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Development and structural behaviour of adhesive free laminated timber beams and cross laminated panels

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HIGHLIGHTS

- Fabricate adhesive free laminated timber (AFLT) beams and cross laminated (AFCLT) timber panels using compressed wood dowels.
- Structural tests on the AFLT beams and AFCLT panels.
- Parametric studies on the AFLT beams and AFCLT panels.
- The test results are benched marked with glulam beams and CLT panels.
- AFLT beams and AFCLT panels offer more sustainable and environmentally-friendly alternatives their glued counterparts.

Keywords:
Adhesive free laminated timber beam
Adhesive free cross laminated timber panel
Structural testing
Compressed wood dowel
Engineered wood product

ABSTRACT

Glued-laminated timber (glulam) beams and cross-laminated timber (CLT) panels are increasingly being used as structural members for buildings, because of their excellent mechanical properties, ability to be processed into larger structural sections and environmental benefits. Nevertheless, the inclusion of adhesives during their production raises environmental concerns due to the release of Volatile Organic Compounds (VOCs) and formaldehyde, which also causes difficulties in recycling. This environmental burden has led to the development of adhesive free laminated timber (AFLT) beams and cross-laminated (AFCLT) panels, which are intended to be used as alternatives to glulam beams and CLT panels in structural applications. In this paper, details of the materials and manufacturing processes for the AFLT beams and AFCLT panels are described, followed by the structural tests and the observed failure modes. Furthermore, parametric studies are carried out to investigate the effects of the following factors on the structural response, i.e. lamella species, dowel species, dowel insertion angles, dowel diameters and configurations, number of dowels (or dowel spacing), section sizes and number of interfaces. It is found that the flexural modulus and flexural strength of the 26 AFLT beams and 26 AFCLT panels are in the range of 1.1–5.3 GPa and 19.3–38.2 MPa, respectively. The experimental results are compared with commonly used glulam beams and CLT panels. The results are useful in understanding the mechanical properties of AFLT beams and AFCLT panels fastened with compressed wood dowels, and constitutes useful structural design information for future construction and structural applications, as well as providing data to validate the finite element modelling. In addition, the study has demonstrated a practical and sustainable approach in timber construction, which may lead to a substantial reduction in the use of structural adhesives and environmental benefits.

1. Introduction

Engineered wood products, such as glued-laminated timber (glulam) beams and cross-laminated timber (CLT) panels, involve adhesive bonding and/or mechanical metallic fastening of timber to make large structural sections and building components (e.g. beams, columns, panels, walls, roofs) for construction applications. Furthermore, these engineered wood products are alternatives to common structural materials such as steel and concrete, and are consumed in large volumes worldwide [1]. This is due to their technical capabilities (e.g. reduced effect of natural defects (such as knots) and more homogenous mechanical properties), cost-competitiveness and environmental benefits [2,3].

However, the predominant use of adhesives and some metal fasteners (e.g. nails) in these engineered wood products affects their end-of-life disposal, reusability, recyclability and overall sustainability [4]. Additionally, there are many issues arising during the manufacturing process, for example, the use of urea–formaldehyde (UF) adhesive is harmful to the environment due to the emission of toxic gases (e.g. formaldehyde and Volatile Organic Compounds (VOCs)), and is also a public health concern [5,6]. Hardeners (e.g. amines and formaldehyde) used in adhesives are irritants and skin sensitizers and therefore, constant exposure could lead to allergic reactions [7]. Additionally, the inhalation of formaldehyde gas is carcinogenic to humans, which highlights the toxicity and hazardous attribute of adhesives [8].

As a result of the points given above, regulatory standards [9–11] aim to limit the use of toxic adhesives in order to reduce the release of formaldehyde and VOCs during the production of engineered wood products [7,12]. The European Commission [13] is also working to improve air quality by reducing the use of toxic adhesives, and this current work entails developing and structural testing adhesive free laminated timber (AFLT) beams and cross-laminated (AFCLT) panels, which is part of a European Union funded project entitled Adhesive Free Timber Buildings (AFTB). The concept utilises the excellent mechanical properties and spring back and moisture-dependent swelling of compressed wood dowels to fasten timber lamellae, to develop structural members (e.g. beams and panels) as suitable alternatives to glulam beams and CLT panels.

Eurocode 5 [14] gives guidance on timber connections with steel dowel fasteners, but, there is no statutory structural design standard for dowel laminated timber members fastened with wooden dowels. Furthermore, there is only a limited number of studies that have dealt with the development and characterisation of dowel laminated timber members [15–20]. These studies would be of greater use if they all, more comprehensively, presented parameters such as the modulus of elasticity and strength values (rather than relative initial stiffnesses and maximum loads), which would be useful for comparisons with other engineered wood products.

Up to date, the work on the dowel laminated timber members is limited [21], especially on compressed wood doweled members. This paper firstly presents the materials and manufacturing processes of the AFLT beams and AFCLT panels, alongside glulam beams and CLT panels. Secondly, the experimental investigation of the structural behaviour of the AFLT beams and AFCLT panels with different parameter changes, such as lamella species, dowel species, dowel insertion angles and configurations, dowel diameters, number of dowels, section sizes and number of interfaces. The structural tests on the load-deflection responses of the beams and panels and their deformation as well as failure modes are presented and discussed. Additionally, the test results of the AFLT beams and AFCLT panels are compared with their adhesive counterparts (e.g. glulam beams and CLT panels), and the main conclusions are summarised. Therefore, this work provides a database of useful mechanical properties of AFLT beams and AFCLT panels (i.e. dowel laminated timber beams and panels manufactured solely from timber), and contributes towards their suitability and optimisation for greener and more sustainable structural and construction applications. This work also enables engineers and researchers to plan the next phase of research on these structures and their use for industry-wide applications.

2. Materials and manufacturing processes

This section describes the materials and manufacturing processes for different types and configurations of AFLT beams and AFCLT panels, which were tested at the University of Liverpool and the University of Lorraine. The AFLT beams and AFCLT panels made use of the spring back and moisture-dependent swelling and improved mechanical properties of the compressed wood dowels. Therefore, the compressed wood dowels were conditioned to relatively lower moisture content (5–8%) compared to the timber lamellae (10–15%), to ensure that they swelled and fit tightly in the laminated beams and panels, when exposed to ambient conditions.

2.1. Compressed wood dowels

Clear wood (i.e. without knots and other visible defects) with straight grain was used to make compressed wood dowels, via a high-temperature mechanical compression process. The wood was compressed radially at a temperature of about 130 °C. Three different species (Scots Pine, Spruce and Beech) of compressed wood dowels were used in the fabrication of the AFLT beams and AFCLT panels. A number of three-point bending tests were carried out to determine their elastic flexural moduli and flexural strengths, which are given in Table 1. The moisture content of the compressed wood dowels was in the range of 5–8%, and their final densities were in the range of 1100–1300 kg/m^3. All the compressed wood dowels were stored in air-tight plastic bags to prevent moisture-dependent swelling before they were inserted into the timber lamellae.

2.2. Fabrication of AFLT beams

The AFLT beams were tested at the University of Liverpool and were grouped into two categories, i.e. AFLT Beam 1 and AFLT Beam 2, in which there are two rows of dowels, as shown in Fig. 1. The Scots Pine lamellae in the beams were kiln dried to moisture contents of 10–15%, and their mean density was 556 kg/m^3 with a coefficient of variation of 14%.

Table 2 gives the labels and details of the AFLT beams. The AFLT Beam 1 (Fig. 1(a)) was a relatively smaller beam which comprised three lamellae, with each lamella having dimensions of 70 mm (width) × 21.5 mm (depth) × 1350 mm (length). AFLT Beam 2 (Fig. 1b and c)) comprised seven lamellae, and each lamella had dimensions of 115 mm (width) × 22.5 mm (depth) × 3150 mm (length). The timber lamellae were clamped, before the holes were drilled. After that, the compressed wood dowels were inserted with a hammer. Five samples of AFLT Beam 1 were manufactured and fastened with two rows of 10 mm compressed Scots Pine dowels (inserted perpendicularly). The distances between the dowels along the length and across the width of the beam were 50 mm and 23 mm, respectively. The dowels were evenly distributed, and the total number of dowels used for AFLT Beam 1 was 54.

Table 1
Diameter, mean density, elastic flexural modulus and flexural strength of compressed Scots Pine, Spruce and Beech dowels.

Species	Diameter [mm]	Density [kg/m^3]	Elastic flexural modulus [GPa]	Flexural strength [MPa]
Scots Pine	10	1300	25	269
Spruce	16	1100	21	158
Beech	10 and 15	1300	24	260

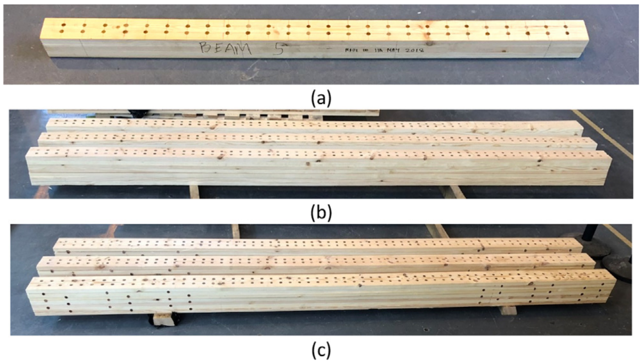

Fig. 1. Images of: (a) AFLT Beam 1 (b) AFLT Beam 2 and (c) AFLT Beam 2 with horizontal dowels.

AFLT Beam 2 was subdivided into seven groups, as described in Table 2 with the aim of investigating the effect of different dowel diameters (10 mm and 15 mm), dowel insertion angles (55° and 90°), dowel spacings (50 mm and 100 mm), dowel species (compressed Scots Pine and Beech), as well as the effect of including horizontal dowels near the opposite ends of the beams to limit relative sliding of the lamellae (Fig. 1(c)).

Three samples of each configuration, given in Table 2, were manufactured and tested (i.e. a total of 21 samples of AFLT Beam 2). It should also be noted that the AFLT Beam 2 with Scots Pine dowels had a staggered dowel arrangement (i.e. 25 and 50 mm offset between the two rows of dowels) compared to the configurations with Beech dowels.

2.3. Fabrication of AFCLT panels

The AFCLT panels were manufactured using the same procedure as the AFLT beams, and grouped into AFCLT Panel 1, AFCLT Panel 2 and AFCLT Panel 3. Their images are shown in Fig. 2 and their labels and details given in Table 3. All the AFCLT panels had a staggered dowel arrangement. Ten samples of AFCLT Panels 1 (three layers) and 2 (five layers) were tested at the University of Liverpool. In comparison, AFCLT Panel 3 (three layers) was tested at the University of Lorraine, using Oak lamellae (with a mean density of 620 kg/m^3) and compressed Spruce dowels. Sixteen samples were manufactured with eight of them having tongue and groove connections between adjacent lamellae, and the remaining eight without, as shown in Fig. 2, to investigate the effect of the tongue and groove connections.

2.4. Manufacturing process of glulam beams and CLT panels

For comparison with AFLT beams and AFCLT panels, glulam beams and CLT panels with similar dimensions were manufactured. However, there was no similar CLT panel comparable to AFCLT Panel 3. Buckland Timber manufactured the glulam beams and CLT panels, in accordance with CEN EN 14080 [22]. For consistency, Scots Pine was the timber species used. Five samples of each type of the glulam beam and the CLT panel were fabricated and tested, namely Glulam Beam 1, Glulam Beam 2, CLT Panel 1 and CLT Panel 2. The aforementioned glulam beams and CLT panels had similar dimensions, and correspond to AFLT Beam 1, AFLT Beam 2, AFCLT Panel 1 and AFCLT Panel 2, respectively.

3. Structural testing

This section gives details of the experimental tests carried out on different AFLT beams and AFCLT panels, to determine their flex-

Table 2
Labels and details of the AFLT beams.

Label	Number of samples	Lamellae (width × depth × length) (mm)	Number of lamellae	Lamella species	Dowel species	Dowel diameter (mm)	Dowel insertion angle* (°)	Dowel spacing (mm)	Number of dowels
AFLTB1	5	70 × 21.5 × 1350	3	Scots Pine	Scots Pine	10	90	50	54
AFLTB2_A	3	115 × 22.5 × 3150	7	Scots Pine	Scots Pine	10	90	100	61
AFLTB2_B	3	115 × 22.5 × 3150	7	Scots Pine	Scots Pine	10	90	50	123
AFLTB2_C	3	115 × 22.5 × 3150	7	Scots Pine	Scots Pine	10	55	100	58
AFLTB2_D	3	115 × 22.5 × 3150	7	Scots Pine	Scots Pine	10	55	50	118
AFLTB2_E	3	115 × 22.5 × 3150	7	Scots Pine	Beech	10	90	50	124
AFLTB2_F	3	115 × 22.5 × 3150	7	Scots Pine	Beech	15	90	50	124
AFLTB2_G	3	115 × 22.5 × 3150	7	Scots Pine	Beech	15	90 and horizontal dowels near the ends of the beams	50	124 plus 36 horizontal dowels

*The reference plane for the dowel insertion angle is the longitudinal plane of the lamellae.

Fig. 2. Images of AFCLT Panels 1–3.

ural modulus and flexural strength based on their initial stiffness, maximum load and geometries, which were compared with the glulam and CLT counterparts. These properties also enable a useful comparison with other engineered wood products. As indicated before, this study comprises of the investigation of the effects of dowel insertion angles, dowel diameters, dowel species, lamella species, configurations, number of dowels, and sections sizes, on the structural properties of the AFLT beams and AFCLT panels.

Descriptive statistics of the mechanical properties and failure modes of the beams and panels tested are reported and discussed. This section, thereby, provides practical reference base and database of the mechanical properties for AFLT beams and AFCLT panels, potentially useful for the design, implementation and improvement of dowel laminated timber structures.

3.1. Experimental test setup

Four-point bending tests were carried out on the AFLT beams and AFCLT panels alongside glulam beams and CLT panels with similar dimensions. The beams and panels were tested broadly in accordance with CEN EN 408 [23] and CEN EN 16351 [24], respectively. Fig. 3 shows sketches of the four-point bending test setup for the beams and panels and Table 4 gives their average dimensions.

The beams and panels were simply supported on steel rollers (50 mm in diameter), and laser displacement sensors were used to record their vertical deflections under loading at mid-span. The four-point bending test rig was equipped with a load cell (Toni Technik), with a capacity of 250 kN and a loading rate set to 0.2 kN/s. Fig. 4 (a) and (b) show images of AFLT Beam 2 and AFCLT Panel 1, respectively, on the four-point bending test rig.

3.2. Experimental results and discussion

The test data including the flexural moduli and flexural strengths of the beams and panels tested in four-point bending, is summarised in Table 5. The failure modes of the AFLT beams and AFCLT panels included tensile failure on the bottom lamellae, fracture around the visible defects (e.g. knots), and propagation of damage along the drilled holes. However, there was no visible damage to the dowels.

The overall flexural modulus of the tested glulam beams and CLT panels ranges from 9.5 to 16.8 GPa (11.6–16.8 GPa for beams and 9.5–13.5 GPa for panels), and their flexural strength from 29.3 to 73.3 MPa (29.3–73.3 MPa for beams and 41.1–55.2 MPa for panels). These values are reasonably close to the range given by Cai and Ross [25] for glulam (flexural modulus (9.0–14.5 GPa) and flexural strength (28.6–62.6 MPa). Based on the values given in Table 5, the average flexural modulus for the relatively smaller glulam beam (Glulam Beam 1) and CLT panel (CLT Panel 1) are about 17–28% greater than those of Glulam Beam 2 and CLT Panel 2, respectively. The average flexural strength of CLT Panel 1 was about 10% greater than CLT Panel 2. The difference was noticeably larger in the average flexural strengths of the glulam beams, which shows that Glulam Beam 1 was about 38% greater than Glulam Beam 2. These differences can partly be explained by the variability of timber and size effect of the glulam beams and CLT panels, as lower flexural strengths would be expected in the larger beams and panels due to the greater number of defects enclosed in larger timber sections.

Overall, the flexural modulus and flexural strength of the 26 AFLT beams and 26 AFCLT panels were 1.1–5.3 GPa (1.1–5.3 GPa for beams and 1.3–3.4 GPa for panels) and 19.3–38.2 MPa (19.3–36.7 MPa for beams and 22.1–38.2 MPa for panels), respectively, as shown in Table 5. These values were significantly lower than those of identical glulam beams and CLT panels with similar overall dimensions. Nevertheless, the AFLT beams and AFCLT panels had greater ductility as a result of the embedment deformations at the interfaces between the lamellae due to shear resistance contributed by compressed wood dowels and their rotation. The ductility estimated is based on the approach proposed by Jorissen and Fragiacomo [26], which is the ratio of the ultimate deflection to the yield deflection, and the results are shown in Table 6. Detailed discussions and analyses of the results of each AFLT beam and AFCLT panel are presented in the following sections.

3.2.1. Test results and analyses of AFLT Beam 1 and glulam Beam 1

Fig. 5 shows the load versus centre deflection plots for five samples of AFLT Beam 1 (AFLTB1_1–AFLTB1_5) and Glulam Beam 1 (GLB1_1–GLB1_5). For AFLT Beam 1, it is evident that there are yielding points of the beams before the ultimate load, associated with large deflections. On the other hand, Glulam Beam 1 showed an almost brittle failure in comparison to AFLT Beam 1. The relatively greater ductility of the AFLT Beam 1 is attributed to the slip between the lamellae fastened with the compressed wood dowels, which perform combined shear and bending deformations in a ductile manner.

The average flexural modulus of AFLT Beam 1 was 4.6 GPa, which was about 30% of Glulam Beam 1 with similar dimensions. Also, the average flexural strength of AFLT Beam 1 was 41% of Glulam Beam 1. Overall, the flexural modulus of AFLT Beam 1 ranged from 3.8 to 5.3 GPa, and flexural strength from 19.3 to 30.9 MPa. In comparison, the flexural modulus and flexural strength of the Glulam Beam 1 ranged from 14.3 to 16.8 GPa and 54.0–73.3 MPa (see Table 5). These values show that the flexural moduli and flexural strengths of AFLT Beam 1 were significantly lower than that of Glu-

Table 3
Labels and details of the AFCLT panels.

Label	Number of samples	Overall dimensions (width × depth × length) (mm)	Longitudinal lamellae (width × depth × length) (mm)	Transverse lamellae (width × depth × length) (mm)	Lamella species	Dowel species	Dowel diameter (mm)	Dowel spacing (mm)	Number of dowels
AFCLTP1	5	600 × 60 × 1500	100 × 20 × 1500	100 × 20 × 600	Scots Pine	Beech	10	100	180
AFCLTP2	5	600 × 100 × 2500	100 × 20 × 2500	100 × 20 × 600	Scots Pine	Beech	10	100	300
AFCLTP3_A (without tongue and groove connections)	8	450 × 75 × 2100	150 × 25 × 2100	150 × 25 × 450	Oak	Spruce	16	150	84
AFCLTP3_B (with tongue and groove connections)	8								

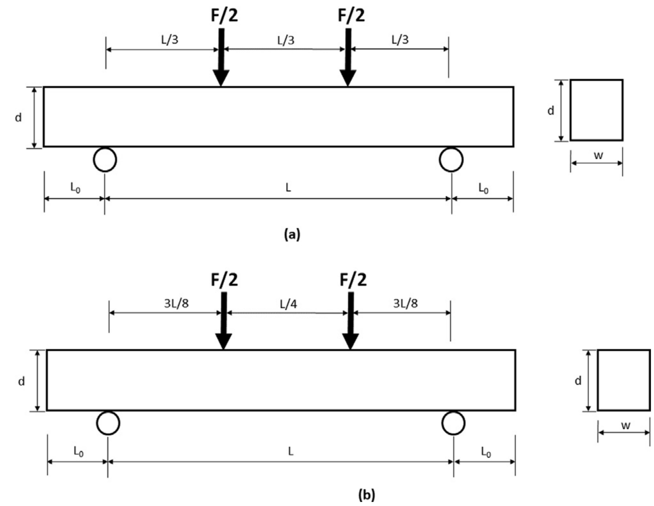

Fig. 3. Sketches of the four-point bending test setup for the beams and panels: (a) the beam [23], (b) the panel [24].

lam Beam 1, but AFLT Beam 1 showed a more ductile response in comparison to Glulam Beam 1.

The failure modes of AFLT Beam 1 are shown in Fig. 6. Cracks originated around the natural defects (i.e. knots) of the bottom lamella and through the drilled holes, and there was no fracture of the dowels. Indeed, it is better to avoid placing bottom lamellae with defects close to the mid-span of the beam. Glulam Beam 1 typically failed due to a fracture close to the centre of the bottom lamella (tensile region).

3.2.2. Test results and analyses of AFLT Beam 2 and glulam Beam 2

The load versus centre deflection plots for 21 samples (i.e. three samples of seven different configurations) of AFLT Beam 2 were similar to those of AFLT Beam 1 (Fig. 5), though magnitudes differ. The samples of AFLT Beam 2 had a more ductile response compared to their glulam counterparts (i.e. Glulam Beam 2) and no dowel fracture. The flexural strengths of AFLT Beam 2 were only analysed when a fracture could be seen. However, due to the ductile responses of some configurations of AFLT Beam 2 and limited crosshead movement of the load cell attached to the four-point bending test rig, some of the beams tested did not exhibit a visible fracture. For example, there were cases whereby only one of the three samples had a visible fracture. Also, the beams with the dowels inserted at an angle of 55°, did not show visible damage in bending. Furthermore, fracture of the beams usually initiated at locations with noticeable defects (e.g. knots). Nevertheless, the samples of AFLT Beam 2 with macroscopic fracture had their flexural strengths analysed alongside Glulam Beam 2, which are given in Table 5. The average flexural strength of AFLT Beam 2 is in a range from 20.2 to 36.7 MPa in comparison to Glulam Beam 2, which ranged 29.3–60.5 MPa. The natural variability of the wood and the random locations of macroscopic defects in the timber lamellae are considered to be the principal causes of the large range of the flexural strengths. Due to the limited sample size, there are no further discussions about the flexural strengths for the different configurations of AFLT Beam 2.

The flexural moduli of the seven configurations of AFLT Beam 2 alongside Glulam Beam 2 are also given in Table 5. AFLT Beam 2 with 10 mm compressed Scots Pine dowels with 50 mm dowel spacing inserted perpendicularly (AFLTB2_B) had a flexural modulus of 78% greater than that of the similar beam but with 100 mm dowel spacing (AFLTB2_A). A similar trend was observed for AFLT Beam 2 with diagonal dowels (compare AFLTB2_C and AFLTB2_D),

Table 4
Average dimensions of the AFLT beams and AFCLT panels tested in four-point bending.

Beam/Panel	Overall length ($L + 2L_0$: mm)	Span (L: mm)	Width (w: mm)	Depth (d: mm)	Support overhang (L_0: mm)
AFLT Beam 1	1350	1161	67	67	94.5
AFLT Beam 2	3150	2709	114	161	220.5
AFCLT Panel 1	1500	1440	591	61	30
AFCLT Panel 2	2500	2400	600	102	50
AFCLT Panel 3	2100	1600	450	75	250

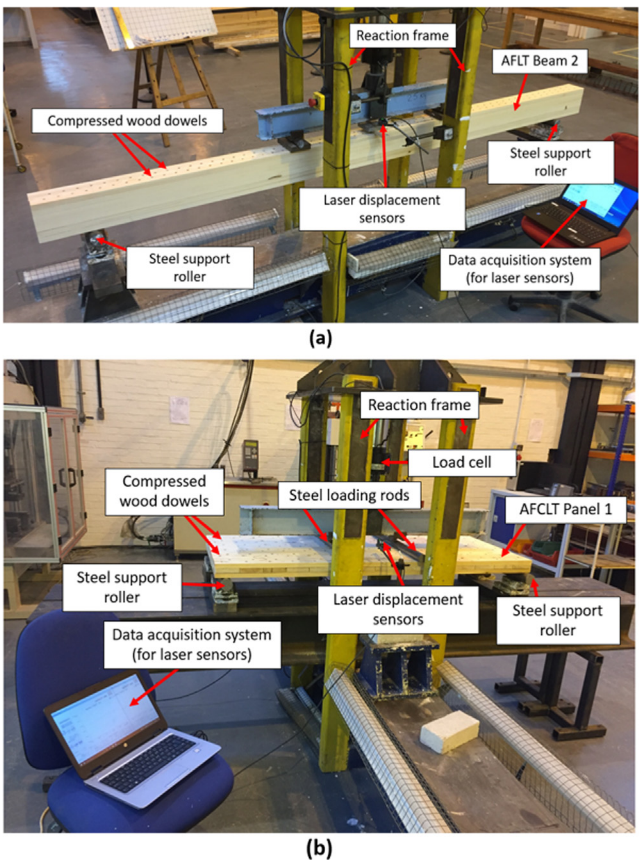

Fig. 4. Images of the four-point bending test rig showing: (a) AFLT Beam 2 and (b) AFCLT Panel 1.

Table 6
Ductility of the beams and panels.

Beam/panel type	Ductility		
	Average	Standard deviation	Range
AFLT beams	2.9	1.0	1.5–4.1
Glulam beams	1.7	0.3	1.2–2.0
AFCLT panels	2.1	0.3	1.8–2.4
CLT panels	1.7	0.1	1.5–1.8

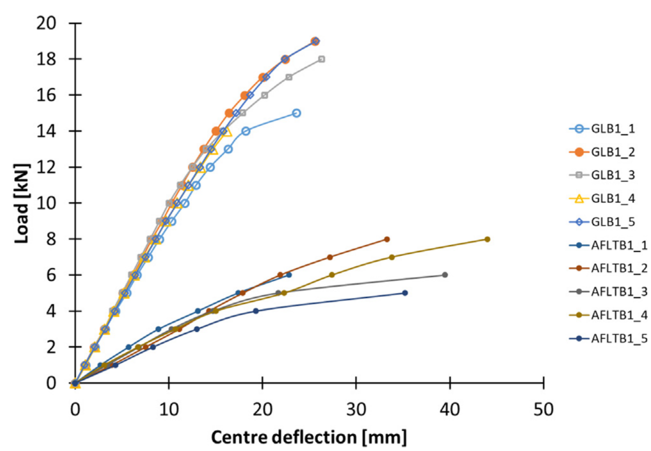

Fig. 5. Comparison of the load versus centre deflection plots for five samples of AFLT Beam 1 (AFLTB1_1–AFLTB1_5) and five samples of Glulam Beam 1 (GLB1_1–GLB1_5).

Table 5
Flexural moduli and flexural strengths of the beams and panels tested in four-point bending.

Beam/panel type	Label	Number of samples	Flexural modulus			Flexural strength		
			Average (GPa)	Standard deviation (GPa)	Range (GPa)	Average (MPa)	Standard deviation (MPa)	Range (MPa)
AFLT Beam 1	AFLTB1	5	4.6	0.6	3.8–5.3	27	3.9	19.3–30.9
Glulam Beam 1	GLB1	5	15.5	1.0	14.3–16.8	65.6	7.7	54.0–73.3
AFLT Beam 2	AFLTB2_A	3	1.4	0.2	1.2–1.6	22.0	N/A	N/A
	AFLTB2_B	3	2.5	0.3	2.2–2.7	34.8	2.8	33.0–36.7
	AFLTB2_C	3	1.4	0.4	1.1–1.8	N/A		
	AFLTB2_D	3	2.5	0.0	2.5	N/A		
	AFLTB2_E	3	2.6	0.3	2.3–2.9	20.2	N/A	N/A
	AFLTB2_F	3	3.7	0.4	3.3–4.1	22.0	N/A	N/A
	AFLTB2_G	3	3.9	0.6	3.4–4.5	26.6	0.9	25.7–27.5
Glulam Beam 2	GLB2	5	12.1	0.6	11.6–12.9	47.7	11.0	29.3–60.5
AFCLT Panel 1	AFCLTP1	5	2.6	0.2	2.3–2.7	23.6	1.5	22.1–25.0
CLT Panel 1	CLTP1	5	12.1	0.9	11.1–13.5	48.6	3.7	44.2–55.2
AFCLT Panel 2	AFCLTP2	5	1.7	0.2	1.3–2.0	N/A		
CLT Panel 2	CLTP2	5	10.3	0.4	9.5–10.7	44.1	2.6	41.1–47.6
AFCLT Panel 3	AFCLTP3_A	8	2.9	0.2	2.6–3.2	32.7	3.4	25.2–36.1
	AFCLTP3_B	8	2.8	0.3	2.5–3.4	30.7	4.1	25.2–38.2

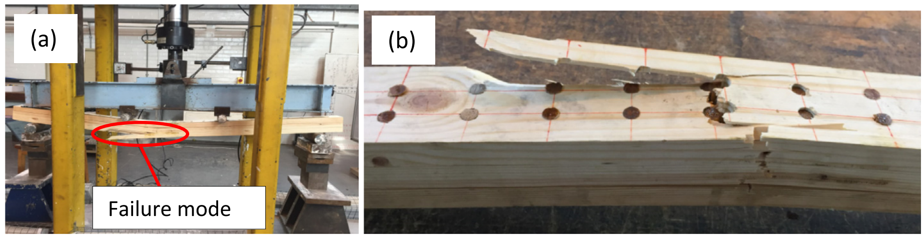

Fig. 6. Images of: (a) Failure of AFLT Beam 1 in four-point bending and (b) Close-up view of the damage on the bottom lamella (tensile region).

and showed that the beam with closely spaced dowels had an 81% greater flexural modulus. In light of the foregoing comments, a greater number of dowels led to a higher flexural modulus. Nevertheless, the flexural modulus of the AFLT Beam 2 with 10 mm compressed Scots Pine dowels with 50 mm dowel spacing inserted perpendicularly/diagonally (i.e. AFLTB2_B and AFLTB2_D) was about one-fifth of a glulam beam with similar dimensions (Glulam Beam 2).

Additionally, there was no significant difference in the flexural modulus of AFLT Beam 2 with different dowel insertion angles (55° and 90°). For example, the AFLT Beam 2 samples with 10 mm compressed Scots Pine dowels with 100 mm dowel spacing, inserted at 55° and 90°, had the same average flexural modulus of 1.4 GPa. Likewise, AFLT Beam 2 with 50 mm dowel spacing had the same average flexural modulus of 2.5 GPa, for the same dowel insertion angles. Based on the test results, the dowel insertion angles appear not to affect the flexural modulus of the AFLT beams significantly.

Two AFLT Beam 2 configurations (AFLTB2_B and AFLTB2_E) give a like-for-like comparison of the influence of dowel species (Scots Pine and Beech). AFLT Beam 2, with 10 mm compressed Beech dowels with 50 mm dowel spacing inserted at 90°, had an average flexural modulus of 2.6 GPa (AFLTB2_E), which was marginally greater than a similar beam with compressed Scots Pine dowels (AFLTB2_B). On this basis, dowel species do not have a significant influence on the flexural moduli of these beams. Additionally, the minor difference in the flexural modulus between AFLTB2_B and AFLTB2_E suggests that there is no significant difference between the normal and staggered arrangements of the dowels.

AFLTB2_E and AFLTB2_F had average flexural moduli of 2.6 GPa and 3.7 GPa, respectively, indicating that using dowels with a diameter of 15 mm leads to a 40% increase in the flexural modulus, when compared with a similar beam with 10 mm dowels. This was expected since the 15 mm dowels resist greater shear forces and limit the relative slip at the interfaces between the lamellae, in comparison to the 10 mm dowels. Also, the AFLT Beam 2 with 15 mm compressed Beech dowels with 50 mm dowel spacing inserted at 90° and 36 of the same set of dowels inserted horizontally (to limit relative sliding of the lamellae (AFLTB2_G)) had an average flexural modulus of 3.9 GPa, which was slightly greater than a similar AFLT Beam 2 configuration without horizontal dowels (AFLTB2_F). Nevertheless, the AFLT Beam 2 with the highest average flexural modulus was AFLTB2_G, which amounted to about one-third of Glulam Beam 2. In general, the flexural modulus of all the configurations of AFLT Beam 2 ranged from 1.1. to 4.5 GPa, which was lower than their glulam counterparts (Glulam Beam 2), which ranged from 11.6 to 12.9 GPa. Fig. 7(a) and (b) show the compressed wood dowels at an insertion angle of 90° and 55°, respectively, embedded in the AFLT beams after testing. From the figure, it can be seen that the localised embedment deformations are caused by relative slippage between lamellae together with the rotation of the dowel that has three times of density of the softwood lamellae.

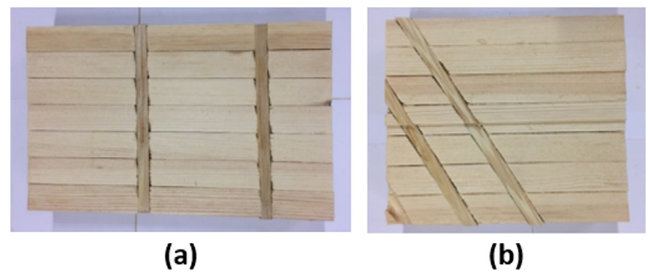

Fig. 7. Image showing the compressed wood dowels (after testing) embedded in the: (a) AFLT Beam 2 (at an insertion angle of 90°), (b) AFLT Beam 2 (at an insertion angle of 55°).

The beams with dowels inserted at an angle of 55° did not show a visible tensile failure. However, there are excessive deformation modes at the maximum applied loads, as shown in Fig. 8(a) and (b) for the configuration with 50 mm and 100 mm dowel spacing, respectively, which highlights their ductile responses. For these beams, there was a counteracting effect from the two rows of dowels (in opposite directions) which led to torsion (i.e. twisting).

3.2.3. Test results and analyses of AFCLT panels 1, 2 and 3 and CLT Panel 1

Fig. 9 shows the load versus centre deflection plots for five samples of AFCLT Panel 1 (AFCLTP1_1–AFCLTP1_5) and five samples of CLT Panel 1 (CLTP1_1–CLTP1_5), when tested in four-point bending. Similar to the AFLT beams, the plots indicate that the five samples of the AFCLT Panel 1 had greater ductility, lower flexural moduli and strengths, when compared to their CLT Panel counterparts.

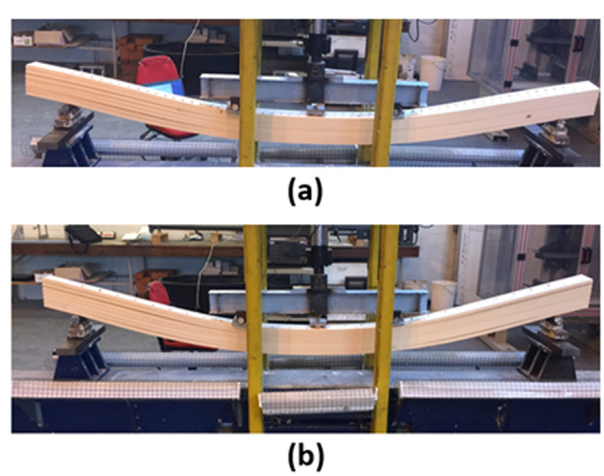

Fig. 8. Deformation mode of AFLT Beam 2 with diagonal dowels (55°) with: (a) 50 mm dowel spacing (AFLTB2_D) and (b) 100 mm dowel spacing (AFLTB2_C).

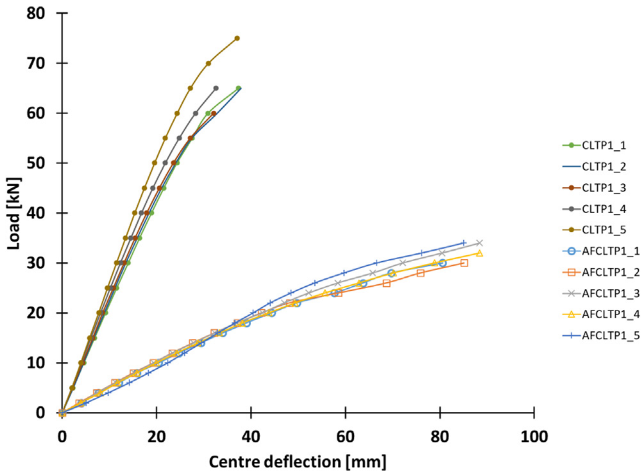

Fig. 9. Comparison of the load versus centre deflection plots for five samples of AFCLT Panel 1 (AFCLTP1_1–AFCLTP1_5) and five samples of CLT Panel 1 (CLTP1_1–CLTP1_5).

The load versus centre deflection plots for the five samples of AFCLT Panel 2 and five samples of CLT Panel 2 were similar to those of AFCLT Panel 1 and CLT Panel 1, respectively, however, their magnitudes were different. Due to the limitation of the configuration of the four-point bending test rig, the five samples of the AFCLT Panel 2 (i.e. largest panel) tested in bending, did not show a visible failure. Therefore, their flexural strengths were not determined, however, their flexural moduli were evaluated.

The average flexural modulus of AFCLT Panel 1 was 2.6 GPa, which was about one-fifth of CLT Panel 1 (12.1 GPa). Furthermore, the average flexural moduli for AFCLT Panel 2 and CLT Panel 2 were 1.7 GPa and 10.3 GPa, respectively, reflecting that the latter is about six times greater than the former. These results also showed that more interfaces within the AFCLT panels (compare AFCLT Panels 1 (three layers) and 2 (five layers)) led to a lower flexural modulus when evaluated as a fraction of their glulam counterparts. Furthermore, the average flexural modulus of the AFCLT Panel 1 was 2.6 GPa, which was 53% greater than that of AFCLT Panel 2 (1.7 GPa). This is considered to be due to the greater slip and/or relative movement occurring due to the greater number of interfaces and adjacent lamellae in the larger panel (AFCLT Panel 2).

AFCLT Panel 1 had an average flexural strength of 23.6 MPa, which was about half of CLT Panel 1 (48.6 MPa). Images of the failure modes of AFCLT Panel 1 are given in Fig. 10(a)–(c), and Fig. 10 (d) shows an image of the compressed wood dowels embedded in AFCLT Panel 1. This panel exhibits different modes of failure, which include a tensile failure originating around a knot alongside damage occurring at the transverse lamellae close to the support rollers. Although the damage on the transverse lamellae coincides with the rows of dowels, there was no damage on the dowels. The mode of failure of CLT Panel 1 was distinctively different from that of AFCLT Panel 1, with a typical brittle failure mode being shown in Fig. 11, which shows delamination around the glue line and rolling shear failure on a transverse lamella.

The average flexural moduli and strengths of AFCLT Panel 3 comprising panels without tongue and groove connections (AFCLTP3_A) and with (AFCLTP3_B), were evaluated and are given in Table 5. The results show that there was no major difference between the mechanical properties of the AFCLT panels with or without tongue and groove connections within the adjacent lamellae.

The flexural moduli and strengths of the AFCLT panels with Oak lamellae and compressed Spruce dowels (AFCLT Panel 3) were 2.5–3.4 GPa and 25.2–38.2 MPa, respectively. In comparison, the AFCLT panels with Scots Pine lamellae and compressed Beech dowels (AFCLT Panels 1 and 2) had flexural modulus ranging from 1.3 to 2.7 GPa and flexural strength from 22.1 to 25.0 MPa (see Table 5). These values show the mechanical properties of AFCLT Panel 3 were greater than those of AFCLT Panels 1 and 2. As there was no visible damage on the dowels, possible reasons for the greater properties include the fact that Oak lamellae have greater stiffness and strength properties compared to the Scots Pine lamellae [27].

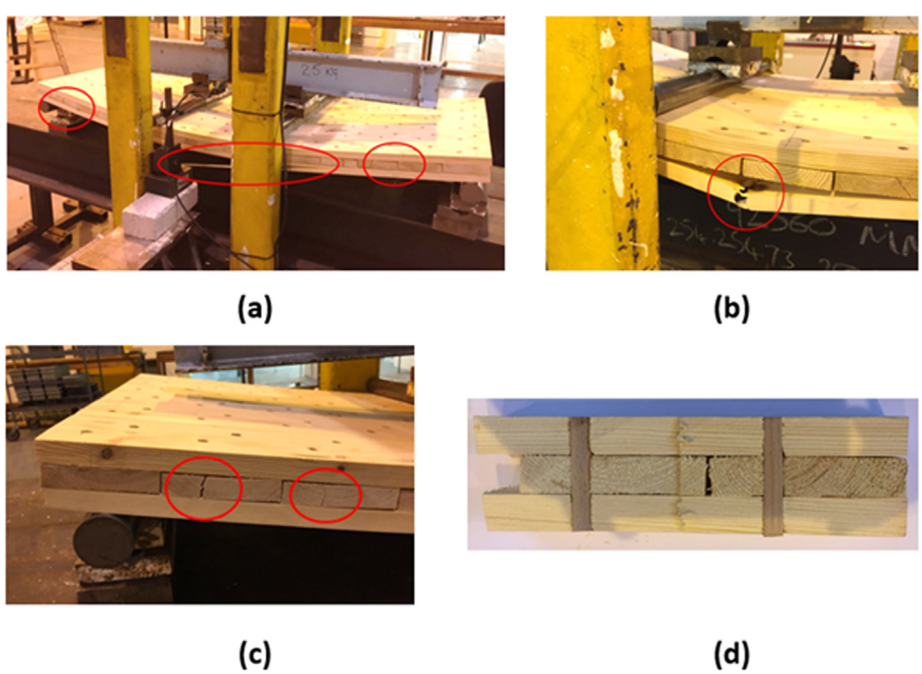

Fig. 10. (a) Failure mode of AFCLT Panel 1 in four-point bending, (b) failure in the vicinity of the knots, (c) damage in the transverse lamellae and (d) compressed wood dowels embedded in the panel.

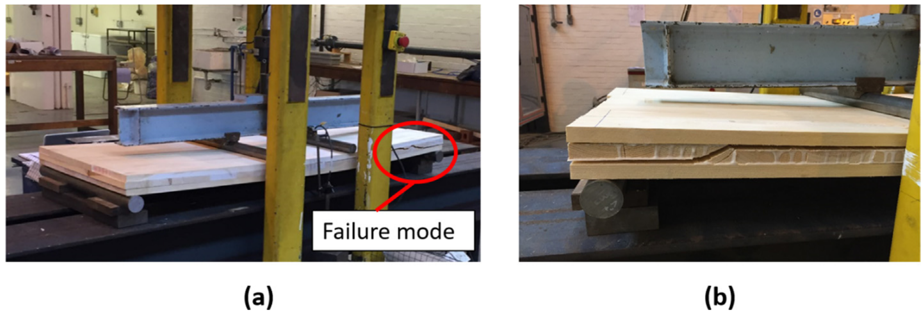

Fig. 11. Typical mode of failure for CLT Panel 1 in four-point bending, Typical mode of failure for CLT Panel 1 in four-point bending, (b) Close-up view showing delamination around the glue line.

Furthermore, the compressed wood dowels used in AFCLT Panel 3 had a diameter of 16 mm, which was greater than those used in AFCLT Panels 1 and 2 (i.e. 10 mm diameter).

4. Conclusions and recommendations

The experimental test results of adhesive free beams and panels have been analysed and compared with their glulam counterparts. In general, the flexural modulus and flexural strength of the 26 AFLT beams and 26 AFCLT panels are in the range of 1.1–5.3 GPa and 19.3–38.2 MPa, respectively. These values are lower than those of the ten glulam beams and ten CLT panels tested with similar overall dimensions, which had flexural moduli of 9.5–16.8 GPa and flexural strengths of 41.1–73.3 MPa. However, in comparison with the usual brittle responses from the glulam beams and CLT panels, the AFLT beams and AFCLT panels yielded more ductile responses as a result of the embedment deformations at the interfaces between the timber lamellae and the rotation of the compressed wood dowel due to its high stiffness and shear resistance. These ductile structural responses suggest a potential for the use of AFLT and AFCLT elements in earthquake zones.

Furthermore, failure modes observed on the AFLT beams and AFCLT panels comprise tensile failure around the bottom lamellae with visible defects (e.g. knots) and fracture propagation along the drilled holes. However, there was no damage to the dowels. Additionally, as the fracture of the AFLT beams and panels typically originated at locations with obvious natural defects (such as knots), visual sorting of the outer timber lamellae to manage these defects, will potentially enhance the mechanical properties of the structural members.

On the basis of the tests and parametric studies carried out in this work, additional conclusions are:

- Compressed wood dowels with larger diameters and a higher number of dowels lead to an increase in the flexural modulus of AFLT beams and AFCLT panels.
- Dowel insertion angles do not affect the flexural moduli of the AFLT beams significantly (based on the loading configuration used in this work).
- Dowel species do not have a substantial effect on the structural properties of the AFLT beams.
- The inclusion of additional horizontal dowels in the configuration near the opposite ends of the AFLT beams, to limit relative sliding of the lamellae, led to only a small increase in the flexural modulus (when compared with a similar beam without horizontal dowels) for the initial trials.
- The tongue and groove connections in the current form within the lamellae of the AFCLT panels do not have a substantial effect on the structural properties.
- The species and mechanical properties of the lamellae have a more significant effect on the structural properties of the AFLT beams and AFCLT panels, compared to those of the compressed wood dowels.
- The relatively larger beams and panels (i.e. those with more lamellae, interfaces and lamellae with greater dimensions) show moderately lower structural properties, which is likely due to larger number of natural defects enclosed in bigger timber sections. Also, this is likely due to more slip and/or relative movement between the lamellae due to the greater number of interfaces enclosed in them.

The uptake of dowel laminated timber beams and panels is currently limited, partly due to the lack of design guidelines and adequate coverage in European standards. Therefore, the experimental work reported herein, provides a good reference database on the structural properties, and adds to the limited knowledge on dowel laminated timber structures, which also contributes towards the development of potentially useful design guidelines or standards.

CRediT authorship contribution statement

Adeayo Sotayo: Data curation, Writing - original draft. **Dan F. Bradley:** Writing - review & editing. **Michael Bather:** Writing - review & editing. **Marc Oudjene:** . **Imane El-Houjeyri:** . **Zhongwei Guan:** Conceptualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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