Glulam Mechanical Characterization

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Abstract. The glued laminated timber (glulam) mechanical properties may be evaluated through the determination of the key mechanical properties of the lamellae that compose that element. Simple bending and tension parallel to the grain tests were performed in order to assess the strength class of three glulam elements. Regarding the bending tests, 8 samples were taken from a glulam beam and assessed. Values for the resistant bending tension and both local and global modulus of elasticity were obtained. For the tension parallel to the grain tests, a total of 120 samples were assessed. The samples were divided regarding the structural element from where they were extracted as well to the type of failure mode found in the tests. The values of the lamellae properties were then used for determination of the properties of the glulam material. The data gathered from the tests was assessed statistically and concluded that the mechanical properties of the glulam elements did not fulfill the required parameters of the normative requirements.

Introduction

Each material used in a construction site should be subjected to a thorough evaluation of its mechanical properties, in order to avoid possible structural hazards. This evaluation comprises not only the characterization of the material properties and its conformity to the allegedly resistant class, but also the inspection to its physical properties. For this purpose, mechanical tests combined to visual inspections are often used to grade the material in terms of strength class.

Many derivative wood products (e.g. glued laminated timber (glulam), plywood, oriented strand boards (OSB) and others) have more uniform mechanical properties than sound wood, mainly due to the intent of minimizing the influence of defects in timber with the production process. This is often achieved by using different layers or fragments of timber glued or compressed in different directions, creating a new material. The glulam manufacturing process consists in the gluing of overlaid lamellae of timber. This overlaying is made in such manner that the orientation of the fibbers in each lamella is parallel to the remaining ones. In order to obtain larger spans, finger-joints or other equivalent connections are used to bond different timber elements in the same horizontal layer. Even with a controlled manufacturing system and machine stress grading, defects must be assessed by visual inspection specially in the section near the loaded areas, since growth defects factors may have a more substantial effect in the failure development than strength factors such as modulus of elasticity (MOE) and modulus of rupture (MOR) [1]. Since knots present in outer laminations are more critical than knots in core lamination [2], the location of knots within a beam and their effect on strength is accounted in an analysis technique called the I_K/I_G method [3] relating the moment of inertia of the knots with that of the cross-section. Further detailing about different performance modeling of glulam elements may be found in [4] where also probabilistic distributions for strength and stiffness are proposed. The standard NP EN 1194:1999 [5] has indicative values for definition of the strength class of glulam elements (Table 1) and also proposes correlation functions to obtain the properties of a glulam element from the properties of the composing lamellae. The MOE of a glulam element is known to be directly related to the MOE of its individual laminations [2] and often predictions of the full scale element is derived from the localized values of MOE in the lamellae [1][6] with good correlations. The work presented in this paper concerns the mechanical characterization of different glulam elements using simple bending tests and tension parallel to the grain tests. The material in study was classified as a GL28h by the manufacturer. The mechanical properties of glulam elements are correlated with the properties of

the composing lamellae in order to obtain the strength class of the material. The key mechanical properties used for correlation are the characteristic tension strength parallel to the grain, $f_{t,0,l,k}$, and the mean MOE in tension parallel to the grain, $E_{0,l,mean}$. In the case of glulam it is both difficult and costly to perform a sufficient large number of full-scale failure tests to give statistical values for a determined laminate combination, and thus modeling prediction and estimation are often considered [7]. For that reason, a reference element was considered in order to minimize the number of tests and to maximize the amount of information collected from the test campaign.

Table 1: Characteristic values of the mechanical properties [MPa] and density [kg/m³] for homogeneous glulam elements [5].

Properties		GL 24h	GL 28h	GL 32h	GL 36h
Bending strength	$f_{m,g,k}$	24	28	32	36
Tension strength	$f_{t,0,g,k}$	16.5	19.5	22.5	26
	$f_{t,90,g,k}$	0.4	0.45	0.5	0.6
Compression strength	$f_{c,0,g,k}$	24	26.5	29	31
	$f_{c,90,g,k}$	2.7	3.0	3.3	3.6
Shear strength	$f_{v,g,k}$	2.7	3.2	3.8	4.3
Modulus of elasticity	$E_{0,g,mean}$	11600	12600	13700	14700
	$E_{0,g,05}$	9400	10200	11100	11900
	$E_{90,g,mean}$	390	420	460	490
Shear Modulus	$G_{g,mean}$	720	780	850	910
Density	$\rho_{g,k}$	380	410	430	450

Experimental tests layout

Bending tests. The bending tests were conducted with reference to EN 408:2003 [8]. The test arrangement is presented in Figure 1. Local and global MOE, $E_{m,l}$ and $E_{m,g}$, and mean bending strength, f_m , were obtained. Displacement control was used for the tests, having in consideration that the maximum applied load was to be reached in 300 ± 120 s. A displacement rate of 0.14 mm/s was found to be suitable for these samples. A total of 8 beams with dimensions $90 \times 200 \times 3600$ mm³ were tested. Each sample height was composed with a minimum of 4 lamellae.

Figure 1: Test arrangement for the bending tests [8], where h is the height of the cross-section, w is the deformation and F is the applied load

Tension parallel to the grain tests. The tension parallel to the grain tests consisted in the application of a load parallel to the timber grain's main direction. The tests were made by displacement control with an increment rate in the interval of [0.03; 0.04] mm/s. The increment rate was chosen for each case regarding a visual inspection of every individual sample, with the intent of reaching the maximum load in the interval of 300 ± 120 s. The elastic parameters were measured by a 50 mm length clip-gauge placed in the middle of the timber sample. The schematics of the tension parallel to the grain tests are shown in Figure 2. Samples were machined by cutting a prismatic piece of wood with $5 \times 10 \times 300$ mm³ and then reducing the cross-section at the middle of the specimen using an electric wood router. The sample gripping part has a larger width and thickness in order to produce a larger contact area and avoid problems of local compression. The middle cross-section is narrower to increase the probability of failure by tension in that area.

Figure 2: Tension parallel to the grain test samples: a) schematics (dimensions in mm); b) specimen.

During the test campaign, 3 elements with different initial manufactured cross-section dimensions ($E1 = 20 \times 220 \text{ cm}^2$, $E2 = 20 \times 100 \text{ cm}^2$ and $E3 = 16 \times 58.5 \text{ cm}^2$) were assessed in a total number of 120 samples. The element E2 was considered as the reference element since the bending tests were performed from specimens derived from this element.

Experimental tests results

Bending tests. After conducting the four point bending tests a mean value for $E_{m,l}$ of 8426.3 MPa and a mean value for $E_{m,g}$ of 8458.3 MPa were obtained. These values were derived from the analysis of the regression line of the load/displacement curve between the values of $0.1F_{\max}$ and $0.4F_{\max}$. The load/displacement curves are presented in Figure 3.b, where a predominantly linear behavior until failure is observed for the tested samples. Although the maximum load is significantly different between different samples, the slope of the curves are confined to a smaller interval range indicating a smaller variation for MOE than for the bending strength. The coefficient of variation was 14.58% and 11.45% for $E_{m,l}$ and $E_{m,g}$, respectively, while f_m presented a coefficient of variation of 28.74%.

Figure 3: Bending tests results: a) failure mechanisms; b) load versus displacement curves.

Table 2: Bending test results for each sample.

Sample	$F_{\max}$ [N]	f_m [MPa]	Density [kg/m^3]	Water content [%]
1	35.32	29.56	434.86	15.09
2	26.3	22.01	405.85	15.01
3	20.44	17.11	406.46	14.19
4	35.99	30.12	408.36	14.62
5	18.13	15.17	454.52	13.84
6	38.42	32.16	385.33	14.93
7	23.29	19.49	381.06	14.28
8	22.19	18.57	398.65	15.02
mean	27.51	23.03	409.39	14.62
CoV (%)	28.74	28.74	5.99	3.20

The most common failure mechanism consisted in the failure of the lower fibbers by tension and creation of horizontal cracks in the proximity of the neutral axis, thus corresponding to the expected bending failure mechanism (see Figure 3.a). The samples that present lower $F_{\max}$ had their failure

conditioned by the presence of nodes and also delamination problems were found in the contact surface between the lamellae. The maximum applied load and bending strength for each sample is presented in Table 2, where a high coefficient of variation is observed for the bending strength regarding the failures due to the influence of defects. The values of density and water content were determined according to standards ISO 3130 [9] and ISO 3131 [10].

Tension parallel to the grain tests. A significant high coefficient of variation was found for the results of tension strength parallel to the grain. In order to minimize that variation, three different types of failure modes were considered and statistically studied. Those failure modes corresponded to the failures occurred: a) in the middle section without the influence of defects; b) due to the direct influence of defects; c) in the gripping area. Modes b) and c) were only considered for the study of the full experimental sample regarding the MOE in the elastic range, whereas were not considered for material strength conformity. The results of the different groups are only calculated to assess the difference and variation between clear wood specimens and specimens with defects, since it is known that MOE the full scale beam might be affected by defects in each lamination [11]. Regarding the stiffness parameters, the results presented a lower coefficient of variation. The results are presented in Figure 4 and Table 3. With respect to a statistical analysis to all samples, an approximation to a lognormal distribution curve was made and characteristic values (5% percentile) were obtained, such that $f_{t,0.1,k} = 14.72$ MPa and $E_{0.1,k} = 5910$ MPa. The mean value for $E_{0.1}$ was found to be equal to 9180 MPa.

Figure 4: Histograms with the results of the tension parallel to the grain tests: a) $f_{t,0.1}$; b) $E_{0.1}$.

Table 3: Results of the tension parallel to the grain tests.

Element	Failure mode	$f_{t,0.1}$ [MPa]		$E_{0.1}$ [MPa]	
		mean	CoV [%]	mean	CoV [%]
E1	all	43.06	49.0	8869	21.9
	mode a)	53.98	18.9	9228	14.7
	mode b)	24.26	29.8	7751	25.4
	mode c)	58.26	26.4	9811	18.1
E2	all	42.32	45.3	9386	21.3
	mode a)	52.62	27.7	9176	17.5
	mode b)	29.07	38.6	9167	23.4
	mode c)	54.14	30.6	9892	22.9
E3	all	40.59	47.2	9222	27.2
	mode a)	49.65	36.7	9771	23.6
	mode b)	23.53	28.8	7996	29.1
	mode c)	51.43	18.5	10513	22.5

Correlations

The properties correlation functions found in NP EN 1194:1999 [5] were used to define the remaining characteristics of the glulam elements. Element E2 was used as reference element and the

characteristics of elements E1 and E3 were taken from it. The obtained values are presented in Table 4.

Table 4: Properties correlation functions [5] and obtained values for all elements and individually.

Property*	Correlation		Elements			
			all	E1	E2	E3
Bending	$f_{m,g,k}$	$= 7 + 1.15 f_{t,0,l,k}$	23.924	22.116	23.956	24.644
Tension	$f_{t,0,g,k}$	$= 5 + 0.8 f_{t,0,l,k}$	16.773	15.516	16.795	17.274
	$f_{t,90,g,k}$	$= 0.2 + 0.015 f_{t,0,l,k}$	0.421	0.397	0.421	0.430
Compression	$f_{c,0,g,k}$	$= 7.2 f_{t,0,l,k}^{0.45}$	24.146	22.949	24.166	24.603
	$f_{c,90,g,k}$	$= 0.7 f_{t,0,l,k}^{0.5}$	2.685	2.538	2.688	2.742
Shear	$f_{v,g,k}$	$= 0.32 f_{t,0,l,k}^{0.8}$	2.750	2.513	2.754	2.844
Modulus of elasticity	$E_{0,g,mean}$	$= 1.05 E_{0,l,mean}$	9.64	9.31	9.86	9.68
	$E_{0,g,05}$	$= 0.85 E_{0,l,mean}$	7.81	7.54	7.98	7.84
	$E_{90,g,mean}$	$= 0.035 E_{0,l,mean}$	0.32	0.31	0.33	0.32
Shear modulus	$G_{g,mean}$	$= 0.065 E_{0,l,mean}$	0.60	0.58	0.61	0.60

* Strength characteristics in MPa and stiffness characteristics in GPa

Since the influence of defects is minimized during the manufacturing process of glulam elements, the previous correlation analysis was also conducted assuming only the test samples with failure mode a). The results are presented in Table 5. By comparing these two analyses it is visible that, for this case, the influence of defects highly decreases the strength characteristics but has little importance to the stiffness characteristics. A correlation between the reference element and the other elements was also made in order to obtain the probable values of hypothetical bending tests made to the other elements. From that correlation element E1 would assume in bending tests a value of $f_m = 21.23$ MPa and $E_{0,g,mean} = 8502$ MPa. Analogously, element E3 would assume the values of $f_m = 23.66$ MPa and $E_{0,g,mean} = 9002$ MPa.

Table 5: Properties correlation functions [5] and obtained values for each element regarding only failure mode a).

Property*	Correlation		Elements		
			E1	E2	E3
Bending	$f_{m,g,k}$	$= 7 + 1.15 f_{t,0,l,k}$	49.221	43.481	30.974
Tension	$f_{t,0,g,k}$	$= 5 + 0.8 f_{t,0,l,k}$	34.371	30.378	21.677
	$f_{t,90,g,k}$	$= 0.2 + 0.015 f_{t,0,l,k}$	0.751	0.676	0.513
Compression	$f_{c,0,g,k}$	$= 7.2 f_{t,0,l,k}^{0.45}$	36.434	34.115	28.242
	$f_{c,90,g,k}$	$= 0.7 f_{t,0,l,k}^{0.5}$	4.241	3.943	3.196
Shear	$f_{v,g,k}$	$= 0.32 f_{t,0,l,k}^{0.8}$	5.715	5.084	3.634
Modulus of elasticity	$E_{0,g,mean}$	$= 1.05 E_{0,l,mean}$	9.69	9.64	10.26
	$E_{0,g,05}$	$= 0.85 E_{0,l,mean}$	7.84	7.80	8.31
	$E_{90,g,mean}$	$= 0.035 E_{0,l,mean}$	0.32	0.32	0.34
Shear modulus	$G_{g,mean}$	$= 0.065 E_{0,l,mean}$	0.60	0.60	0.64

* Strength characteristics in MPa and stiffness characteristics in GPa

Material conformity

The test results were compared to the indicative values of the standard NP EN 1194:1999 [5], in order to assess about the material conformity. The material was assumed to be a GL28h from the manufacturer information. The mean value of density in the tests is similar to the suggested for GL28h with an admissible coefficient of variation. Assuming the values in Table 5 it is observed that the strength properties of the tested material are consistent with the normative values for a GL28h class. However, the stiffness properties are lower than the normative requirements, and therefore the material could not be graded as a GL28h.

Conclusions

A total of 8 bending tests and 120 tension parallel to the grain tests were conducted in order to assess the strength class of three different glulam elements. A reference element was considered in order to minimize the number of tests. Properties correlation functions were used to obtain the mechanical properties of the glulam elements regarding the properties of the composing lamellae. With respect to the normative standards, that establish the minimum required values for specific class strength, it was concluded that the elements in study did not achieve a suitable performance. A visual inspection conducted to the samples and its failure modes in the tension parallel to the grain tests provided evidence that the strength properties are highly influenced by the presence of defects. The samples without any natural defect presented significantly higher values for the strength properties. The stiffness properties were less influenced by the presence of defects. Regarding the importance of the influence of defects and also the not fulfillment of the minimum normative values of the given strength class, it is suggested that larger dimensional test samples should be considered. With these samples it is intended to include the stress redistribution effect between lamellae.

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