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Determination of characteristic strength and stiffness values in glued laminated beams of Argentinean *Eucalyptus grandis* according to European standards

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Abstract The present paper reports the results of an investigation regarding the determination of characteristic strength and stiffness values in glued laminated beams of fast-growth Argentinean *Eucalyptus grandis* according to the criteria established in European standards. An empirical research project with 100 beams in structural sizes and 191 finger-jointed laminations was carried out. Test results allow to analyse the mechanical property values of this glued laminated timber in comparison with those adopted by the strength class system established in the European standard EN 1194 (1999), and they reveal a very high ratio of modulus of elasticity to density. Test results were also compared with values obtained by means of the equations provided by EN 1194 (1999). The effectiveness of the criteria established in this European standard for determining mechanical properties in beams of this deciduous species is analysed through the discussion of test results and those obtained from calculations based on lamination properties.

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Bestimmung der charakteristischen Festigkeits- und Steifigkeitswerte nach europäischen Normen von Brettschichtholzträgern aus *Eucalyptus grandis* aus Argentinien

Zusammenfassung Im vorliegenden Beitrag werden die Ergebnisse einer Studie zusammengefasst, in der die charakteristischen Festigkeits- und Steifigkeitswerte von Brettschichtholzträgern aus argentinischem *Eucalyptus grandis* nach europäischen Normen bestimmt wurden. Untersucht wurden 100 Brettschichtholzträger und 191 Keilzinkenverbindungen. Die Versuchsergebnisse erlauben einen Vergleich der mechanischen Eigenschaften dieses Brettschichtholzes mit Festigkeitsklassen nach EN 1194 (1999). Die Ergebnisse zeigen ein sehr großes Verhältnis von Elastizitätsmodul zu Rohdichte. Die Versuchsergebnisse wurden auch mit den Ergebnissen der Gleichungen nach EN 1194 (1999) verglichen. Die Anwendbarkeit dieser europäischen Norm zur Bestimmung der charakteristischen Werte von Brettschichtholz aus dieser Laubholzart wurde anhand der Versuchsergebnisse und anhand der Regeln zur Berechnung der Tragfähigkeit von Brettschichtholz an den Lamelleneigenschaften untersucht.

1 Introduction

Eucalyptus grandis is one of the most important renewable species cultivated in Argentina (INTA 1995). Up to the present neither systematic studies regarding the mechanical properties of glued laminated timber of this fast-growth timber species have been developed nor production requirements and quality controls established by the Argentinean Institute for Standardization (IRAM). As a consequence, it is not considered as a reliable material for structural purposes even though it has been employed in many structures.

With the purpose of specifying performance and production requirements and defining a strength class system for this material in Argentina, a national project was organised by the Argentinean Timber Technological Network (RITIM) and carried out by universities and enterprises. *Eucalyptus grandis* was the only deciduous species included in this project (Piter 2005). Laboratory tests and analytical investigations were carried out according to the criteria established in European standards, even though EN 1194 (1999) is intended primarily only for coniferous species.

According to European standards, glued laminated timber must fulfil performance and production requirements related to timber, adhesives, finger joints and glue lines between laminations (Colling 1995b). A strength class system and criteria for obtaining the mechanical properties are established in EN 1194 (1999). According to these criteria, characteristic strength and stiffness values may be determined by tests or by calculation based on lamination properties. The most important mechanical properties to be obtained from tests are bending strength and stiffness, and all other strength and stiffness values may be derived from them. Strength and stiffness in tension parallel to the grain are the most important lamination properties for calculating the characteristic values of this material by means of the equations provided by this standard.

One of the requirements specified in EN 386 (1996) for glued laminated timber components is that timber shall be strength graded. Results of a previous investigation provided a visual method for strength grading sawn timber of Argentinean *Eucalyptus grandis* according to European standards (Piter et al. 2004a). This report allows us to analyse different strength, stiffness and density profiles and the corresponding limits for the main grading parameters in comparison with the international strength class system established in EN 338 (2003). The above mentioned research also revealed particularities for this timber species such as high ratios of modulus of elasticity (MOE) to density and strength to density, which are similar to those corresponding to poplar and coniferous species. In particular, the ratio of MOE to density is higher than the same ratio for all strength classes for deciduous species according to EN 338 (2003). Other important features, reported in the above mentioned research, are that the relation between tensile and bending strength amounts to 0.63 and the mean value of MOE in tension is only 6% higher than the corresponding value for MOE in bending. These relations obtained from results of static tests carried out according to EN 408 (2004) allow us to derive the tensile properties of laminations from the bending properties according to the criteria established in European standards.

For the present project it was decided to utilise boards belonging to the highest and the second grades according to the above mentioned visual method for strength grading sawn timber of Argentinean *Eucalyptus grandis*. Adhesives meeting the requirements of the Argentinean standard IRAM 45055 (2002), which is similar to prEN 301 (2001), are available in Argentina. Therefore, the project aimed at defining a strength class system for glued laminated beams of this timber species continued with the following stages: i) determination of characteristic strength and stiffness values for beams obtained from bending tests carried out on structural-sized specimens according to EN 408 (2004), ii) determination of the characteristic bending strength for finger joints according to EN 385 (2002), iii) calculation of characteristic strength and stiffness values for beams by means of the equations provided by EN 1194 (1999), and iv) comparison of the mechanical properties obtained from bending tests with those derived from lamination properties. For the production of finger joints and beams the requirements of EN 386 (1996) were met.

The aim of this paper is to present and discuss the results of an investigation regarding the determination of characteristic strength and stiffness values in glued laminated beams of fast-growth Argentinean *Eucalyptus grandis* according to the criteria established in EN 1194 (1999). The effectiveness of the criteria established in this European standard for determining the mechanical properties in glued laminated beams of this deciduous species is analysed through discussion and comparison of the values obtained from static tests with the results based on lamination properties.

2 Materials and methods

The material was provided by a producer, who also manufactured all the required beams and finger joints in a plant that meets the requirements given in EN 386 (1996). A total of 100 horizontal glued laminated beams were manufactured for bending tests. With the aim of obtaining representative samples regarding the usual dimensions of this material in Argentina, and for economical reasons, each beam was composed of 10 laminations. The nominal sizes of the lamination cross-section were 25 mm in thickness and 100 mm in width. Boards with these nominal sizes for the cross-section are normally used in Argentina. 50 beams were made with homogeneous cross-section by employing laminations belonging to the strength class 2 according to the above mentioned method for visually grading sawn timber of Argentinean *Eucalyptus grandis* (see Table 1). They represented the poorest strength class in this project, which was identified as GL 2. Other 50 beams represented the highest grade and they were named GL 1. 25 of them were

Table 1 Strength, stiffness and density characteristic values with parameter limits corresponding to the strength classes defined in the method for visually grading sawn timber of Argentinean *Eucalyptus grandis*

Tabelle 1 Charakteristische Festigkeits-, Steifigkeits- und Rohdichtewerte und zugehörige Grenzwerte der Sortierparameter für eine visuelle Festigkeitssortierung von *Eucalyptus grandis* Schnittholz aus Argentinien

Strength class	Limits for the grading parameters	$f_{m,k}^{(1)}$ N/mm^2	$E_{0,\text{mean}}^{(2)}$ N/mm^2	$\rho_{\text{mean}}^{(2)}$ kg/m^3	$\rho_k^{(2)}$ kg/m^3
1	Without pith, fiss.$^{(3)}$ and large defects. Knot ratio $\leq 1/3$	28.1	13 900	550	430
2	Without pith, fiss.$^{(3)}$ and large defects. Knot ratio $> 1/3$	22.5	12 900	570	420

(1) characteristic bending strength corrected to a reference depth of 150 mm and adjusted for sample size according to EN 384 (2004); (2) corrected to a reference moisture content of 12% according to EN 384 (2004); (3) fissures exceeding the maximum length established in European standards for strength classes above C18. (Piter et al. 2004a)

(1) Charakteristische Biegefestigkeit umgerechnet auf eine Bezugshöhe von 150 mm und unter Berücksichtigung des Stichprobenumfangs nach EN 384 (2004); (2) umgerechnet auf eine Bezugsfeuchte von 12% nach EN 384 (2004); (3) Risse länger als Höchstwerte für Festigkeitsklassen über C18 in den europäischen Normen. (Piter et al. 2004a)

manufactured with homogeneous cross-sections (GL 1h) and they were composed only of laminations assigned to the strength class 1. Other 25 beams presented combined cross-sections (GL 1c). In this case, and according to the requirements established in EN 1194 (1999), 2 laminations of the highest strength class were positioned in the outer regions of the beams whereas laminations of the poorest grade were used in the inner zones.

191 finger-jointed laminations with the above mentioned nominal sizes for the cross-section were selected for flatwise bending tests. 138 of them were assigned to the strength class 1, whereas the other 53 were assigned to the strength class 2. A melamine-urea formaldehyde adhesive, which meets the requirements established in IRAM 45055 (2002) and prEN 301 (2001) for adhesives type II, was used in all cases.

After transporting the material to the laboratory, it was conditioned in a room at 20 °C temperature and 65% relative humidity. Actual dimensions and measurements for each test piece were taken after conditioning in normal climate, and made to an accuracy of 1%. Static tests in bending were carried out according to the procedures of EN 408 (2004) and EN 385 (2002) for beams and finger joints, respectively. All specimens were placed symmetrically on the supports and loaded at one-third span length. Beams were tested edgewise, with a finger joint of the outermost lamination located in the tension zone of the central third. Finger-jointed laminations were tested flatwise, with the joint located in the centre of the span. A loading machine Shimadzu UH 1000 kN, capable of applying loads with adequate rate of movement of the loading-head and accuracy of 1% was used for all tests. For calculating the local MOE in beams, deformations were taken as the average of measurements on both faces at the neutral axis, and were measured at the centre of a central gauge length of five times the depth of the section. Two extensometers with a resolution of 0.01 mm were used.

Strength and MOE obtained from bending tests were calculated using the standard solution. Moisture content and density were calculated according to the procedures of ISO 3130 (1975) and ISO 3131 (1975), respectively, using a clear full cross section taken from the test specimen after the static test.

3 Results and discussion

The main results for the mechanical properties corresponding to beams subjected to bending tests are summarised in Table 2. The sizes of the beam cross-section presented mean values of 90.9 mm in width and 202.6 mm in depth.

Table 2 Summary of the results for mechanical and density properties corresponding to beams subjected to bending tests

Tabelle 2 Mechanische Eigenschaften und Rohdichte für die in Biegeversuchen verwendeten Brettschichtholzträger

Strength class		$f_{m,g}^{(1)}$ N/mm^2	$E_{0,g}^{(2)}$ N/mm^2	$\rho_g^{(2)}$ kg/m^3
GL 1	Mean	40.4	18 000	570
($n = 50$)	COV (%)	17	11	7
	Characteristic	$f_{m,g,05} = f_{m,g,k} = 28.8$	$E_{0,g,\text{mean}} = 18\,000$	$\rho_{g,k} = 510$
GL 2	Mean	33.6	18 100	600
($n = 50$)	COV (%)	20	10	6
	Characteristic	$f_{m,g,05} = f_{m,g,k} = 23.3$	$E_{0,g,\text{mean}} = 18\,100$	$\rho_{g,k} = 540$

(1) corrected to a reference depth of 600 mm and to a reference width of 150 mm according to EN 1194 (1999); (2) corrected to a reference moisture content of 12% according to EN 384 (2004); (n) sample size

(1) umgerechnet auf eine Bezugshöhe von 600 mm und auf eine Bezugsdicke von 150 mm nach EN 1194 (1999); (2) umgerechnet auf eine Bezugsfeuchte von 12% nach EN 384 (2004); n ist die Anzahl der Prüfkörper

Moisture content showed a mean value of 13.5% with a coefficient of variation (COV) of 2% for the 50 beams of GL 1, whereas the mean value for the 50 beams of GL 2 was 11.7% with a COV of 9%.

Beams of strength class GL 1 show higher strength values ($f_{m,g}$), with lower COV than those of GL 2, and both strength classes exhibit almost the same values for local MOE ($E_{0,g}$). The results for density (ρ_g) are included in Table 2 even though they are only indicative values for glued laminated timber according to EN 1194 (1999). These results show that it is not possible to find density differences between these two grades for practical purposes, in line with data presented in Table 1. Curiously, both mean and characteristic density values corresponding to GL 2 are slightly higher than those of GL 1. A very high ratio of MOE to density is confirmed for glued laminated timber of this deciduous species, which may be an important advantage for structural purposes. The ratios obtained in the present research for the mean values amount to 31.6 for GL 1 and 30.2 for GL 2 and they are also higher than those reported by Castro and Paganini (2003) for mixed glued laminated timber of poplar and *Eucalyptus grandis* in different combinations.

A detailed analysis shows that no strength and stiffness differences between the 25 homogeneous and the 25 combined glued laminated beams can be found. The results obtained from tests confirm a similar bending behaviour for both homogeneous and combined beams, which were manufactured according to the criteria established in the European standard.

With the purpose of detecting the origin of failures, test results for the 100 beams were discriminated by strength class and type of failure and are presented in Table 3. 90% of the failures developed from a finger joint (FJ failures) in GL 1. Beams with this type of failure exhibit lower strength values than those corresponding to beams with failures developed from wood (W failures), in line with data reported by Colling (1995a). The percentage of FJ failures decreases (74%) in GL 2 and, in contrast to the previous case, beams with FJ failures show higher strength values than those corresponding to W failures. These percentages are congruent with the more rigorous limit for knot ratio established for laminations of strength class 1 than that required for strength class 2. Results also confirm that finger joints shall be considered a strength determining factor for this case. The improvement of end-joint quality appears to be more important for increasing the strength of this glued laminated timber than the adoption of more stringent limits for the parameters in the above mentioned visual method for strength grading the laminations.

Table 3 Bending strength results ($f_{m,g}$) for the 100 tested beams separated by strength class and type of failure

Tabelle 3 Ergebnisse der Biegeversuche von 100 Brettschichtholzträgern, unterteilt nach Festigkeitsklasse und Bruchart

	Strength class GL 1 ($n = 50$)		Strength class GL 2 ($n = 50$)	
	FJ failures(2) ($n = 45$)	W failures(3) ($n = 5$)	FJ failures(2) ($n = 37$)	W failures(3) ($n = 13$)
Mean (N/mm^2)(1)	39.9	44.6	35.0	29.6
COV (%)	17	11	19	18

(1) corrected to a reference depth of 600 mm and to a reference width of 150 mm according to EN 1194 (1999); (2) failures developed from a finger joint; (3) failures in wood

(1) umgerechnet auf eine Bezugshöhe von 600 mm und eine Bezugsdicke von 150 mm nach EN 1194 (1999); (2) Keilzinkenbruch; (3) Holzbruch

In order to compare the strength and stiffness values obtained from tests with those adopted in the strength class system established in EN 1194 (1999), the lower 5th percentile ($f_{m,g,05} = f_{m,g,k}$) of bending strength as well as the mean value of MOE ($E_{0,g,\text{mean}}$) are included in Table 2. Strength values of GL 1 and GL 2 compare relatively well with those required in the strength class system for GL 28 and GL 24, respectively. It is important to point out that the MOE mean values found in this research are higher than those required for all strength classes according to EN 1194 (1999), which is intended primarily only for coniferous species. The characteristic values shown in Table 2 for density ($\rho_{g,k}$) also satisfy the values required for all strength classes in this European standard.

With the aim of comparing the results obtained from static tests with those derived by calculations depending on lamination properties, the characteristic values corresponding to strength classes 1 and 2 of this sawn timber were utilized (see Table 1). Since the relation between tensile and bending properties of this timber species compares well with that adopted in the international strength class system established in EN 338 (2003) (Piter et al. 2004a), the characteristic strength value in tension ($f_{t,0,l,k}$) and the mean value of MOE in tension ($E_{0,l}$) for laminations may be derived from the values presented in Table 1. Therefore, it may be assumed that $f_{t,0,l,k} = 0.6 \times 28.1\,\text{N/mm}^2 = 16.9\,\text{N/mm}^2$ and $E_{0,l} = 13\,900\,\text{N/mm}^2$ for strength class 1 whereas $f_{t,0,l,k} = 0.6 \times 22.5\,\text{N/mm}^2 = 13.5\,\text{N/mm}^2$ and $E_{0,l} = 12\,900\,\text{N/mm}^2$ for strength class 2.

According to EN 1194 (1999) the characteristic bending strength of end joints ($f_{m,j,k}$), obtained from flatwise bending tests, shall meet the following requirement: $f_{m,j,k} \geq f_{m,j,k,r}$ where $f_{m,j,k,r}$ is the required characteristic bending strength for end joints. In order to verify this condition, the results obtained from flatwise bending tests with 191 finger-jointed laminations, carried out according to EN 385 (2002), are presented in Table 4. The sizes of the specimen cross-section presented mean values of 95.7 mm in width

Table 4 Strength and density results for 191 finger-jointed laminations subjected to flatwise bending tests
Tabelle 4 Ergebnisse der Biegefestigkeit und der Rohdichte von 191 flachkantgeprüften Keilzinkenverbindungen

Strength class		$f_{m,j}$ N/mm^2	$\rho^{(1)}$ kg/m^3
1	Mean	49.7	600
($n = 138$)	COV (%)	17	17
	Characteristic	$f^{(2)}_{m,j,k} = 35.9(24.0)^{(3)}$	$\rho_{j,k} = 430$
2	Mean	46.9	590
($n = 53$)	COV (%)	19	14
	Characteristic	$f^{(2)}_{m,j,k} = 32.5(21.7)^{(3)}$	$\rho_{j,k} = 460$

(1) corrected to a reference moisture content of 12% according to EN 384 (2004); (2) assuming a Log-Normal distribution according to EN 385 (2002); (3) corrected to a reference depth of 150 mm according to EN 384 (2004)
(1) umgerechnet auf eine Bezugsfeuchte von 12% nach EN 384 (2004); (2) unter Annahme einer Lognormalen Verteilungsfunktion entsprechend EN 385 (2002); (3) umgerechnet auf eine Bezugshöhe von 150 mm nach EN 384 (2004)

and 20.1 mm in depth. The finger-jointed laminations of strength class 1 showed a mean moisture content of 13.7% with a COV of 8%, whereas the mean value for the finger-jointed laminations of the second grade was 13.5% with a COV of 4%.

The mean and the characteristic strength values found for the best grade are slightly higher than those corresponding to the second grade. These results are congruent with the similarity found for density in both grades and with the absence of defects in the proximity of finger joints. Results previously reported (Piter et al. 2004b) confirmed a high correlation of 0.81 between MOE and strength for this timber species and proved that it may advantageously perform in a machine strength grading process. Therefore, a strength increase would be possible in this case by means of a machine strength grading, which is in line with previous reports related to other timber species (Colling and Ehlbeck 1992, Colling 1995a). Neither correction to a reference depth nor adjustment of sample size are required for $f_{m,j,k}$ in European standards. With the purpose of comparing the bending strength of end joints with that corresponding to sawn timber, $f_{m,j,k}$ was corrected to a reference depth of 150 mm according to EN 384 (2004) and presented in Table 4. The corrected values of $f_{m,j,k}$ corresponding to strength class 1 (24.0 N/mm^2) and to strength class 2 (21.7 N/mm^2) are lower than the corresponding characteristic strength values presented in Table 1 for sawn timber of this species. The difference is more important for the best grade (17%) than for the poorest grade (4%), which is congruent with the higher tolerance adopted for knot ratio in the poorest grade than in the best grade and with the absence of knots in the proximity of end joints. These results confirm a lower bending strength for finger-jointed laminations than for timber itself if both are corrected to the same reference depth.

Table 5 presents the main data and the results for mechanical properties obtained by calculations. It is important to point out that the required characteristic bending strength for end joints ($f_{m,j,k,r} = 8 + 1.4 f_{t,0,l,k}$), which amounts to 31.7 N/mm^2 for GL 1 and 26.9 N/mm^2 for GL 2, is easily exceeded by that of $f_{m,j,k} = 35.9$ N/mm^2 for GL 1 and $f_{m,j,k} = 32.5$ N/mm^2 for GL 2, respectively. The demanded values represent 88% and 83% of the found values for GL 1 and GL 2, respectively. Consequently, the requirement established in EN 1194 (1999) is easily fulfiled in this case, which is not congruent with the very high number of failures developing from finger joints that were found in the tested beams (see Table 3). The results obtained in the present research account for the convenience of adopting a more stringent requirement for $f_{m,j,k}$ than that established in EN 1194 (1999), which has been a controversial theme (Gehri 1992). The small depth of the finger-jointed laminations tested in bending (20.1 mm), considering the criteria adopted in (EN 384 2004), may be a reason for obtaining high values of $f_{m,j,k}$ which easily satisfy the demanded values.

Strength values calculated by equations ($f_{m,g,k} = 7 + 1.15 f_{t,0,l,k}$) compare relatively well with those obtained from tests. The characteristic strength values obtained from tests are 9% and 4% higher than the analytical values for GL 1 and GL 2, respectively (see also Table 2). MOE is the property presenting the more important differences between test results and values obtained by calculations ($E_{0,g,\text{mean}} = 1.05 E_{0,l,\text{mean}}$). Test results for $E_{0,g,\text{mean}}$ are 23% and 34% higher than the analytical values for GL 1 and GL 2, respectively. These important differences may only partially be explained by the slightly higher value of MOE in tension than in bending (6%) that were found for sawn timber of Argentinean *Eucalyptus grandis* (Piter et al. 2004a). Density values obtained by equations ($\rho_{g,k} = 1.1 \rho_{l,k}$) are also lower than those obtained by tests but the differences are not important and they are congruent with other results, as it was mentioned above.

Table 5 Properties of glued laminated timber obtained by calculation based on lamination properties
Tabelle 5 Berechnung der Brettschichtholzeigenschaften in Abhängigkeit von den Lamelleneigenschaften

Strength class	$f_{t,0,l,k}$ N/mm^2	$E_{0,l,\text{mean}}$ N/mm^2	$\rho_{l,k}$ kg/m^3	$f_{m,j,k}$ N/mm^2	$f_{m,j,k,r}$ N/mm^2	$f_{m,g,k}$ N/mm^2	$E_{0,g,\text{mean}}$ N/mm^2	$\rho_{g,k}$ kg/m^3
GL 1	16.9	13 900	430	35.9	31.7	26.4	14 600	470
GL 2	13.5	12 900	420	32.5	26.9	22.5	13 500	460

4 Conclusions

Strength and stiffness in structural-sized glued laminated beams of fast-growth Argentinean *Eucalyptus grandis* were analysed in tests and through calculations based on lamination properties. Bending tests with 100 beams and 191 finger-jointed laminations, belonging to two different strength classes, were carried out. Strength values corresponding to the highest (GL 1) and to the poorest (GL 2) strength class compare relatively well with those required in the international system established in the European standard EN 1194 (1999) for GL 28 and GL 24, respectively. GL 1 and GL 2 exhibit higher mean values for MOE than those required for all strength classes according to this European standard. Results also confirm a very high ratio of MOE to density for this glued laminated timber, which may be an important advantage for structural purposes. A detailed analysis shows that an important percentage of failures developed from finger joints, which shall be considered as an important strength determining factor in this case. The research also reveals that a strength increase would be possible by means of machine strength grading the laminations and by improving the quality of finger joints. Characteristic strength and stiffness values were also obtained by means of calculations based on lamination properties. Characteristic strength values obtained by tests are slightly higher than those obtained with the equations provided in EN 1194 (1999). The comparison between test and analytical results also accounts for the convenience of adopting a more stringent condition for the required characteristic bending strength for finger joints than the one established in the European standard. The property presenting the more important differences between test and analytical results is MOE. MOE mean values obtained from tests are significantly higher than those obtained from calculation.

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