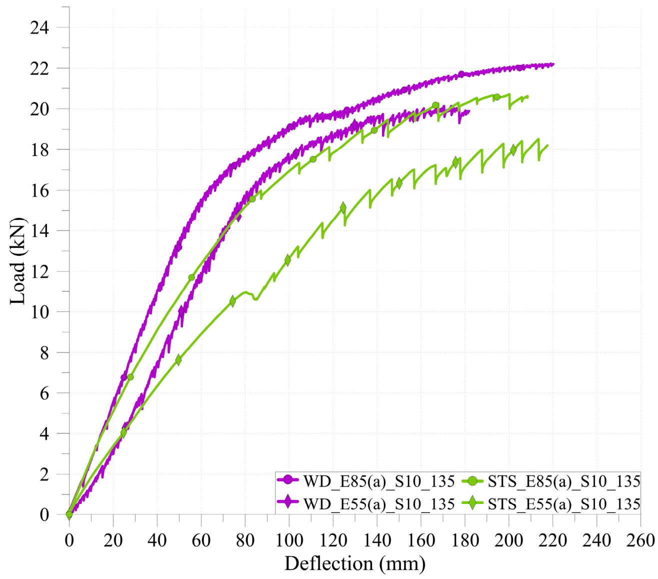


Figure 10. Curves of beams with 135-degree fasteners (A-type).

Table 4. Comparison of bending stiffness based on various factors.

			Stiffness, K	
Factor	**Variation**	**Specimens**	**kN/mm**	**Percentage**
Material	STS	No. 17–24 *	0.343	107.86%
	Wooden dowel	No. 5–12 *	0.318	100.00%
Spacing	100 mm	No. 7–10, 19–22	0.237	144.73%
	150 mm	No. 13, 14, 25, 26	0.164	100.00%
Angle	45-degree (V)	No. 5, 6, 17, 18	0.650	274.26%
	90-degree	No. 7–10, 19–22 **	0.237	100.00%
	135-degree (A)	No. 11, 12, 23, 24	0.198	83.54%

* only the specimens with 100 mm spacing, ** beams with 100 mm spacing and from two sources of wood.

The spacing of the fasteners influences the beams' structural behaviour as well. With a decrease in spacing, the bending stiffness of the beams increases. Table 4 shows the stiffness of the beams composed of transversal fasteners with either 100 or 150 mm spacing. Overall, 100 mm spacing results in about 44.7% greater stiffness than 150 mm. The values are shown in Table 4. Figure 11 delineates the load-deflection curves of eight beams with wooden dowels inserted at 90-degree angles. The bending stiffness of beams using a 150 mm interval is about 60% that of beams using 100 mm spacing. When fasteners' spacing rises to 200 mm, laminated beams' bending stiffness is less than 50% of the value of those with 100 mm spacing. Figure 12 shows the bending behaviour of six beams laminated with STSs. The stiffness of beams using 150 mm spacing is only 85% of that of those using 100 mm spacing.

The insertion angles of transversal fasteners influence the bending behaviour of laminated beams. Table 4 shows the experimental results as well as the percentages of beams with three angles of fasteners. Figure 13 shows the load-deflection curves of the beams with 100 mm spacing wooden dowels. The beams composed of 45-degree dowels possess 43.5% higher bending stiffness than those with 90-degree fasteners. On the other hand, the bending stiffness of the beam with 135-degree dowels is only about 78% of that in specimens with 90-degree pegs, demonstrating that the A-type inclined dowel reduces the beam's bending stiffness. Figure 14 shows the testing results of the specimens laminated by STSs using 100 mm spacing. Among the three angles, the beams with 45-degree screws possess more than 400% greater bending stiffness than the other two beams, revealing considerable structural performance. The stiffness of beams with 135-degree STSs is only about 93% of the value of those with perpendicular STSs. Like the tendency shown for wooden dowels, the A-type pattern of STSs does not enhance the bending stiffness of laminated beams.

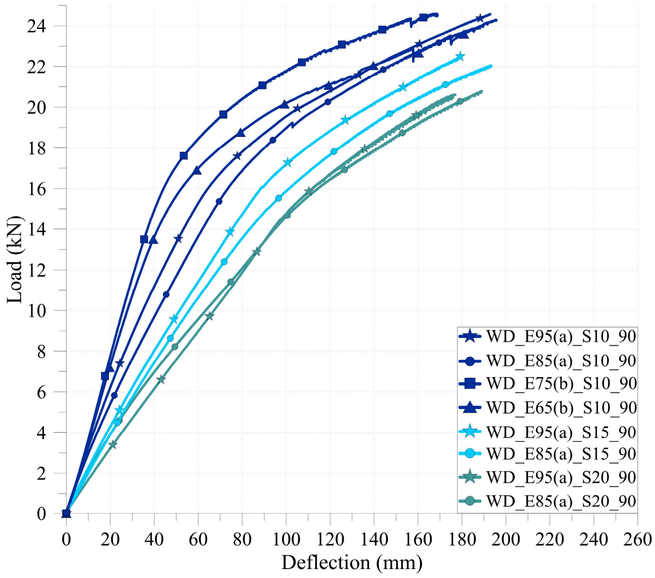


Figure 11. Testing curves of beams with WDs in 3 different spacings.

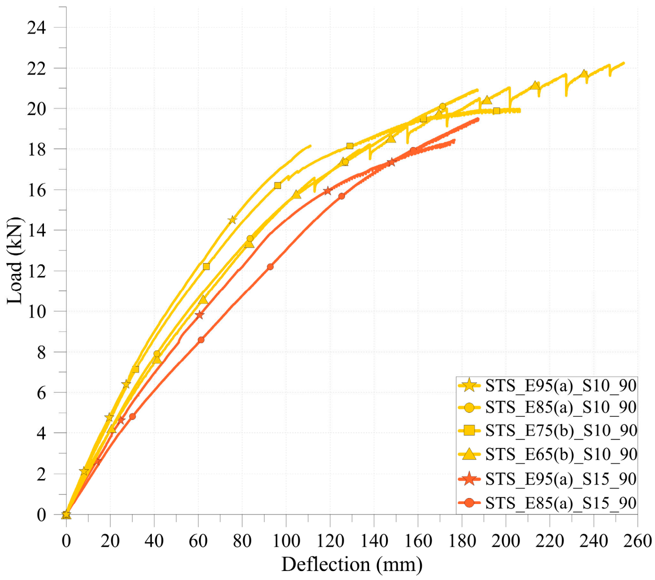


Figure 12. Testing curves of beams with STSs in 2 different spacings.

In addition to the rigidity, the profiles of the curves differ significantly among the three angles or patterns. The curves of the beams with 45-degree wooden dowels, i.e., a V-type pattern, may suddenly slump and then moderately climb, forming a conspicuous zigzag outcome. This phenomenon is illustrated in Figures 8 and 13 and can be attributed to the friction between wooden planks and round dowels. When the laminated beams are bent, relative displacement between the adjacent laminae occurs along the inclined wooden dowels. The friction or the bonding reaction on the wooden dowels' surface provides a reaction against the planks' movement. The specimens with 90-degree inserted wooden dowels demonstrated a smooth curve. The beams with 135-degree wooden dowels, i.e., a V-type pattern, consist of slightly jittering curves whose volatility is smaller compared to those using dowels inserted at 45 degrees. Unlike the profiles shown in wooden dowel beams, different angles of STSs cause the opposite behaviour in laminated beams. The specimens with 45-degree inclined STSs exhibit stable curves whose vibration is subtle. On the contrary, beams with 135-degree STSs demonstrated more bumpy curves than the other two types. This response can be seen in Figures 9 and 14. In terms of both stiffness and curve stability, 135-degree inclined STSs do not improve the bending behaviour at all.

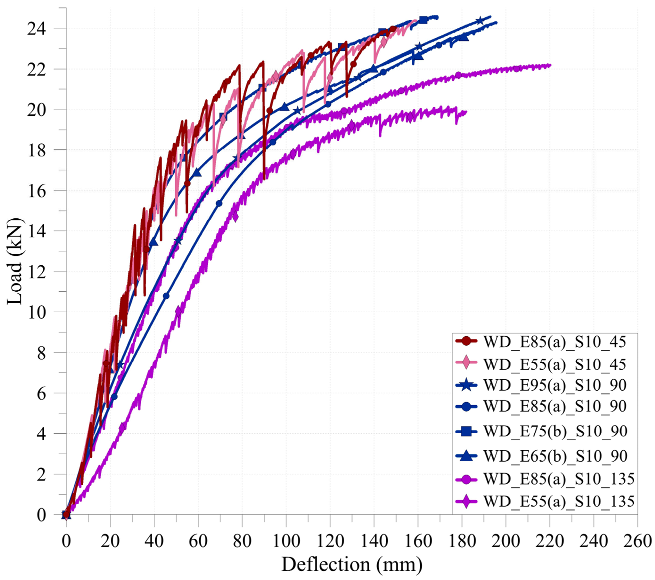


Figure 13. Testing curves of beams with WDs at 3 different angles.

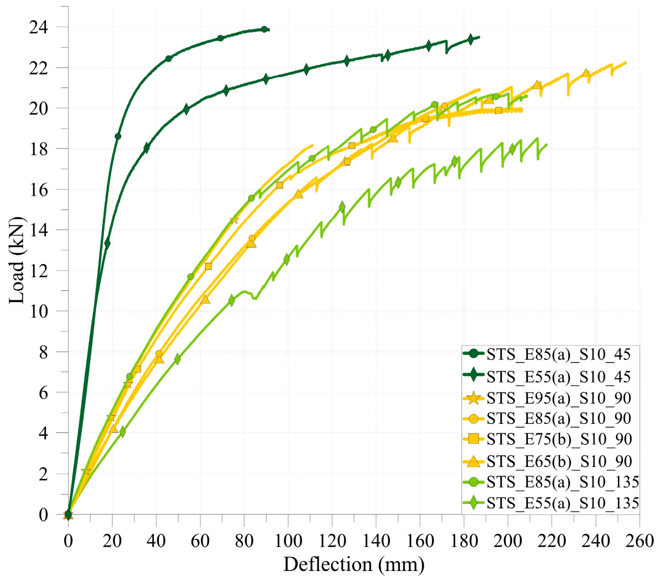


Figure 14. Testing curves of beams with STSs at 3 different angles.

Comparing the bending stiffness of glue- and non-glue-laminated timber demonstrates that non-glue elements produce less rigidity compared to glulam. The stiffness of the most rigid non-glue-laminated beams, STS_E55(b)_S10_45 and STS_E85(b)_S10_45, is just 48.6% of the mean value of glued laminated timber. Compared to the results demonstrated by former studies, this efficiency is comparable and considerable. The second-most rigid profiles, WD_E55(b)_S10_45 and WD_E85(b)_S10_45, exhibit only 24.3% stiffness compared to the glulam. The performance of these four specimens reveals the efficiency of 45-degree inclined or so-called V-type array fasteners. The perpendicularly fastened beams, i.e., those with 90-degree inserted fasteners, demonstrate no more than 17% of glulam's bending stiffness. This phenomenon can be attributed to the size effect of the large dimension of the beam, similar to the conclusion drawn by Sotayo et al. [5,25]. With a greater dimension than earlier studies' specimens, this study's beams may encounter more uncertainty during manufacturing. For example, as mentioned in the previous section, wooden dowels have to be ablated to penetrate the 300 mm- or even 420 mm-long holes. Nevertheless, the specimens with inclined fasteners, which are inserted by means of this study's procedures, exhibit considerable bending stiffness.

As far as failure is concerned, the specimens did not reveal critical cracks or detachment of laminae. Although the beams deformed significantly, as depicted in Figure 15, no tensile fracture occurred in the bottom of the specimens, seemingly demonstrating no bending failure. Only one specimen demonstrated a certain split of the wooden fibre in the bottom laminae, as shown in Figure 16. Nevertheless, it is not a longitudinal fracture of the fibre. This phenomenon explains why the data analysed here do not recognise ultimate load. The most significant damage was the local compressive failure between fasteners and planks. Figure 17 illustrates the relative displacement of the wooden dowel and the compressional buckling on the laminae. While the wooden fibre around the planks' holes deformed and the gap increased, the wooden dowel remained sound. This could be due to the greater density of the dowels made of hardwood. Wooden dowels inserted at both 45-degree and 90-degree angles demonstrated this type of deformation or failure. On the other hand, use of an STS results in similar failure as well, particularly with an STS close to the end of the beams. As depicted in Figure 18, the projecting STS seems to remain globally vertical after testing. This outcome indicates local compressive failure between STS and laminae, which is similar to the damage seen in wooden dowels. In addition to the globally vertical STS, the relative displacement between adjacent planks implies insufficient laminating effect in this profile. Although the beams deformed considerably, as illustrated by Figures 15 and 18, the wooden planks remained in contact. Both 45- and 90-degree inserted fasteners, including STSs and wooden dowels, demonstrate the same outcomes. As far as the beams with 135-degree/A-type STSs are concerned, however, the laminae may detach significantly, particularly in the planks near both supports. Figure 19 shows the detachment of wooden planks along the inclined dowels. Due to this slippage as well as the friction between two materials, the wooden fibre of wooden planks tears near the dowels, as shown in Figure 20. When A-type laminated beams deform, the wooden dowels globally rotate and somewhat protrude out of the top and bottom of the planks. Figures 21 and 22 demonstrate this damage outcome of 135-degree inserted wooden dowels. The considerable gap between dowels and planks as well as the fracture in the wooden fibre on the planks are depicted in Figure 22.

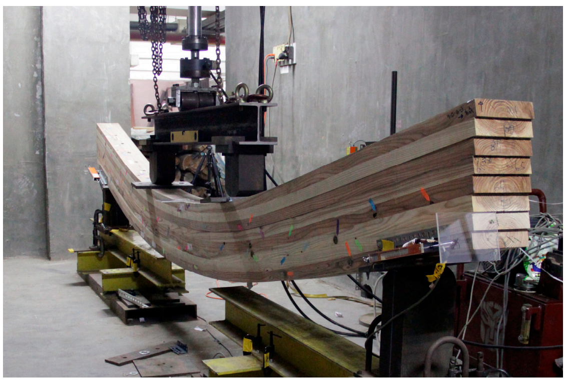


Figure 15. Deformation of DLT beam and relative displacement between planks.

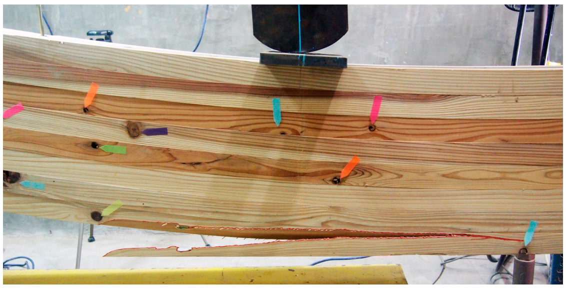


Figure 16. Split in wooden fibre in the bottom of the beam.

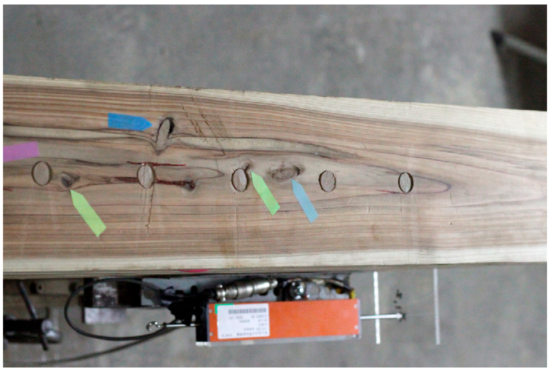


Figure 17. Failure of 90-degree wooden dowel.

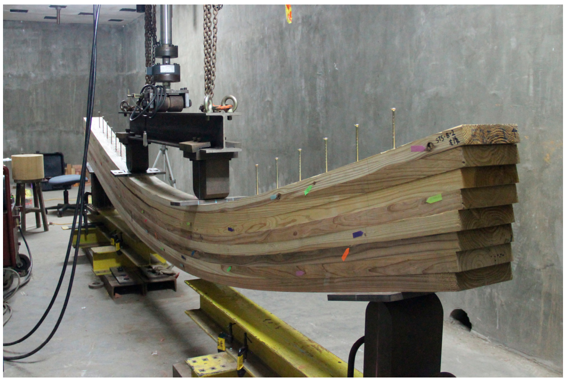


Figure 18. STS remaining globally vertical.

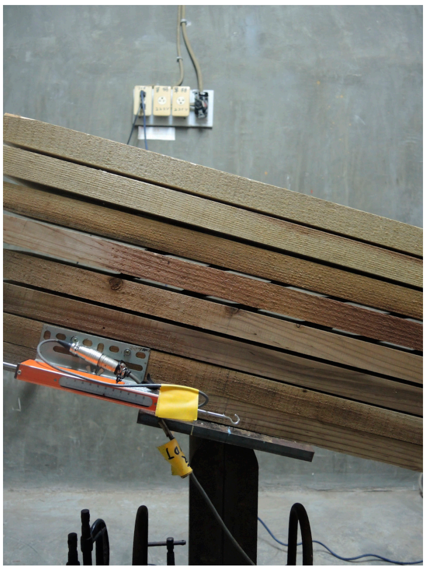


Figure 19. Detachment between planks of beams with A-type dowel.

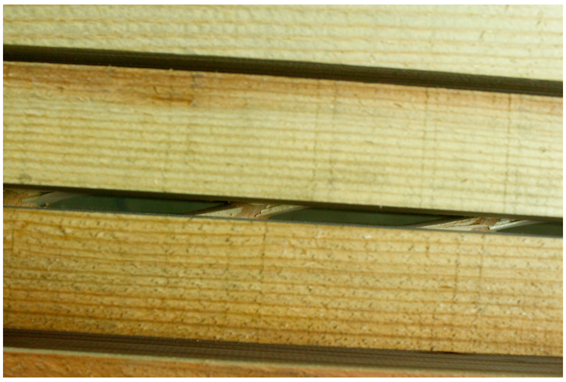


Figure 20. Split of wooden fibre on planks adjacent to dowels.

Figure 21. Protruding wooden A-type dowel.

Figure 22. Vacant between A-type dowel and hole.

6. Discussion

In this study, we manufactured a variety of composite beams made of three materials. In addition to the experiment, designers or engineers may need analytic methods to predict composite beams' structural behaviour. After testing and data analyses, this study aimed to verify two analytic methods or equations by comparing the calculated values to experimental results. One method was based on Eurocode 5 (EC5), and the other theoretic model was proposed by Tomasi et al. [26].

With regard to the testing, experimental EI value can be determined by Equation (1) and has been analysed in the former section. EC5 consists of a series of equations to determine the effective bending stiffness of composite beams. These equations are based on the gamma method (γ-method) and intended for calculating the theoretical EI:

$$\mathrm{EI}_{(eff)} = \sum_{i=1}^{8} \left(E_i \times I_i + \gamma_i \times E_i \times A_i \times {a_i}^2\right) \tag{2}$$

$$\gamma_i = \left(1 + \frac{\pi^2 \times E_i \times A_i \times S_i}{K_{ser,i} \times l^2}\right)^{-1} \tag{3}$$

$$K_{ser,i} = \left(\rho_m^{1.5} \times \frac{d}{23}\right) \tag{4}$$

where γ_i is a factor that represents the composite efficiency of each lamina with mechanical connectors. Equation (3) is intended for calculating the γ. In this equation, π is Pi, S_i the spacing of fasteners, $K_{ser,i}$ is the slip modulus of the fasteners, and l is the length of the span. Equation (4) is derives the fasteners' slip modulus. Here, ρ_m is the density of the dowel, and d is its diameter.

Clearly, the equations have not taken the fasteners' angle into account. To integrate the influence of inclined fasteners, Tomasi et al. proposed Equation (5) [26]. This theoretic model is based on EC5 and comprehensively involves the inserting angle and thread length of the screws:

$$K_{ser,i,a} = \left(\rho_m^{1.5} \times \frac{d}{23}\right)\cos^2\alpha + \left(30 \times S_g \times d_t\right)\sin^2\alpha \tag{5}$$

where α is the angle of the fasteners to the shear plane, S_g is the embedded length of the thread of screws, and d_t is their outer diameter.

Based on Equations (1)–(5), this study appraises various EIs, including experimental, non-composite, fully composite and those derived from two theories. By means of Equation (6), proposed by Gutkowski et al., the composite efficiency μ of diverse laminated beams can be estimated [27]:

$$\mu = \frac{EI_{comp} - EI_{min}}{EI_{max} - EI_{min}} \tag{6}$$

Table 5 shows various EI values and the associated composite efficiency μ of the 22 non-glue-laminated timber beams. Since the comparison aimed to verify the analytic models for mechanical fasteners, glulam was excluded from the discussion. We focussed on the feasibility of associated equations for wooden dowels and STSs. According to three sets of data, both EC5 and Tomasi's methods overestimated the EI of beams laminated with vertically inserted fasteners, including wooden dowels and STSs. Beams with 90-degree fasteners exhibit higher bending stiffness than both V-type and A-type laminated specimens do. This tendency is different from the experimental results.

The methods of EC5 and Tomasi reveal divergent analytic results for inclined fasteners. As far as the inclined fasteners are concerned, EC5 tends to overestimate the EI of beams with wooden dowels. Based on EC5′s equations, beams composed of inclined wooden dowels reveal greater $\mathrm{EI}_{\text{theo-EC5}}$ than those with inclined STSs. This order also differs from the results of testing. This phenomenon can be attributed to the fact that EC5′s equations take the diameter of the fasteners into account. In this study, the wooden dowels possessed a 19 mm diameter, while the diameter of the STSs was only 8 mm. This difference resulted in the discrepancy between beams laminated by wooden dowels and STSs. On the other hand, Tomasi's method may underline the laminating effect of STSs compared to wooden dowels. Regarding both V-type and A-type patterns, STS beams possess greater $\mathrm{EI}_{\text{theo-tomasi}}$ than the associated pairs with wooden dowels. With the same angles of fasteners and a similar class of laminae, STSs lead to higher theoretical stiffness compared to wooden dowels. This tendency agrees with the results of the bending test. This can be attributed to the fact that Tomasi's model reflects the withdrawal property of the screw, i.e., the length of its thread. During drilling, the STS causes a certain compression in the normal direction of wooden planes, and this effect contributes to improving the friction between laminae.

Overall, both methods do not effectively demonstrate the reinforcing efficiency of inclined fasteners, particularly the V-type array STS. One reason for this is that the analytical models have not sufficiently integrated the contribution of the screw's thread. The withdrawal capacity of the screw's head and subsequent friction between laminae can restrict the relative movement between wooden planks. Another important reason is that the theoretical models cannot use the prestressing effect of the STS, which may cause an arching effect, as illustrated in Figure 2a). The predictive efficiency of analytical methods for inclined fasteners should be further modified.

Table 5. EI and composite efficiency according to different theories.

	Code	Experiment	EC 5	EC 5	Tomasi	Tomasi
		EI_{exp}	$EI_{theo\text{-}EC5}$	$\mu_{theo\text{-}EC5}$	$EI_{theo\text{-}Tomasi}$	$\mu_{theo\text{-}Tomasi}$
No.		**N-m^2**	**N-m^2**		**N-m^2**	
5	WD_E85(b)_S10_45	393,269.96	2,203,736.45	0.632	1,625,127.20	0.463
6	WD_E55(b)_S10_45	323,395.86	1,791,584.61	0.701	1,387,969.53	0.540
7	WD_E95(a)_S10_90	215,651.85	2,541,965.28	0.657	4,523,809.52	-
8	WD_E85(a)_S10_90	175,549.63	2,375,289.86	0.677	4,313,725.49	-
9	WD_E75(b)_S10_90	316,009.06	2,020,118.87	0.663	3,942,307.69	-
10	WD_E65(b)_S10_90	292,540.95	1,891,558.13	0.683	3,641,509.41	-
11	WD_E85(b)_S10_135	222,676.71	2,209,448.31	0.632	1,6284,44.01	0.462
12	WD_E55(b)_S10_135	167,149.88	1,748,085.75	0.709	1,392,240.02	0.549
13	WD_E95(a)_S15_90	157,514.35	2,190,175.86	0.558	4,265,873.02	-
14	WD_E85(a)_S15_90	142,398.21	2,042,602.50	0.586	4,058,823.53	-
15	WD_E95(a)_S20_90	122,800.46	1,896,162.87	0.493	3,942,307.69	-
16	WD_E85(a)_S20_90	124,165.57	1,807,134.31	0.516	3,735,849.06	-
17	STS_E85(b)_S10_45	740,917.24	1,444,294.87	0.406	2,672,338.24	0.763
18	STS_E55(b)_S10_45	694,797.09	1,227,952.02	0.494	2,019,766.66	0.822
19	STS_E95(a)_S10_90	168,595.81	1,694,951.22	0.436	3,253,859.87	0.850
20	STS_E85(a)_S10_90	146,799.13	1,626,207.33	0.457	3,019,741.75	0.860
21	STS_E75(b)_S10_90	135,262.83	1,357,055.03	0.440	2,639,456.63	0.869
22	STS_E65(b)_S10_90	120,393.44	1,291,440.36	0.465	2,411,257.79	0.880
23	STS_E85(b)_S10_135	151,413.35	1,442,227.53	0.407	2,664,766.88	0.764
24	STS_E55(b)_S10_135	114,529.89	1,227,954.09	0.494	2,019,768.26	0.822
25	STS_E95(a)_S15_90	130,200.60	1,343,319.07	0.336	3,077,719.18	0.787
26	STS_E85(a)_S15_90	112,941.62	1,293,904.26	0.357	2,847,227.30	0.803

7. Conclusions

In this study, the bending behaviour of non-glue-laminated timber was evaluated by full-scale four-point bending tests. Prior to the testing, the manufacturing procedures of these beams were established and executed successfully, demonstrating the viability of the techniques applied in this study. The bending stiffness of the non-glue beams made by various laminating techniques was determined and compared. By comparing the experimental and analytical results concerning bending stiffness, we estimated the the feasibility and shortcomings of various theoretical models.

Laminating techniques and profiles influence beams' bending behaviour. Overall, the use of STSs leads to a 7.86% higher bending stiffness than the use of WDs. Although 90- and 135-degree WDs result in slightly greater rigidity, 45-degree STS beams exhibit considerably higher stiffness than those with 45-degree WDs, and this significant discrepancy affects the overall mean values. As far as fastener' spacing is concerned, 100 mm spacing resulted in about 44.7% greater bending stiffness than a 150 mm interval. Both STS- and WD-laminated beams revealed a similar tendency. Fasteners' insertion angles determined beams' bending stiffness. Beams with 45-degree inclined fasteners, i.e., a V-type pattern from the side view, exhibited the greatest stiffness among the three layouts of specimens. This was particularly true for 45-degree STSs. Despite larger dimensions than former studies' specimens, the 45-degree STS beams in this study exhibited considerable bending stiffness: about 48.6% of that of glulam. In addition to the stiffness, according to their testing curves, STS beams possess smooth deflecting processes. On the contrary, the 135-degree fasteners, i.e., the A-type pattern, are not helpful for enhancing beams' bending stiffness. The 135-degree WDs may cause unfavourable damage between laminae and the contact surface between planks and dowels. Two theoretical methods adopted in this study contribute to an effective analytic estimation of the EI of laminated timber elements. Basically, both models do not effectively demonstrate the laminating efficiency of 45-degree inclined fasteners, particularly of STSs. The withdrawal capacity as well as the restricting effect in the normal direction of planks should be further integrated in the analytical models.

The manufacturing processes and laminating techniques could be adjusted to improve the structural performance of non-glue timber elements. For example, the spacing as well as the allocation of the fasteners could be optimised. Clearly, the profiles used in this study do not cause longitudinal cracks in the plank. The production method for wooden dowels could be enhanced to cause more friction or shear resistance. Thus, the correlation between dowels' transversal capacity and beams' bending behaviour needs to be determined quantitatively. Finally, analytical theories could be improved to better predict the behaviour of inclined STSs.

Author Contributions: Conceptualization, Y.-H.Y.; Methodology, Y.-H.Y.; Software, Y.-C.Y.; Validation, Y.-C.Y.; Formal analysis, Y.-H.Y. and Y.-C.Y.; Investigation, Y.-C.Y.; Resources, Y.-H.Y.; Data curation, Y.-H.Y. and Y.-C.Y.; Writing—original draft, Y.-H.Y. and Y.-C.Y.; Writing—review & editing, Y.-H.Y.; Visualization, Y.-C.Y.; Supervision, Y.-H.Y.; Project administration, Y.-H.Y.; Funding acquisition, Y.-H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Science and Technology Council (NSTC) in Taiwan. The grant number is 'MOST 107-2221-E-006-056-MY2'. The APC was funded by the project 'MOST 111-2221-E-006-054-MY2'.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Haller, P.; Helmbach, C.; Yeh, Y.-H. *Bauweisen, Konstruktionen, Tragwerke und Verbindungen im Holzbau*; TU Dresden: Dresden, Germany, 2013; ISBN 9783867803441.
2. Fritzen, K. Alte Deckenbauart neu entdeckt. In *Magazine: Bauen mit Holz*; Bruderverlag: Köln, Germany, 2011.
3. O'Loinsigh, C.; Oudjene, M.; Ait-Aider, H.; Franning, P.; Pizzi, A.; Meghlet, E.-M. Experimental study of tim-ber-to-timber composite beam using welded-through wood dowels. *Constr. Build. Mater.* **2012**, *36*, 245–250. [CrossRef]
4. Jelušič, P.; Kravanja, S. Flexural analysis of laminated solid wood beams with different shear connections. *Constr. Build. Mater.* **2018**, *174*, 456–465. [CrossRef]
5. Sotayo, A.; Bradley, D.F.; Bather, M.; Oudjene, M.; El-Houjeyri, I.; Guan, Z. Development and structural behaviour of adhesive free laminated timber beams and cross laminated panels. *Constr. Build. Mater.* **2020**, *259*, 119821. [CrossRef]
6. Bui, T.A.; Oudjene, M.; Lardeur, P.; Khelifa, M.; Rogaume, Y. Towards experimental and numerical assessment of the vibrational serviceability comfort of adhesive free laminated timber beams and CLT panels assembled using compressed wooden dowels. *Eng. Struct.* **2020**, *216*, 110586. [CrossRef]
7. Gubana, A. State-of-the-Art Report on high reversible timber to timber strengthening interventions on wooden floors. *Constr. Build. Mater.* **2015**, *97*, 25–33. [CrossRef]
8. Li, Z.; Feng, W.; He, M.; Chen, F.; Sun, X. Bending performance of nail laminated timber: Experimental, analytical and numerical analyses. *Constr. Build. Mater.* **2023**, *389*, 131766. [CrossRef]
9. Zhang, C.; Lee, G.; Lam, F. *Study of Massive Timber Walls Based on NLT and Post Laminated LVL*; Timber Engineering and Applied Mechanics Laboratory: Vancouver, BC, Canada, 2018; pp. 1901–2424.
10. Hassanieh, A.; Valipour, H.; Bradford, M. Experimental and analytical behaviour of steel-timber composite connections. *Constr. Build. Mater.* **2016**, *118*, 63–75. [CrossRef]
11. Hassanieh, A.; Valipour, H.R.; Bradford, M.A. Load-slip behaviour of steel-cross laminated timber (CLT) com-posite connection. *J. Constr. Steel Res.* **2016**, *122*, 110–121. [CrossRef]
12. Hassanieh, A.; Valipour, H.; Bradford, M. Experimental and numerical study of steel-timber composite (STC) beams. *J. Constr. Steel Res.* **2016**, *122*, 367–378. [CrossRef]
13. Loss, C.; Davison, B. Innovative composite steel-timber floors with prefabricated modular components. *Eng. Struct.* **2017**, *132*, 695–713. [CrossRef]

14. Loss, C.; Frangi, A. Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms. *Eng. Struct.* **2017**, *138*, 229–244. [CrossRef]
15. Loss, C.; Piazza, M.; Zandonini, R. Connections for steel-timber hybrid prefabricated buildings. Part I: Experimental tests. *Constr. Build. Mater.* **2016**, *112*, 781–795. [CrossRef]
16. Loss, C.; Piazza, M.; Zandonini, R. Connections for steel-timber hybrid prefabricated buildings. Part II: Innovative modular structures. *Constr. Build. Mater.* **2016**, *112*, 796–808. [CrossRef]
17. Schiro, G.; Giongo, I.; Sebastian, W.; Riccadonna, D.; Piazza, M. Testing of timber-to-timber screw-connections in hybrid configurations. *Constr. Build. Mater.* **2018**, *171*, 170–186. [CrossRef]
18. Fonseca, E.M.M.; Leite, P.A.S.; Silva, L.D.S.; Silva, V.S.B.; Lopes, H.M. Parametric Study of Three Types of Timber Connections with Metal Fasteners Using Eurocode 5. *Appl. Sci.* **2022**, *12*, 1701. [CrossRef]
19. Geiser, M.; Furrer, L.; Kramer, L.; Blumer, S.; Follesa, M. Investigations of connection detailing and steel properties for high ductility doweled timber connections. *Constr. Build. Mater.* **2022**, *324*, 126670. [CrossRef]
20. Derikvand, M.; Hosseinzadeh, S.; Fink, G. Mechanical Properties of Dowel Laminated Timber Beams with Connectors Made of Salvaged Wooden Materials. *J. Arch. Eng.* **2021**, *27*, 04021035. [CrossRef]
21. Pereira, M.C.d.M.; Sohier, L.A.P.; Descamps, T.; Junior, C.C. Doweled cross laminated timber: Experimental and analytical study. *Constr. Build. Mater.* **2021**, *273*, 121820. [CrossRef]
22. Giordano, L.; Derikvand, M.; Fink, G. Bending Properties and Vibration Characteristics of Dowel-Laminated Timber Panels Made with Short Salvaged Timber Elements. *Buildings* **2023**, *13*, 199. [CrossRef]
23. El-Houjeyri, I.; Thi, V.-D.; Oudjene, M.; Khelifa, M.; Rogaume, Y.; Sotayo, A.; Guan, Z. Experimental investigations on adhesive free laminated oak timber beams and timber-to-timber joints assembled using thermo-mechanically compressed wood dowels. *Constr. Build. Mater.* **2019**, *222*, 288–299. [CrossRef]
24. Dourado, N.; Pereira, F.; Lousada, J.; de Moura, M. Experimental and numerical analyses of wood boards joining using wood-pin connectors. *Constr. Build. Mater.* **2019**, *222*, 556–565. [CrossRef]
25. Sotayo, A.; Bradley, D.; Bather, M.; Sareh, P.; Oudjene, M.; El-Houjeyri, I.; Harte, A.M.; Mehra, S.; O'Ceallaigh, C.; Haller, P.; et al. Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. *Dev. Built Environ.* **2019**, *1*, 100004. [CrossRef]
26. Tomasi, R.; Crosatti, A.; Piazza, M. Theoretical and experimental analysis of timber-to-timber joints connected with inclined screws. *Constr. Build. Mater.* **2010**, *24*, 1560–1571. [CrossRef]
27. Gutkowski, R.; Brown, K.; Shigidi, A.; Natterer, J. Laboratory tests of composite wood–concrete beams. *Constr. Build. Mater.* **2008**, *22*, 1059–1066. [CrossRef]
28. Malo, K.A.; Abrahamsen, R.B.; Bjertnæs, M.A. Some structural design issues of the 14-storey timber framed building "Treet" in Norway. *Eur. J. Wood Wood Prod.* **2016**, *74*, 407–424. [CrossRef]
29. *CNS 11031*; Structural Glued-Laminated Timber. China National Standards, Bureau of Standards, Metrology and Inspection, Ministry of Economic Affairs: Taipei City, Taiwan, 2014.