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Mechanical characterisation of structural laminated bamboo

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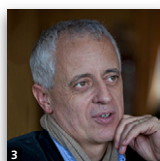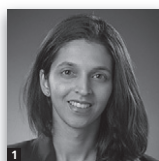
Low carbon construction materials are needed to reduce carbon dioxide emissions in the built environment. Laminated bamboo is an example of such a material. However, to be used in structural applications, fundamental mechanical properties are needed to establish the design values used in architecture and engineering practice. Recent studies on laminated bamboo have focused on the use of timber standards for small clear specimens, with little work published on structural-scale testing. The work presented in this paper is the first study to utilise structural-scale test methods for timber in a multi-laboratory test programme to investigate all mechanical properties of an outdoor laminated bamboo product. The study provides a comparison of the full-scale structural performance with conventional timber and a pathway for use in engineering design and practice. The work shows that laminated bamboo is comparable to conventional timber and timber-based products in structural properties and forms a foundation for the use of laminated bamboo in design and construction.

Notation

A	cross-sectional area
a	distance between load introduction point and nearest support
b	specimen width
$E_{c,0}$	local compressive modulus parallel to grain
$E_{c,0,mean}$	mean local compressive modulus parallel to grain
$E_{c,90}$	local compressive modulus perpendicular to grain
$E_{c,90,mean}$	mean local compressive modulus perpendicular to grain
E_m	local bending modulus
$E_{m,mean}$	mean local bending modulus
$E_{t,0}$	local tensile modulus parallel to grain
$E_{t,0,mean}$	mean local tensile modulus parallel to grain
$E_{t,90}$	local tensile modulus perpendicular to grain
$E_{t,90,mean}$	mean local tensile modulus perpendicular to grain
$f_{c,0,mean}$	mean compressive stress parallel to grain
$f_{c,90,mean}$	mean compressive stress perpendicular to grain
$f_{m,mean}$	mean bending modulus of rupture
$f_{t,0,mean}$	mean tensile stress parallel to grain
$f_{t,90,mean}$	mean tensile stress perpendicular to grain
$f_{v,0,mean}$	mean shear stress parallel to grain
h	specimen height
h_0	measuring length for the local E-modulus
I	second moment of inertia of the specimen cross-section
k	index for characteristic strength value
l	specimen length
l_1	measuring length for the E-modulus
u_{mean}	mean moisture content
α	Weibull scale parameter
β	Weibull shape parameter
μ	mean value
μ_0	median value
ρ_{mean}	mean density

1. Introduction

Globally, laminated bamboo is being increasingly investigated for structural applications as a sustainable material for construction. Although the material has been shown to be a low carbon alternative (van der Lugt, 2008; van der Lugt and Vogtländer, 2015; van der Lugt et al., 2006, 2009; Vogtlander et al., 2010), its use is limited due to a lack of fundamental mechanical properties for design. Furthermore, to be included in design standards, characteristic values based on

experimental test methods are necessary, which requires extensive testing. Structural applications of laminated bamboo have been demonstrated in full-scale construction and vary from short-span bridges to two-storey housing (Xiao, 2016). The studies have shown that this material can be effectively used as a construction material (Huang *et al.*, 2013; Xiao, 2016; Xiao *et al.*, 2010). Although global research has explored the use of laminated bamboo in structural applications, the reported studies typically focus on small clear specimens to establish mechanical properties (i.e. Correal *et al.*, 2010; Sharma *et al.*, 2015; Yang *et al.*, 2014). Comprehensive structural-scale testing has yet to be fully explored.

In this study, the mechanical properties of an outdoor laminated bamboo product were investigated utilising structural-scale test methods for timber in order to gain a comparison of the structural behaviour of the two materials and to provide a pathway for the use of laminated bamboo in engineering design and practice. To explore any variability in testing, testing was conducted at two laboratories – Graz University of Technology (TUG), with experience in wood testing, and Cambridge University (CU), with experience in bamboo testing. Tests were divided equally when possible or, if not, conducted at a single laboratory based on the facilities available.

2. Experimental methodology

2.1 Material
A commercially produced outdoor laminated bamboo product, Moso Bamboo N-Finity (manufactured by Moso International BV), was used in this work. The specimens were manufactured in China and composed of caramelised bamboo strips laminated with a phenol formaldehyde resin. To allow for longer members to be manufactured, a hook joint was incorporated into the material; however, this was not an engineered connection (Figure 1(a)). Samples were manufactured and cut to specified dimensions (Table 1) and shipped to the respective laboratories. To maintain clarity and consistency, industry terminology is used here to describe the orientation of an individual strip of bamboo within a laminated board. A single strip is obtained from the culm wall, as shown in Figure 1(b). After processing, there are two commercial orientations of the individual laminate in the final board product, edgewise (Figure 1(c)) and flatwise (Figure 1(d)), which differ in the axis of the radial direction of the original culm wall. When laminated into beams, the edgewise and flatwise orientations are markedly different when viewed in cross-section (Figures 1(e) and 1(f)). Where appropriate, the mechanical properties of the two orientations were investigated and the obtained strength or modulus referenced the orientation (edgewise or flatwise). The tests were conducted parallel or perpendicular to the fibre direction as indicated in the notation subscript; for example for compressive stress (f_c) perpendicular
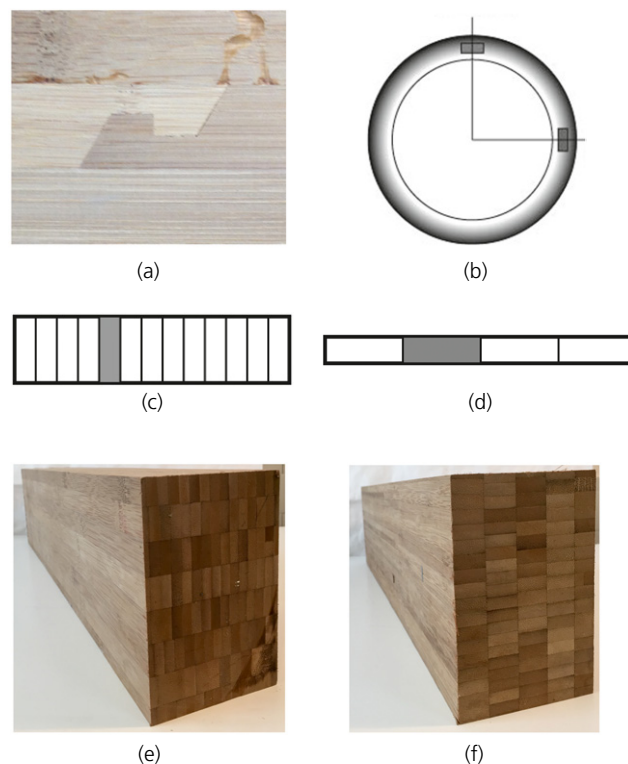

Figure 1. Industry terminology for laminate orientation within a single board: (a) hook joint; (b) radial culm; (c) edgewise board; (d) flatwise board; (e) edgewise section; (f) flatwise section

to grain ($_{90}$) in the edgewise orientation ($_{EW}$), the notation used is $f_{c,90,EW}$.

2.2 Experimental testing
The scope of testing included bending, tension and compression tests parallel and perpendicular to grain, as well as shear parallel to grain. The tests were conducted in accordance with EN 408: Timber structures – Structural timber and glued laminated timber – determination of some physical and mechanical properties (CEN, 2012). The standard was applied to laminated bamboo using the structural timber guidelines. The specimens were stored in humidity- and temperature-controlled environments prior to testing, maintained at 20°C (±2°C) and 65% (±5%) relative humidity in both laboratories. In larger the specimens, the variation in thickness was documented at points along the length of the material and reported as the average. Moisture content was determined by the oven-dry method following ON ISO 13061 (ISO, 2014). Density was measured based on the full cross-section of the specimen according to EN 384 (CEN, 2010) and on small specimens according to ON ISO 13061 (ISO, 2014). Table 1 summarises the specimen dimensions and quantities tested at each laboratory. The following brief sections summarise each test method. Preliminary tests were conducted to validate and determine testing

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Test	Orientation	Dimensions: mm	Number of samples	
			TUG	CU
Bending	Edgewise	$2440 \times 140 \times 90$	20	20
	Flatwise		20	20
Compression parallel	—	$540 \times 90 \times 140$	—	40
Compression perpendicular	Edgewise	$70 \times 45 \times 90$	20	20
	Flatwise		20	20
Tension parallel	Single-ply	$2440 \times 140 \times 18$	40	—
	Dogbone	$1520 \times 90 \times 30$	—	40
Tension perpendicular	Edgewise	$70 \times 45 \times 180$	20	20
	Flatwise		20	20
Shear parallel	Edgewise	$300 \times 32 \times 55$	—	40
	Flatwise		—	40

Table 1. Summary of specimen dimensions and sample sizes

parameters. In accordance with EN 408 (CEN, 2012), all tests were conducted in displacement control to achieve failure load (F_{max}) within 300 ± 120 s.

2.2.1 Bending

Four-point bending tests were carried out at both laboratories. The test method allowed some variability in testing speed, with the average loading rate approximately 10 mm/min. The local E-modulus was determined from the displacement taken on both sides of the specimen at midspan and midheight of the specimen, as shown in Figure 2(a). As per EN 408 (CEN, 2012) the local E-modulus was calculated from

1.
$$E_{\mathrm{m}} = \frac{al_1^2(F_2 - F_1)}{16I(w_2 - w_1)}$$

in which a is the distance between the load introduction point and the nearest support, l_1 is the measuring length for the local E-modulus, I is the second moment of inertia of the specimen cross-section, $F_2 - F_1$ is the increase of the load in the range where the regression has a correlation coefficient of 0·99 or better and $w_2 - w_1$ is the corresponding rise in displacement.

2.2.2 Tension perpendicular to grain

Tension perpendicular to grain testing was carried out at both laboratories. The test setup and specimen details are shown in Figure 2(b). The specimens were bonded to Sitka spruce ends using a polyurethane adhesive (Purbond HB S309) and clamped for a minimum of 24 h before testing. The specimens were capped with a steel plate using wood screws and connected to the frame using a threaded rod fixed to a ball joint to cancel any moment (Figure 2(b)). The shape of the timber differed between the two laboratories due to the type of attachment to the test frames, but both were in accordance with EN

408 (CEN, 2012). The test method allowed some variability in testing speed, with the average loading rate approximately 0·4–0·6 mm/min. Displacement was measured on both sides of the specimen with high-accuracy extensometers over the specified gauge length to obtain the local E-modulus. As per EN 408 (CEN, 2012), the local E-modulus was calculated using

2.
$$E_{\mathrm{t},90} = \frac{(F_{40} - F_{10})h_0}{(w_{40} - w_{10})bl}$$

in which $F_{40} - F_{10}$ is the increase in load between $0 \cdot 1 F_{\mathrm{max,est}}$ and $0 \cdot 4 F_{\mathrm{max,est}}$ and $w_{40} - w_{10}$ is the corresponding rise in displacement, h_0 is the measuring length for the local E-modulus, b is the width of the specimen and l is the length of the specimen.

2.2.3 Compression perpendicular to grain

Compression perpendicular to grain testing was also carried out at both laboratories. The test method allowed some variability in testing speed, with the average loading rate approximately 0·4–0·6 mm/min. To obtain the local E-modulus, displacement was measured with high-accuracy extensometers on both sides of the specimen over the specified gauge length (Figure 2(c)). As per EN 408 (CEN, 2012), the local E-modulus was calculated using

3.
$$E_{\mathrm{c},90} = \frac{(F_{40} - F_{10})h_0}{(w_{40} - w_{10})bl}$$

where the terms are as defined earlier.

2.2.4 Tension parallel to grain

Tension parallel to grain tests were carried out on both a single-ply board (Figure 3(a)) and a laminated section (Figure 3(b)).
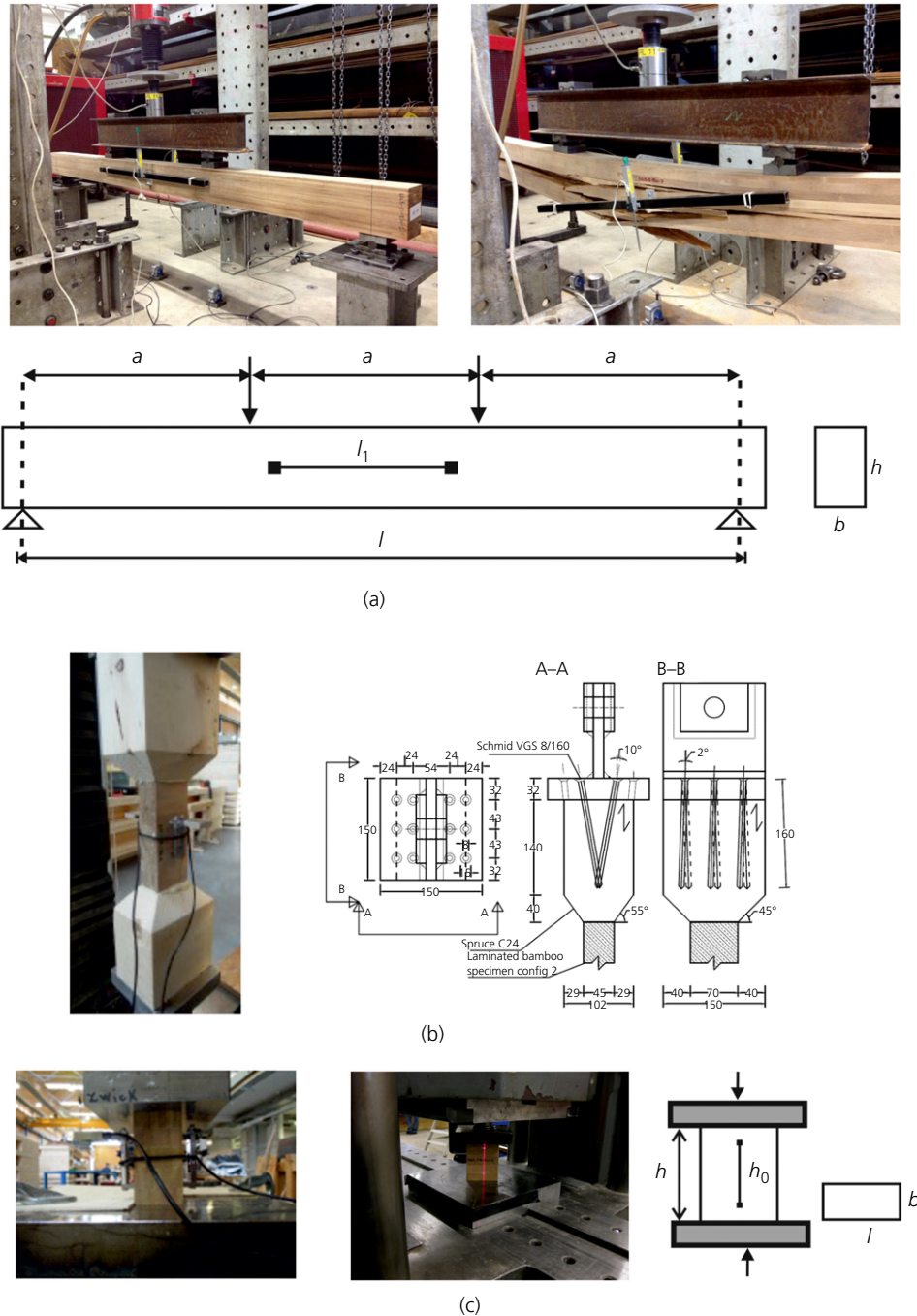
Figure 2. Experimental test methods: (a) four-point bending;
(b) tension perpendicular to grain (dimensions in mm);
(c) compression perpendicular to grain

Single-ply laminated bamboo was tested at TUG utilising a tension testing machine (GEZU 850) in load control (Figure 3(a)). The end cross-sections of the test specimens were gripped by clamping plates. The local E-modulus was measured with two displacement transducers on the side faces over the specified gauge length. As per EN 408 (CEN, 2012),

the E-modulus was calculated using

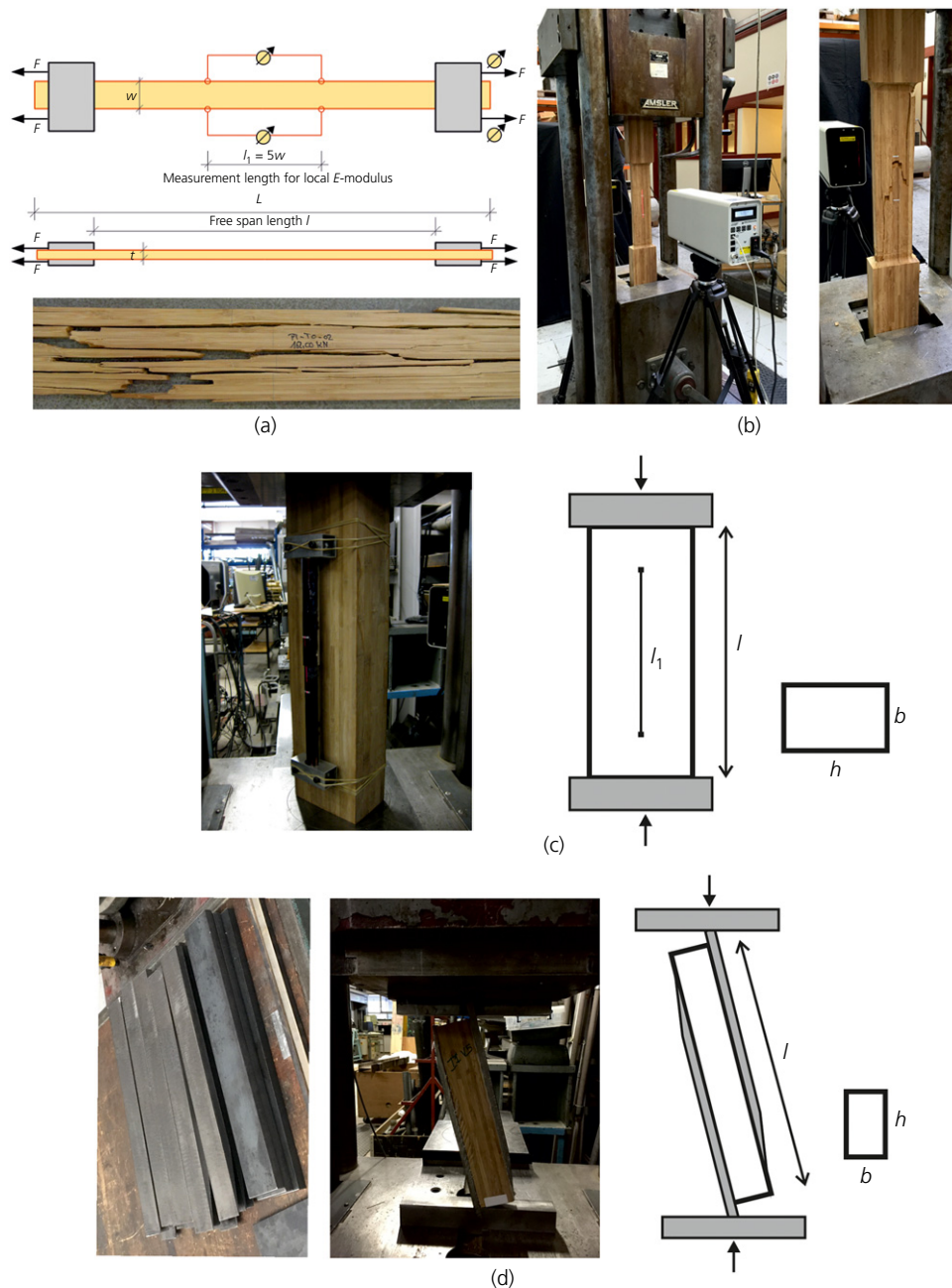4. $$E_{t,0} = \frac{l_1(F_2 - F_1)}{A(w_2 - w_1)}$$

Figure 3. Experimental test methods: (a) tension parallel to grain,
single-ply board; (b) tension parallel to grain, laminated section;
(c) compression parallel to grain; (d) shear parallel to grain

in which l_1 is the measuring length for the E-modulus, A is the cross-sectional area, $F_2 - F_1$ is the increase in load in the range where the regression has a correlation coefficient of 0·99 or better and $w_2 - w_1$ is the corresponding rise in displacement.

The laminated section was tested at CU in an Amsler test frame with mechanical wedge grips that increased the gripping force with increasing load. Preliminary tests indicated that the full cross-section resulted in a grip-induced failure. Modification of the rectangular section into a dogbone specimen, as shown in Figure 3(b), allowed for failure to occur in the specimen. The test method allowed some variability in testing speed, with the average loading rate approximately 4·5 mm/min. Displacement was measured on the wide face of the specimen with high-accuracy extensometers over the specified gauge length to obtain the local E-modulus, which was calculated using Equation 4.

2.2.5 Compression parallel to grain

Compression parallel to grain testing was carried at CU. The test method allowed some variability in testing speed, with the average loading rate approximately 0·6–0·8 mm/min. The local E-modulus was obtained through displacement measurements on both sides of the specimen. Specially designed compressometers were used on either side of the specimen to measure the displacement over the specified gauge length and displacement was measured using high-accuracy laser extensometers (Figure 3(c)). As per EN 408 (CEN, 2012), the E-modulus was calculated using

5. $$E_{c,0} = \frac{l_1(F_2 - F_1)}{A(w_2 - w_1)}$$

where the terms are as in Equation 4.

2.2.6 Shear

Shear parallel to grain tests were carried out at CU. The test method allowed some variability in testing speed, with the average loading rate approximately 0·7–0·9 mm/min. The test setup and specimen details are shown in Figure 3(d). The specimens were bonded to 10 mm thick sandblasted steel plates (Figure 3(d)). A high shear strength two-part epoxy (Araldite 2015) consisting of a resin and a hardener that cured at room temperature was used bond the specimens to the plate. The specimens were manually clamped and left to cure for 24 h before testing. After each test, the specimens were documented and the plates were cleaned and reused, roughening the steel plate surface for each test.

3. Results

The following sections present the results of the testing programme, which are also summarised in Table 2. A comparison of the results with other published experimental studies using EN 408 (CEN, 2012) test methods is presented in Table 3. The table shows the characteristic values, when provided, from experimental studies on Norway spruce (Jenkel *et al.*, 2015; Steiger and Arnold, 2009), glue laminated spruce (De Lorenzis *et al.*, 2005) and thermally modified beech wood (Widmann *et al.*, 2012). The experimental results are shown in Figures 4 and 5. Characteristic, or nominal, values were determined as the fifth percentile as per EN 384 (CEN, 2010) and are shown in the figures and summarised in Table 2.

3.1 Bending

In both edgewise and flatwise orientations, failure at the longitudinal joint (see Figure 1(a)) was observed on the tension face at midspan. The bending strength and local E-modulus results from the respective test series were comparable. The results are shown in Figures 4(a) and 4(b). Comparison of the laminate orientation indicates a slight increase in the bending strength (14%) and local E-modulus (6–13%) in the edgewise orientation (Figures 4(a) and 4(b)).

There is some correlation between the specimen density and bending local E-modulus, a relationship that is often observed in timber studies. In the laminated bamboo, the correlation is strongest between density and the bending modulus. The results from TUG in both the edgewise ($R^2 = 0·51$) and flatwise ($R^2 = 0·56$) orientations suggest a similar relationship, which is common in timber. However, the results from the two laboratories differ greatly, with the results from CU showing no correlation (edgewise $R^2 = 0·01$ and flatwise $R^2 = 0·03$); therefore, this observation is not definitive. Both laboratory results indicated that the correlation between the local bending modulus and modulus of rupture is low in the edgewise orientation ($R^2 = 0·31–0·35$) and non-existent in the flatwise orientation ($R^2 = 0·01–0·10$). In comparison with timber, the correlation is typically strong (i.e. $R^2 = 0·74$), which Olsson *et al.* (2012) attribute to the relationship between strength and stiffness at the location of failure. The low correlation in the laminated bamboo suggests that ultimate failure may not be governed by the local bending stiffness at midspan.

3.2 Tension perpendicular to grain

In tension perpendicular to grain, the results varied between the laboratories (Figures 4(c) and 4(d)). As shown in the figures, the CU results showed a higher coefficient of variation (CoV) in tensile strength (CoV = 0·32) and local E-modulus (CoV = 0·24). The flatwise orientation has a slightly better strength and modulus (∼10%) in comparison to the edgewise orientation.

3.3 Compression perpendicular to grain

In compression perpendicular to grain, the typical failure was splitting of the individual laminates. The results from CU showed a higher strength and CoV compared with the TUG results (Figure 4(e)). The opposite trend was observed in the local E-modulus, with the CU measurements nearly 7% lower than the mean value determined at TUG (Figure 4(f)). The two laboratories utilised different measurement sensors, but with the same accuracy, so it is unclear whether the variation is material- or test-based. The results also show a slight increase in strength in the edgewise orientation and a small decrease in the local E-modulus.

3.4 Tension parallel to grain

The tension parallel to grain tests utilised two types of specimens (full-scale and a small sample) and thus the results were not combined into a single dataset. A 30% increase in mean tensile strength and an 8% increase in mean local modulus was observed in the dogbone specimen compared with the single-ply specimen (Figures 5(a) and 5(b)). The wider distribution of the joints in the laminated section may be the source of the increase in strength, but further investigation is needed to determine in-service performance. The failure mode of the material was similar between the single-ply and laminated section, with failure dominated by brittle failure in the longitudinal direction.

Strength: N/mm^2	Orientation		EW/FW
	Edgewise (EW)	Flatwise (FW)	
Bending			
$f_{m,mean}$ (TUG)	61·7 (0·05)	56·6 (0·07)	1·09
$f_{m,mean}$ (CU)	66·7 (0·06)	58·6 (0·06)	1·14
$f_{m,k}$ (TUG)	56·4	49·3	1·14
$f_{m,k}$ (CU)	59·3	52·2	1·14
$E_{m,mean}$ (TUG)	9093 (0·05)	8612 (0·03)	1·06
$E_{m,mean}$ (CU)	10 412 (0·07)	9178 (0·08)	1·13
Tension parallel			
$f_{t,0,mean}$ (TUG)	39·1[a] (0·11)		—
$f_{t,0,mean}$ (CU)	50·0[a] (0·12)		—
$f_{t,0,k}$ (TUG)	31·8[a]		—
$f_{t,0,k}$ (CU)	39·9[a]		—
$E_{t,0,mean}$ (TUG)	8062[a] (0·05)		—
$E_{t,0,mean}$ (CU)	8713[a] (0·10)		—
Tension perpendicular			
$f_{t,90,mean}$ (TUG)	3·8 (0·22)	4·2 (0·24)	0·90
$f_{t,90,mean}$ (CU)	3·4 (0·32)	4·3 (0·18)	0·80
$f_{t,90,k}$ (TUG)	2·3	2·5	0·92
$f_{t,90,k}$ (CU)	1·6	2·9	0·55
$E_{t,90,mean}$ (TUG)	1279 (0·07)	1443 (0·07)	0·89
$E_{t,90,mean}$ (CU)	1295 (0·24)	1346 (0·13)	0·96
Compression parallel			
$f_{c,0,mean}$ (CU)	39·5 (0·07)		—
$f_{c,0,k}$ (CU)	34·4		—
$E_{c,0,mean}$ (CU)	8166 (0·08)		—
Compression perpendicular			
$f_{c,90,mean}$ (TUG)	12·1 (0·10)	10·4 (0·07)	1·16
$f_{c,90,mean}$ (CU)	12·0 (0·08)	12·1 (0·11)	0·99
$f_{c,90,k}$ (TUG)	9·9	9·1	1·09
$f_{c,90,k}$ (CU)	9·7	10·2	0·95
$E_{c,90,mean}$ (TUG)	1219 (0·10)	1295 (0·07)	0·94
$E_{c,90,mean}$ (CU)	1197 (0·08)	1206 (0·11)	0·99
Shear parallel			
$f_{v,0,mean}$ (CU)	7·4 (0·18)	7·6 (0·08)	0·97
$f_{v,0,k}$ (CU)	4·6	6·5	0·71
Density			
ρ_{mean} (TUG)	666 (0·05)		
ρ_k (TUG)	641		
Moisture content			
u_{mean} (TUG)	8·6% (0·10)		

[a]Tension parallel to grain test method differed, see Section 2.2.4 for more information

Table 2. Summary of experimental test results and characteristic values for laminated bamboo. The values obtained from Graz University of Technology (TUG) and from Cambridge University (CU) are indicated and the CoV is shown in parentheses

	Density	Compression		Tension		Shear	Flexure	
	ρ_{mean}: kg/m^3	$f_{c,0,k}$: MPa	$E_{c,0,mean}$: MPa	$f_{t,0,k}$: MPa	$E_{t,0,mean}$: MPa	$f_{v,k}$: MPa	$f_{m,k}$: MPa	$E_{0,mean}$: GPa
Laminated bamboo[a]	666	34·4	8166	32	8062	5	49	8612
C24 – EN 338[b]	420	21	370	14	370	4	24	11 000
GL 24 h – EN 14080:2013-06[c]	420	24	300	19·5	300	3·5	24	11 500
Norway spruce[d,e]	—	44[h]	18 254[h]	122[h]	15 793[h]	6	48[i]	13 361[i]
Glue laminated spruce[f]	450	32	8600	—	8472	—	50	—
Thermally modified beech[g]	580	48·7[h]	—	14	—	—	31	12 800

[a]Present study
[b]CEN (2009)
[c]CEN (2013)
[d]Steiger and Arnold (2009)
[e]Jenkel et al. (2015)
[f]De Lorenzis et al. (2005)
[g]Widmann et al. (2012)
[h]Test not conducted in accordance with EN 408 (CEN, 2012)
[i]Experimental mean

Table 3. Comparison of characteristic strength, stiffness properties (mean values) and density (mean values) for laminated bamboo, strength classes for structural timber and glulam and experimental testing parallel to grain in accordance with EN 408 (CEN, 2012)

3.5 Compression parallel to grain

In compression parallel to grain, the tests were conducted at CU and the results were repeatable for both the compressive stress (CoV = 0·07) and E-modulus (CoV = 0·08), as shown in Figures 5(c) and 5(d). The ultimate failure of the material was buckling, representing the strength of the sample dimension and aspect ratio, rather than the ultimate strength. The buckling behaviour differed from the expected shear failure in timber, yet is consistent with other compression studies on laminated bamboo (Huang et al., 2013; Li et al., 2013). Research has been conducted on the influence of the aspect ratio on the compressive strength (i.e. Li et al., 2015), but additional work is needed to determine the appropriate test parameters to obtain the ultimate strength of the material.

3.6 Shear parallel to grain

The two orientations showed comparable shear strengths, but the variability between the orientations differed significantly (Figure 5(e)). The edgewise orientation had approximately twice the CoV (CoV = 0·18) than the flatwise orientation (CoV = 0·08). In accordance with EN 408 (CEN, 2012), specimens with greater than 20% failure in the plate–specimen interface were excluded from the analysis, which was approximately half of the samples.

For comparison, all of the results are shown in Figure 5(e). The strength difference between the two orientations was

negligible. The results suggest that a larger sample size is needed to fully characterise the shear strength of the material. The correlation between the density and shear stress parallel to grain was found to be moderate, with the edgewise orientation indicating a stronger correlation ($R^2 = 0·42$) than the flatwise ($R^2 = 0·18$). The sample size of the tests was small due to the exclusion of results due to failure in the interface. Further testing is therefore needed to evaluate the relationship, if any, between the properties.

3.7 Density

As noted in Table 2, the mean density of all samples was 666 kg/m^3 (CoV = 0·05). Figure 5(f) shows the variation in density for all specimens, with each type of test categorised by orientation: edgewise, flatwise and no orientation for parallel to grain compression and tension. The bending specimens showed significant variation in density within and between laboratories, for both orientations, which may contribute to the observed differences in strength. Figure 5(f) also shows comparable density between the edgewise compression and tension perpendicular to grain samples, suggesting that the specimens were manufactured from the same batch. In contrast, the flatwise orientation specimens have greater variation within and between laboratories in all tests. The density did not correlate strongly with the strength properties, with the exception of the local bending modulus and shear strength. Further investigation of the fibre volume fraction, density and
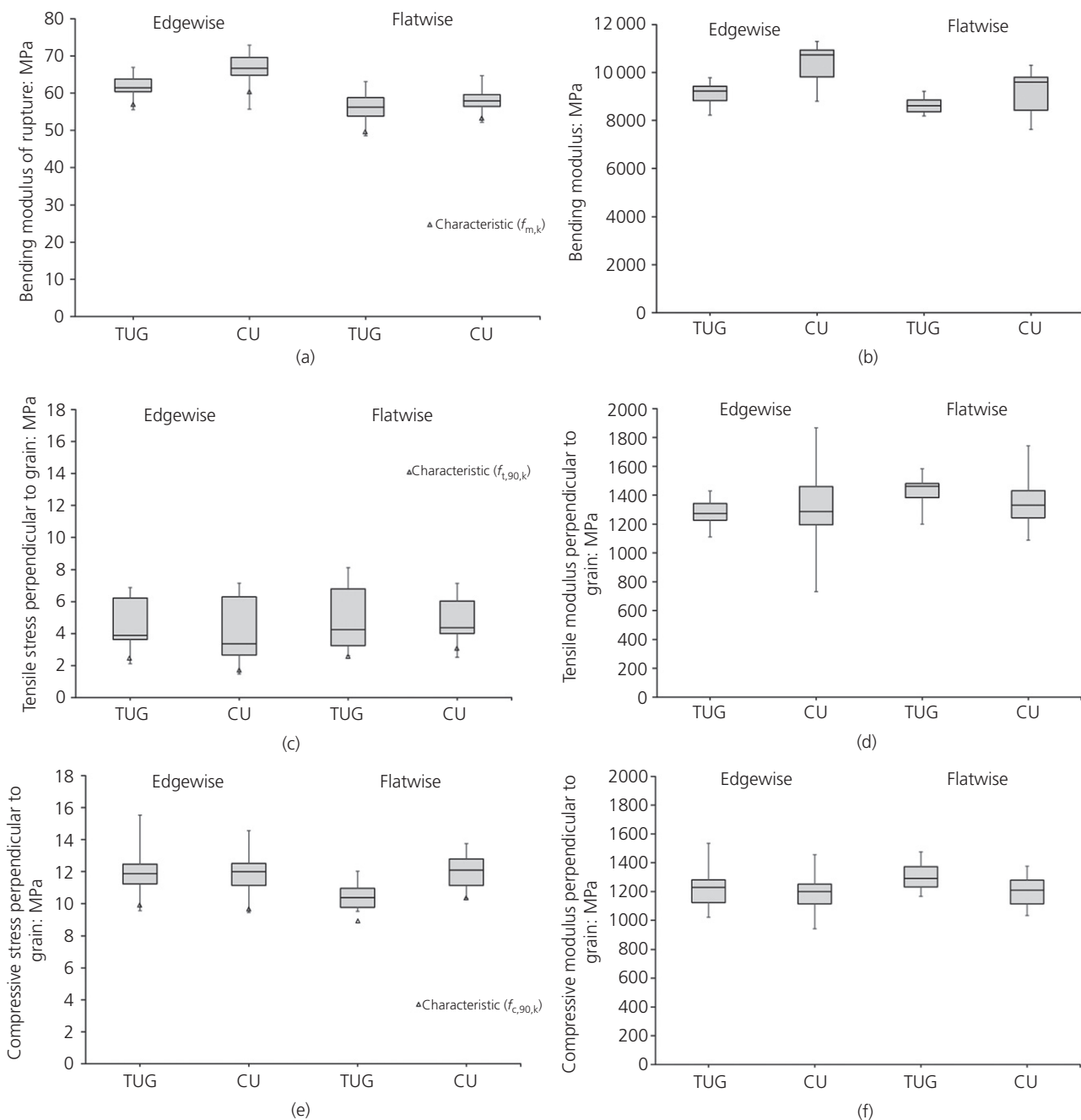
Figure 4. Experimental results and characteristic values for
bending and perpendicular to grain tests: (a) bending modulus of
rupture; (b) bending modulus; (c) tensile stress perpendicular to
grain; (d) tensile modulus perpendicular to grain; (e) compressive
stress perpendicular to grain; (f) compressive modulus
perpendicular to grain

strength would elucidate relationships, if any, between the
properties.

4. Statistical analysis

In addition to the determination of the mechanical properties,
this study provided an opportunity to explore uncertainties in
experimental testing through a comparison of the individual

laboratory results. Due to the large variation between the
laboratories, the test results (bending, and perpendicular to
grain tension and compression) were analysed using a two
sample t-test using SPSS (IBM Corp., 2013; Quirk, 2015).
The hypothesis was that the mean population means are
equal (H_0: $\mu_1 = \mu_2$) and the alternate that they are unequal
(H_A: $\mu_1 \neq \mu_2$). The single-source datasets (compression, tension
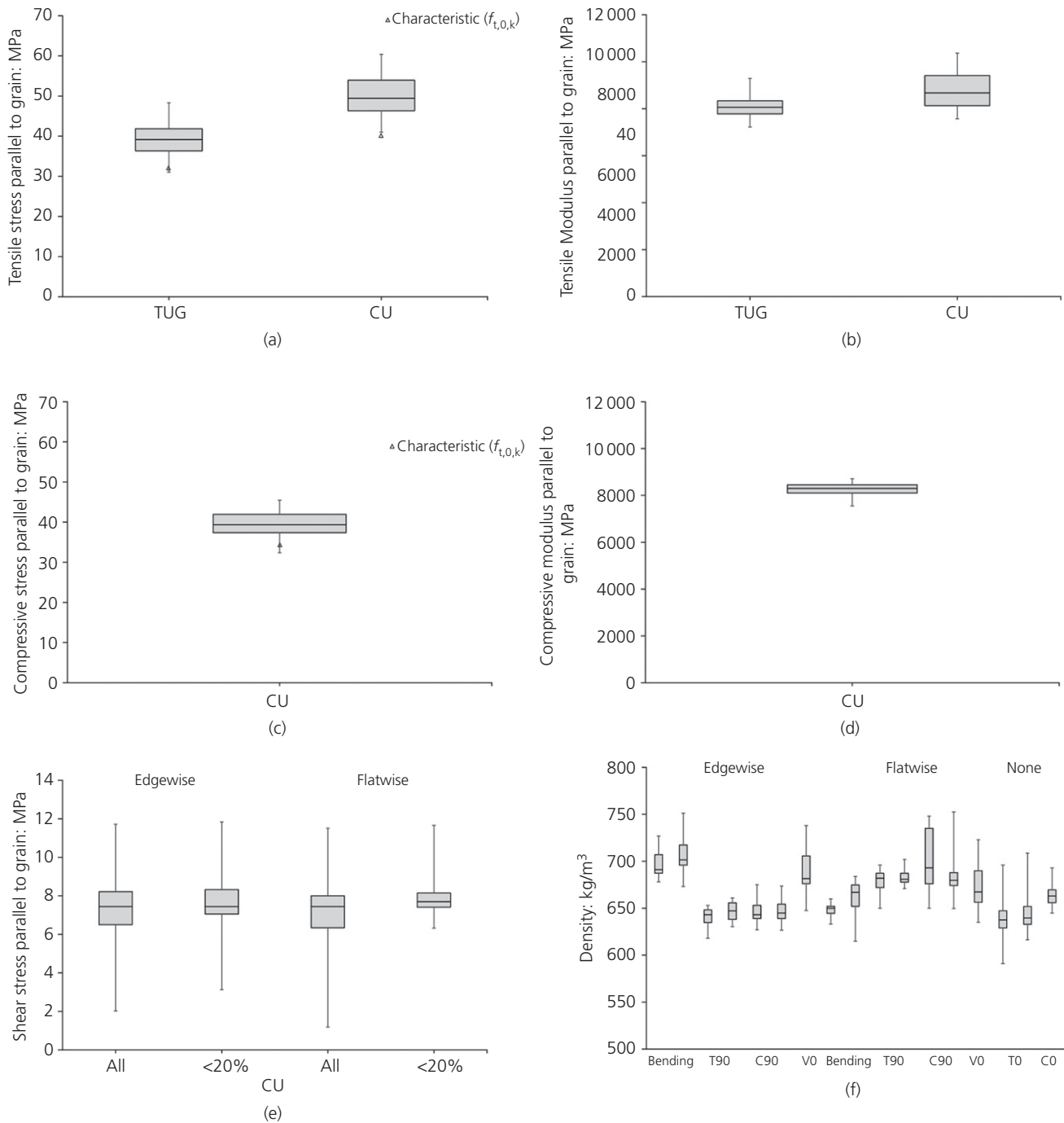
Figure 5. Experimental results and characteristic values for parallel to grain tests and specimen density for all tests: (a) tensile stress parallel to grain; (b) tensile modulus parallel to grain; (c) compressive stress parallel to grain; (d) compressive modulus parallel to grain; (e) shear stress parallel to grain; (f) density for all tests conducted

and shear parallel to grain) were analysed to test the median value (μ_0) as a hypothetical mean (H_0: $\mu_0 = \mu$) using a t-test, with $\alpha = 0.05$. The results of the analysis are presented and discussed below.

4.1 Bending

The analysis accepted the null hypothesis and indicated that the flatwise orientation bending stress was not significant (p-value = 0.09). The null hypothesis was rejected for the

flatwise orientation local E-modulus, which was borderline significant ($0.01 \leq p \leq 0.05$) and highly significant ($p \leq 0.005$) for the edgewise orientation in both the bending stress and local E-modulus. The analysis thus indicates that the variation between the two datasets is significant and they cannot be pooled.

4.2 Tension perpendicular to grain
The statistical analysis was not significant ($p > 0.05$) for all results with the exception of the flatwise tensile local E-modulus, which was borderline significant ($0.01 \leq p \leq 0.05$). The results indicate that the data can be pooled into a single source. Comparison of the two orientations showed less variation in the flatwise tensile stress perpendicular to grain ($p = 0.67$) than the edgewise orientation ($p = 0.15$).

4.3 Compression perpendicular to grain
For the perpendicular to grain compression stress and the local E-modulus, the analysis was not significant ($p > 0.05$) in the edgewise orientation. The flatwise orientation was highly significant for the perpendicular to grain compressive stress and local E-modulus ($p \leq 0.005$). The results indicate that the edgewise orientation results can be pooled and the flatwise cannot.

4.4 Compression parallel to grain
For the compression parallel to grain, the median stress ($\mu_0 = 39$ MPa) was selected as the test statistic to compare the hypothesis ($\mu_0 = \mu$). The t-test analysis indicated that it is indicative of the population mean ($p > 0.05$). For the compressive local E-modulus parallel to grain, the median was hypothesised as ($\mu_0 = 8250$ MPa) and the t-test indicated that it is representative of the population mean ($p > 0.05$).

4.5 Tension parallel to grain
Two different test methods were used to determine the tension parallel to grain strength and local E-modulus, thus the datasets were not combined. In the single-ply tests, the median stress ($\mu_0 = 39$ MPa) and median modulus ($\mu_0 = 7997$ MPa) were selected as the test statistics to compare the hypothesis ($\mu_0 = \mu$). The analysis indicated that both values are representative of the population mean ($p > 0.05$). For the laminated section, the median stress ($\mu_0 = 49$ MPa) and median modulus ($\mu_0 = 8532$ MPa) were selected as the test statistics to compare the hypothesis ($\mu_0 = \mu$). The analysis indicated that both values were representative of the population mean ($p > 0.05$).

4.6 Shear parallel to grain
For shear parallel to grain, two orientations were tested. The analysis was applied to the specimens that passed the <20% failure in the interface, as per the standard. In the edgewise orientation, the median stress ($\mu_0 = 7.1$ MPa) was selected as the test statistic to compare the hypothesis ($\mu_0 = \mu$) and was indicative of the population mean ($p > 0.05$). For the flatwise orientation, the median stress ($\mu_0 = 7.6$ MPa) was determined to be representative of the population mean ($p > 0.05$).

4.7 Statistical comparison of parallel testing
The results indicate that there was significant variation between the two laboratories, which can be attributed to material variation, as well as variations in machinery and test methods. Although the material was obtained from the same batch, the rejection of the null hypothesis (H_0: $\mu_1 = \mu_2$) indicates that the experimental results were not from the same population and therefore cannot be pooled. The null hypothesis is not probable even if samples are treated by the same operator; however, test parameters such as variable loading rate and measurement devices may have had an influence on the results.

The study suggests that existing timber test methods provide a foundation from which to develop engineered bamboo standards, but additional investigation is required to determine the appropriate test parameters. Furthermore, while the sample size was determined in accordance with EN 408 (CEN, 2012), the variation suggests that a larger number of samples is required to obtain an accurate estimate of the material strength. To explore the reliability of the mechanical properties in comparison with the characteristic values, the sample distributions were further investigated.

5. Weibull two-parameter cumulative distribution functions
Bamboo is an anisotropic material with significant variation in both the raw and processed material. Reliability-based failure methods have been explored for composite materials to predict and model performance (Barbero *et al.*, 2000), as well as for graded timber (Faber *et al.*, 2004). A reliability-based approach for engineered bamboo would provide a way in which to account for uncertainty and variation in materials, as well as testing methods. To investigate the use of reliability-based failure prediction, a cumulative distribution function of a two-parameter Weibull distribution is shown in Equation 6 (Weibull, 1951).

$$6. \quad F(q) = 1 - \exp\left[-\left(\frac{q}{\alpha}\right)^{\beta}\right]$$

Here, F is the probability of failure, q is the property under investigation, β is a shape parameter and α is the scale parameter for the distribution. The results from the laboratory testing were used to determine q using a median rank estimator and the parameters α and β were determined using linear regression. Reliability is given as

$$7. \quad R(q) = \exp\left[-\left(\frac{q}{\alpha}\right)^{\beta}\right]$$

The reliability plots for the mechanical properties are shown in Figures 6 and 7. The results from the two laboratories are
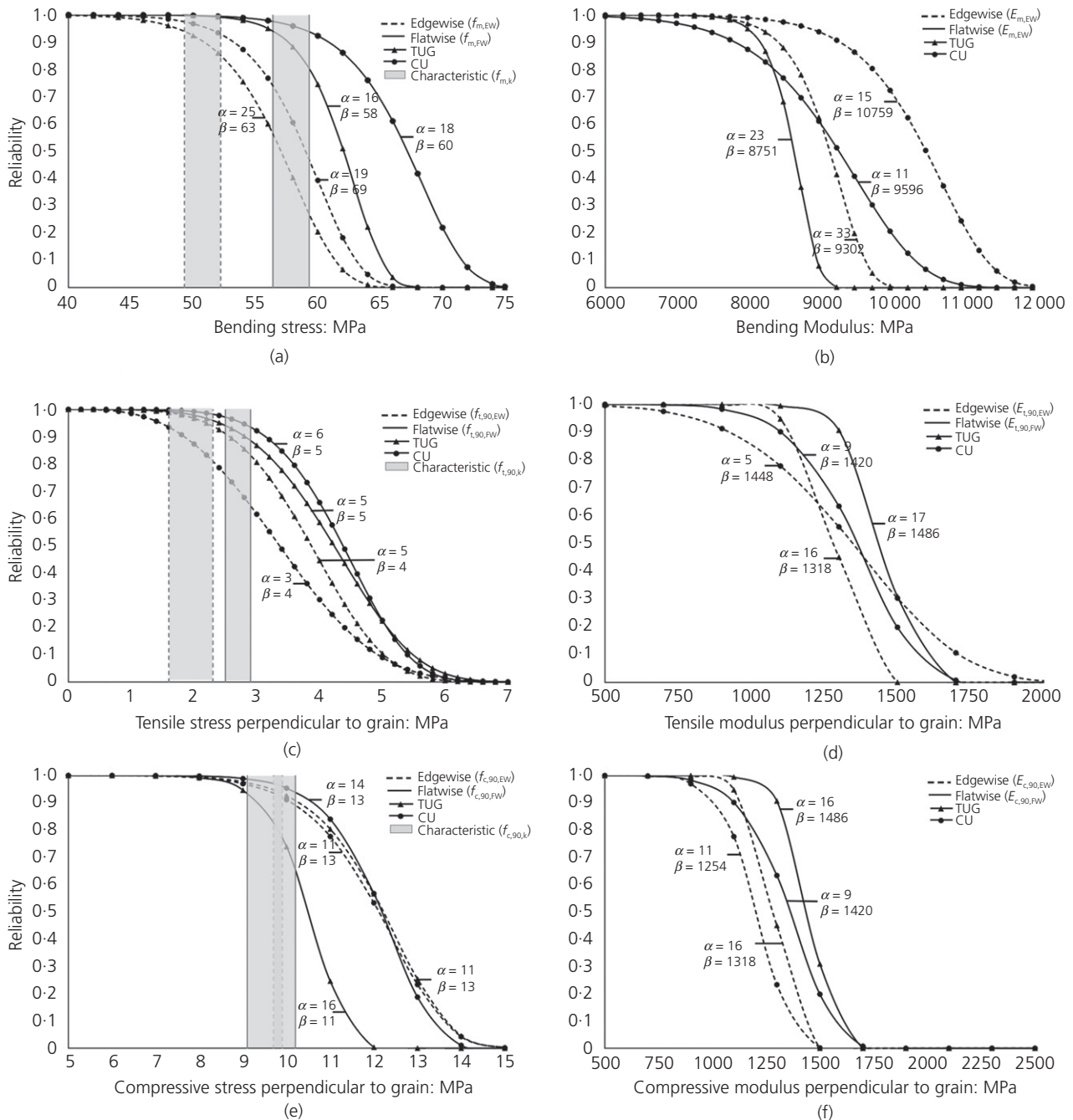
Figure 6. Reliability curves and characteristic values for bending
and perpendicular to grain tests: (a) bending modulus of rupture;
(b) bending modulus; (c) tensile stress perpendicular to grain;
(d) tensile modulus perpendicular to grain; (e) compressive stress
perpendicular to grain; (f) compressive modulus perpendicular to
grain

differentiated by markers, with the TUG results indicated with
triangles and the CU results represented by circles. The dashed
lines indicate the edgewise orientation and the flatwise orien-
tations are represented with solid lines. In the tension and com-
pression parallel to grain tests there is no orientation and a
solid line is used. The characteristic stress is indicated by with

grey shaded area. The scale (α) and shape (β) parameters for
each dataset are also indicated in the figures.

As expected, the characteristic values represent a conservative
estimate of predicted strength. The reliability curves provide a
preliminary investigation of where there are areas of acceptable
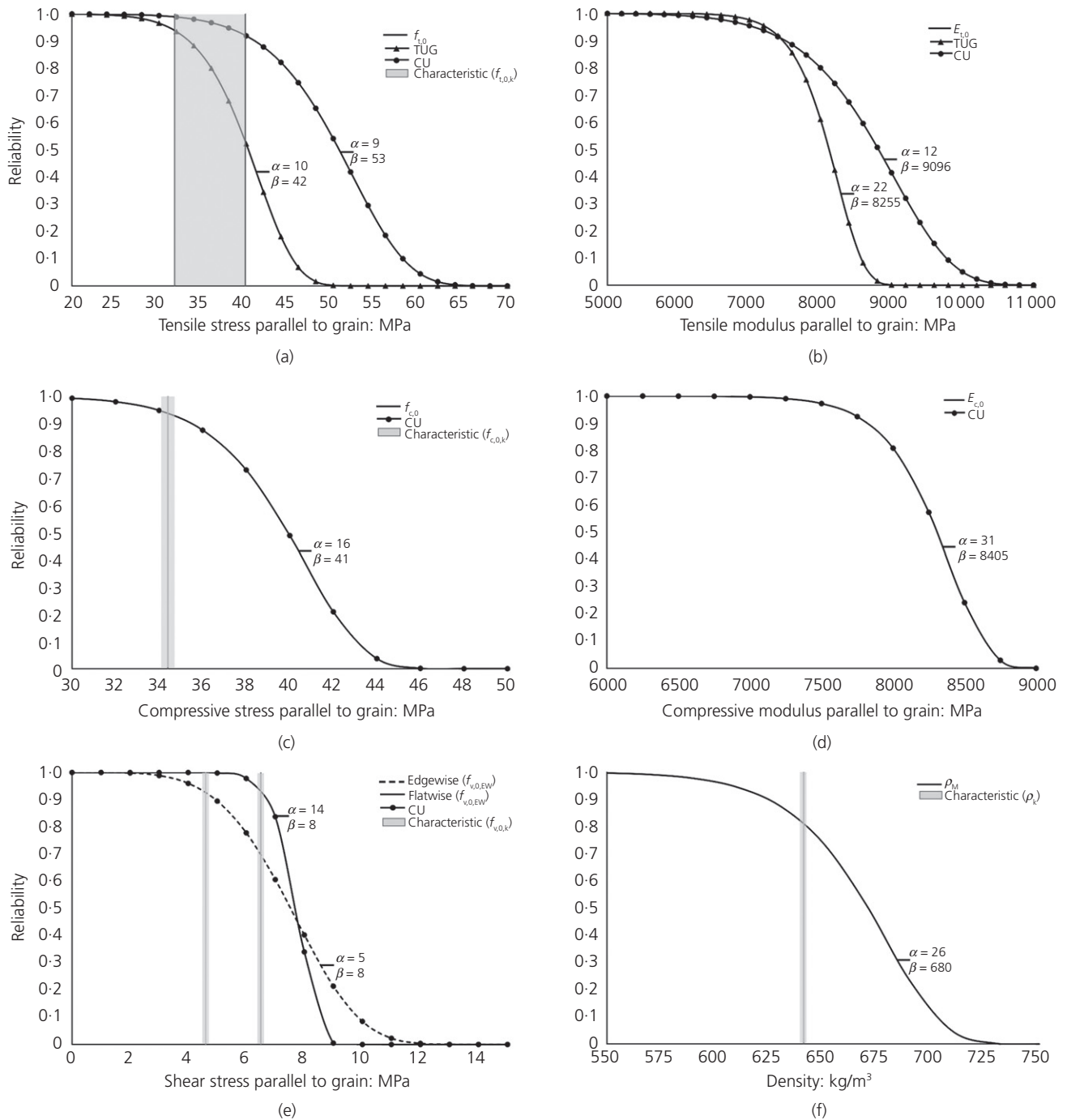
Figure 7. Reliability curves and characteristics values for parallel to grain tests: (a) tensile stress parallel to grain; (b) tensile modulus parallel to grain; (c) compressive stress parallel to grain; (d) compressive modulus parallel to grain; (e) shear stress parallel to grain; (f) density

stress and where the reliability drastically changes. In particular, the shear strength parallel to grain illustrates a drastic change in the failure stress (Figure 7(e)). The accuracy of this estimate would be improved by additional testing to increase the sample size.

Specimen density is shown in Figure 7(f), with the characteristic density (641 kg/m^3) highlighted by the vertical line. In comparison with the other properties, the characteristic density has a slightly lower reliability ($\sim$0·8). This reflects the inherent material and manufacturing variability, which requires

additional investigation. Furthermore, the reliability curve provides a basis to explore grading of engineered bamboo, building upon reliability-based grading methods for timber (Faber *et al.*, 2004; Kohler *et al.*, 2007; Steiger and Arnold, 2009). As discussed in the previous section, the correlation of density and strength was moderate for the bending modulus and shear strength. The other properties do not have a clear relationship that can be developed for the grading of engineered bamboo.

Reliability-based failure prediction is a potential method to form the foundation for characterisation of mechanical properties and can be expanded to building component performance. In comparison with traditional empirically based design methods, which rely on significant experimental testing, reliability methods, combined with some experimental testing, would allow for the determination of lower bound confidence intervals. Furthermore, multiple random material property values can be generated for use in numerical modelling. This approach would allow for greater exploration of the material, particularly in innovative structures and structural components and systems.

6. Timber test standards for laminated bamboo

The mechanical properties of laminated bamboo can be obtained through the application of timber standards. This study allowed for direct comparison with timber and timber-based products using structural-scale testing standards. Standards such as EN 408 (CEN, 2012) have been developed specifically for the behaviour of timber and further work is needed to evaluate testing parameters to determine the influences, if any, on the structural properties obtained from testing. Factors such as loading rate, gauge length for modulus of elasticity and specimen dimensions need to be established with consideration of the inherent properties of laminated bamboo. This study demonstrated that timber standards and design codes are a pathway to characterisation of the material and form the foundation for moving the field forward towards adoption in design and engineering practice.

7. Summary

The study presented in this paper is the first to characterise the structural properties of engineered bamboo based on full-scale structural timber testing standards. The study was conducted through parallel testing at Graz University of Technology (TUG) and Cambridge University (CU). Multi-laboratory testing allows for assessment of uncertainty, as well as the variation of testing parameters. The results show that laminated bamboo has properties that are comparable to timber and glue-laminated timber products. The study is considered to provide a lower-bound estimate of strength, as the location of failure was often at a non-engineered joint used to manufacture longer lengths. Additional research is needed on the development of a 'finger joint' to create longer lengths and spans in laminated bamboo. The flexibility of the material is unique

and differs greatly from timber, suggesting that there is greater potential for the material in innovative structural design.

Comparison of the results from the two laboratories revealed that, while the tests produced similar results, the variation within and between laboratories differed significantly. The study indicates that future work is needed to determine the source of variation in testing, as well as the validity of the timber testing standard in regard to engineered bamboo. The use of reliability analysis to obtain characteristic values for design was presented to explore the potential for future standardisation of the material. Overall, the study validated the need for globalised standard test methods for characterisation and the advantage of multi-laboratory testing in assessing uncertainty. The work has shown that a combined approach to characterisation and standardisation is needed to move engineered bamboo towards being an accepted material for design and engineering practice.

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