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ORIGINAL

Evaluation of glue line shear strength of laminated timber structures using block and core type specimens

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Abstract Monitoring and evaluation of glued laminated timber structures in service is essential to warrant its integrity, where non-destructive techniques play an important role. This paper describes the results obtained on glued laminated timber beams of maritime pine, with and without preservative treatment, and of spruce, exposed to natural outdoor environment as well as to artificial weathering. The assessment of glue lines' shear strength was investigated through the extraction and testing of cores parallel and perpendicular to the glued lines and block shear specimens with 50 mm × 50 mm and 20 mm × 20 mm shear area. The results highlight the different performances of the various types of specimens tested, showing that the measured shear strength depends on the specimen size and that the size effect depends on the material strength giving a decreasing modification factor with the increase of strength in opposition to the constant factor suggested by standard EN 14080. They also show that shear testing of cores drilled perpendicular to the glued joints may be a promising tool in the assessment of glulam structures on site.

1 Introduction

Glued laminated timber structures are used worldwide in buildings and bridges. As happens with other structural materials, monitoring and evaluation of glued laminated timber structures in service are essential to control their durability and to prevent premature degradation and/or failure. This is particularly important for timber exposed to weather, although it is also required for interior structures.

The assessment of the integrity of glued laminated timber structures requires a general overview of the structural functioning and integrity of joints and members, including design, construction and modification errors, the assessment of the environmental conditions to which the structure is exposed, as well as moisture content, cracks, and integrity of glue-lines assessment (Cruz 2007; Gaspar 2010; Dietsch and Tannert 2015).

However, apart from visual inspection, there is a lack of reliable methods to assess the integrity of glued structural members in use and to evaluate the quality and possible degradation of glue lines.

There has been a growing interest in assessing the integrity of bonded joints in structures in service through non-destructive and/or semi-destructive methods, in addition to visual inspection, to quantify their chemical and physical degradation and estimate their residual strength.

Non-destructive techniques are generally based on correlations between non-destructive measurements and a specific material property, namely the strength and modulus of elasticity. Ultrasound wave propagation is an example of a non-destructive technique that has been studied to evaluate glued joints in timber structures (Bodig 2000; Maeva et al. 2004; Dill-Langer et al. 2005a).

Sanabria et al. (2011a) present a comprehensive review on non-destructive evaluation (NDE) methods used for

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the in-situ diagnosis of glued laminated timber members. These include computed tomography methods that can detect the absence of adhesive in wood composites (Hu and Gagnon 2007; Osterloh et al. 2008; Sanabria et al. 2011c) but are not suitable for application on site. Ultrasonics are easily portable and are sensitive to delaminated interfaces but, in the case of wood, the use of coupling agents like gel, grease or liquid may penetrate wood and change its surface properties. Dry contact is therefore preferred for glulam inspection (Dimanche et al. 1994; Dill-Langer et al. 2005a, b). The reproducibility is limited by the adjustment of the coupling pressure at each insonified position. Besides, ultrasonic imaging based on continuous transducer scanning is generally not possible. Air-coupled ultrasonics (ACU) may overcome these drawbacks, especially since developed transducers (Kunkle et al. 2006) and electronics allowed its use on thick structural members (Algernon et al. 2008).

Normal transmission air-coupled ultrasound and developed signal processing algorithms were successfully applied by Sanabria et al. (2011a) to detect bonding defects in multilayered glulam beam. Adhesive penetration in defect regions and non-adherent dry glue regions have also been assessed with this method (Sanabria et al. 2011c). Sanabria et al. (2011b) describe the application of ACU to assess lack of adhesive in glued solid wood. A longitudinal normal through-transmission measurement set-up and data evaluation based on voltage level measurements of recorded A-scans allow for the precise imaging of areas with and without adhesive due to the different acoustic impedance of the glue line in each case. The impact of the heterogeneity of wood structure in the amplitude measurements and the reproducibility of the ACU technique identifying the main sources of variation are analysed.

Senalik (2013) used X-ray computer tomography and acousto-ultrasonic measurements to detect and assess wood decay. A modified impulse-echo technique used in conjunction with a decay-rate analysis of the collected signals was able to detect and assess wood decay within a glulam beam even at an incipient stage. This inspection method requires access to only one side of the beam and its results are consistent with decay located using X-ray computer tomography. The decay-rate approach was found to lead to an overall rate of false calls of 7.2% (despite the wood variability due to the presence of splits, orientation and thickness of growth rings).

Garab et al. (2010) used ultrasonic wave propagation to determine crack depth in glulam beams, in addition to visual inspection. Velocity measurements perpendicular to the grain were found suitable for detecting hidden internal defects of glulam beams, particularly the crack depth. Besides, decayed areas in the cross sections could be mapped by stress wave velocity measurements perpendicular to the grain in the lamellae. The acoustic technique was found particularly useful to measure the real depth of cracks of irregular shape, where the feeler gauge is not able to penetrate the full depth. One limitation identified in that paper for this method was the presence of paint in the cracks. Similarly, it is expected that its application to detect and measure delaminated glue lines may be limited in the case of partially adherent adhesive.

Dietsch and Tannert (2015) discussed the feasibility and limitations of methods currently available to assess and map cracks (namely crack gauges, radiography and ultrasound-echo), glue type (visual inspection, boiling, spectral analysis) and strength of glue-lines, with emphasis on shear cores. These authors state that potential alternative options for the assessment and mapping of cracks [optical devices, laser scanning, the use of different stress wave based techniques, including ultrasound-echo-technique (UET), or radiography (X-ray)] require a straight crack of sufficient width. Shear waves and reflection measurements are suitable to assess small cracks or delaminations. The propagation of sound waves through material (stress waves) could prove promising with respect to assessing the integrity of glue-lines, since it can provide information on the distribution of interior defects. But not only some stress wave techniques are unsuitable for onsite inspections, as the exact location of defects may be difficult to establish and it may not be able to distinguish between one large defect and grouped small ones. Air coupled UET seems to be able to overcome some of these limitations.

However, disregarding their apparent integrity, shear strength of the glued lines must be assessed, as this is one key factor determining the strength of glulam members.

The biggest drawback of non-destructive techniques to predict the strength of timber structures is the relatively low correlation between the non-destructive parameters and the strength of the material (Kasal and Anthony 2004). Complementing non-destructive techniques with a semi-destructive evaluation can increase confidence in the assessment of the material strength and stiffness (Kasal et al. 2003). In semi-destructive techniques, a small sample is removed from the member and subsequently tested, and the specimen size is sufficiently small so that the decrease in the strength of the structure is negligible. The extraction and subsequent test of cores is an example of this approach. The extraction of cores from wood structures in service allows obtaining small-size specimens for testing the glued joint without compromising the strength of the structure.

The strength assessment of glued joints is commonly performed by shear tests according to standard EN 14080 (2013), a test usually applied to the quality control of glued joints of laminated timber elements after manufacture or in service.

The European Standard EN 14080 (2013) specifies that the test pieces may have the form of a test block (test piece of rectangular right-angled prismatic form, Fig. 1a) or of a drilled core (35 mm diameter cylindrical specimen drilled out from the face of the element, Fig. 1b). It is assumed that in practice the first type of specimen is removed from the ends of the elements, after manufacture, while drill cores are most suitable for testing glued joints of structures in service, allowing the extraction in any section of the element to inspect. Additionally, the removal of test block pieces from structures in service is rarely possible unless part of the structure is seriously damaged or is to be removed from the structure.

According to EN 14080 (2013), the drilling of glued laminated timber element to extract cores with approximately 35 mm diameter should be done perpendicular to the face in such a way that the glued joint is located in the middle of the core. The specimen is then machined to provide a flat surface perpendicular to the glued joint, where load is applied, resulting in a rectangular shearing area (Fig. 1b). In both cases, test specimens are loaded in the direction of the grain.

These core specimens can be used to derive the local shear strength of glue lines. However, since the quality of glue lines may vary significantly within and between members and only one glue line is assessed in each drilling, multiple specimens must be taken to get global estimates (Tannert et al. 2012). In addition, it needs machining to produce two parallel faces for load application.

Test specimens with the glue line perpendicular to the axis of the drill core are also specified by EN 14080 (2013) for assessing glue lines between glulam components of block glued glulam (Fig. 1c, d).

For in-situ evaluation, smaller test specimens may also be drilled perpendicular to the glue lines, reaching several glue lines with minimal impact on the strength of the member to be inspected. Such alternative drill cores may also be tested with their cylindrical shape, thus avoiding extra time and cost consuming operations.

This technique has been used to determine physical properties of wood and other materials (Kasal and Anthony 2004) and various types of cylindrical specimens were proposed. During inspection of wooden bridges, it is usual to extract cores of diameter not exceeding 20 mm (using equipment driven manually or by electric power) to detect biological attack or to measure the depth of preservative treatment (Ross et al. 2005). Selbo (1962) and Outinen and Koponen (2001) applied this method to measure the shear strength of glued joints of laminated timber.

With the purpose of evaluating glued joints of structural members in service, Selbo (1962) successfully developed the drilling equipment (corer) and the shear test device at

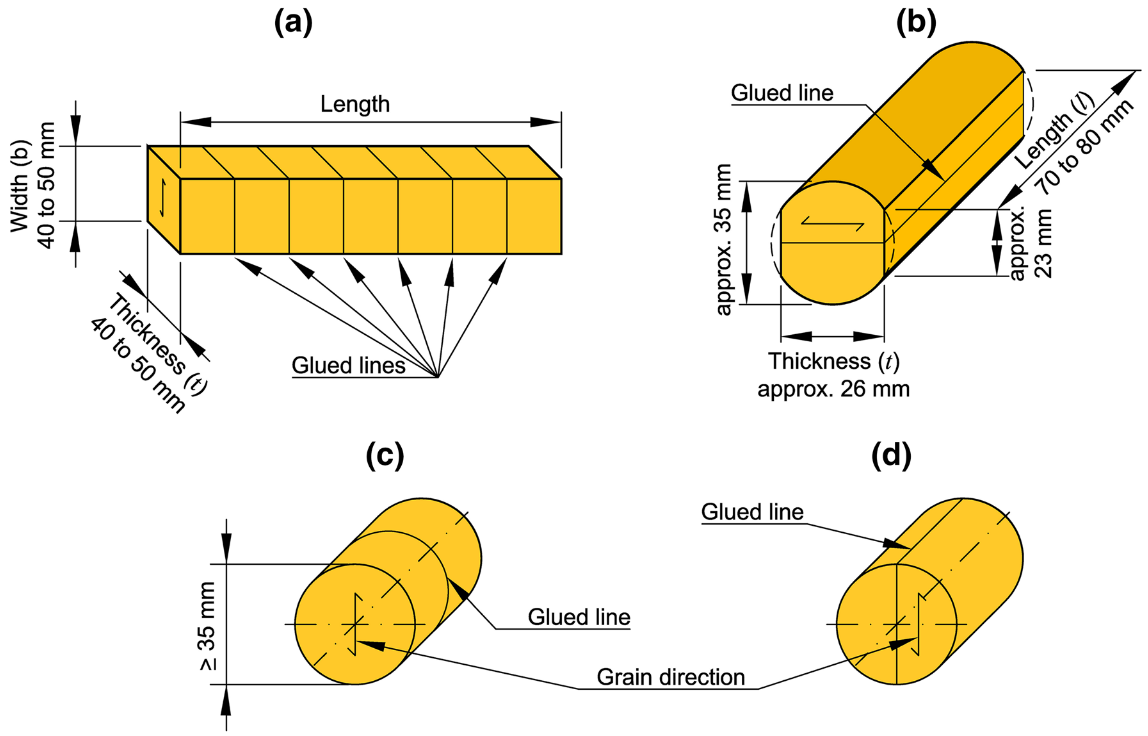

Fig. 1 Specimens for the shear test of *glued lines* according to EN 14080, for glulam and glued solid timber: **a** block specimen, **b** drill core with machined parallel plane surfaces; and for *glued lines* between glulam components of block glued glulam: **c** *glued line* perpendicular to the axis of the drill core, **d** *glued line* parallel to the axis of the drill core

Forest Products Laboratory and evaluated the shear strength of glue lines of cylindrical specimens with a diameter of about 25 mm extracted perpendicularly to the glue lines. The cores were cut in a drill press trying various corer and cutting speeds. Good results were obtained on laminated Douglas-fir (*Pseudotsuga menziesii* Mierbel Franco) and southern pine using 295 rpm and cutting velocities between 0.5 and 2.5 mm/s. Reasonable results were obtained for corer speeds of 475, 715 and 870 rpm at the same cutting velocities. However, above 870 rpm wood starts to burn. The glue lines shear strength obtained on Douglas-fir glulam is somewhat lower (between 0 and 14%) than the one obtained with the standard block specimen of ASTM D 905 (1994) with a shear area of 50.8 mm×38.1 mm. Selbo (1962) also concluded that the tolerance required in the shearing tool hole, to insert the specimen, significantly affected the tests, resulting in less pure shear. Because of this tolerance, together with the compression of the wood under the shear members, the axis of the specimen and the axis of the cylindrical holes into which the specimen is inserted will be at a slight angle with each other at the time of failure. A double action at the glued joint, consequently, will occur that exerts a certain amount of tension perpendicular to the joint. Since wood is weaker in tension perpendicular to the grain than in shear, this double action could contribute to the lower shear values obtained with the cylindrical specimen. However, the results indicated that this method is sufficiently promising to test glued laminated timber members in service.

Outinen and Koponen (2001) also made successful experiments with 32 mm diameter drilled shear specimen. In this case, the objective was to develop a faster method, compared to the block-shear test, to assess the shear strength of glue lines for production quality control. These authors tested drilled specimens, extracted perpendicularly to the glue lines: (a) after notched, in an identical device used for block specimens; and (b) not notched, in a special device with round holes. Ageing of the specimens was also done, following either standard ASTM D1183 (2003) (treatment c) for block specimens or standard EN 391 (2001) for drilled shear specimens. Shear strength values of drilled specimens were higher (30–70%) than the results of traditional block specimens. Ageing according to ASTM D1183 (2003) reduced the shear strength of block specimens by about 20% and ageing according to methods A and C of EN 391 reduced the shear strength of drilled shear specimens by about 19 and 10%, respectively.

Previous works conducted by the authors aimed to assess the ageing effects on the glued lines shear strength and delamination as well as chemical degradation of various glued laminated timber products available on the market, as compared to glulam produced from untreated or preservative treated maritime pine timber (Gaspar et al. 2009, 2010a). The research program presented here included the production and ageing of glulam members of several types and the assessment of their glued lines, using blocks and drill cores extracted and tested as described below. Special attention was given to cores extracted perpendicular to the glued joint. Of main concern were the practical feasibility of core drilling and testing, and the verification of size effects in the case of block specimens to assess glued lines strength according to the standard EN 14080 (2013), as it does not take into account the species influence, evaluating its applicability to maritime pine timber glulam.

2 Materials and methods

2.1 Materials

This work focuses on glued laminated timber beams made of spruce (*Picea abies* H. Karsten) glued with Phenol-Resorcinol-Formaldehyde (PRF) and Melamine-Urea-Formaldehyde (MUF) type adhesives, and maritime pine (*Pinus pinaster*, Ait.) glued with a PRF adhesive. The test program included maritime pine (MP) timber with a deep preservative treatment, made prior to bonding, with Tanalith E 3492 to a target retention suitable for weather exposure with or without ground contact [use class 4, EN 335 (2013)], followed by kiln drying.

A first group of 12 glulam beams was used to check the influence of the block specimens' size on the shear strength in comparison with the modification factor specified in EN 14080 (2013). From these 12 beams, 6 were of spruce wood, 2 were of untreated maritime pine and 4 were of maritime pine preservative treated as mentioned above. These beams underwent no weathering/ageing.

The spruce beams, acquired from a glulam manufacturer, were glued with a PRF type adhesive, with two different cross sections. Four of them had three lamellas and cross section of 0.08 m×0.13 m (width×height) and the other two had 5 lamellas and cross section of 0.09 m×0.23 m (width×height).

The maritime pine beams were glued in a glulam manufacturing plant, with a PRF type adhesive currently used in the glulam factory according to the manufacturer instructions, having 5 lamellas and cross section of 0.08 m×0.15 m (width×height). The manufacture was done by curing at room temperature (18 °C on average), for 24 h.

A second group of glulam beams was used to compare the shear strength on block and core specimens and evaluate the performance of the cores extracted perpendicular to the glued lines.

This group involved 21 glued laminated timber beams of maritime pine, 10 of which were glued after a copper azole preservative deep treatment. Maritime pine was glued in laboratorial environment with a PRF adhesive to produce 6 lamella beams with 0.115 m × 0.2 m × 1.5 m. Prior to gluing (less than 6 h from adhesive spreading) each lamella was planed to obtain a suitable surface for bonding. The adhesive was mixed according to the manufacturer's instructions by a mechanical process, so as to obtain a homogeneous mixture, and then applied with an adhesive comb, at a spreading rate of 500 g/m^2. Clamping pressure of 0.76 MPa was applied to the beams for 24 h in a conditioned environment at 20 °C. After this period, the beams were conditioned in a standardized environment (65 ± 5% relative humidity, 20 ± 2 °C) until equilibrium moisture content, and then planed on side faces to the final dimensions.

The total number of spruce beams was 18, eight of which were glued with a MUF adhesive (0.12 m × 0.24 m × 1.50 m), and the other ten beams were glued with a PRF adhesive (eight with 0.08 m × 0.13 m × 1.50 m, and two with 0.09 m × 0.225 m × 1.50 m). These beams were bought from a glulam manufacturer.

As the use of core specimens is intended for the evaluation of structures in service, this experimental work was done over aged material using the second group of glulam beams. Natural and artificial weathering was applied to beams of all types. For natural weathering, the beams were exposed to the weather during 3, 6, 9, 15 or 21 months.

The beams were put on a fully exposed rig placed on a flat roof of the Polytechnic Institute of Leiria, spaced from each other, and placed about 0.9 m above ground and oriented so that one of the vertical faces was facing South. A transparent protection coating was applied to all surfaces, as recommended in practice, to prevent premature degradation. During the natural exposure, the climatic data was registered, obtaining average annual temperature of 15.6 °C, varying from −3.1 to 40,1 °C, and average relative humidity of 75% (being 85% in the most humid month), and annual average rainfall was 541 l/m^2, with 151 l/m^2 in the most rainy month. The maximum moisture content measured on glued laminated timber beams made of spruce, untreated maritime pine and treated maritime pine was 19.8, 27.1 and 31%, respectively.

Artificial weathering was conducted in a climatic chamber Fitoclima, imposing one or three ageing cycles, each one composed of a humid cold (95% RH, 15 °C) period during 4 weeks followed by a dry hot (30% RH, 45 °C) period during 4 weeks. The moisture content measured in the three wood types was similar over the time, ranging between 6 and 17%.

After the ageing period, some beams exhibited visible delamination, however, specimens were extracted where no visible delamination was present.

2.2 Equipment and procedure for core extraction and testing

Within the scope of this research program, an experimental campaign was first carried out involving the development and testing of suitable drilling tools. A shearing tool for testing both prismatic and cylindrical specimens was also developed.

2.2.1 Cutting tool (corer) and drilling procedure

Owing to the fibrous structure of wood, extraction of high quality cores is difficult because friction between the corer and the core surface may lead to shear failure while drilling (Kasal and Anthony 2004). Good corers should not leave marks or torn grain on the specimen surface.

The size of the corer is critical. Although lower diameters have less impact on the structure, such cores are difficult to extract successfully because of friction between the corer and the core surface, and lateral motion (that increases with the drilling speed), which is detrimental to the core surface smoothness and may lead to its premature breaking. Additionally, larger diameters are expected to give less variability between individual shear test results, because for bigger specimen, larger amount of material is tested, which is more representative of the wood material. In other words, if lower diameter is used, there is a greater risk of the small specimens being unusual.

A corer was developed, aiming at a quick and easy extraction of the core with minimal lateral motion, as there was not such a commercial tool available with the required length. Suitable cores were extracted with a corer obtained by extending in length a commercial core drill of about 140 mm × 25 mm in diameter (Fig. 2).

It was observed that lateral motion may be reduced if the drilling shank and the corer tube are tightly connected, preferably by soldering or threading. In addition, the core surface quality is improved with increased drilling speed. However, excessive warming can cause burning of the wood, especially for long cores, namely for speeds above 1450 rpm; refrigeration with compressed air helps to reduce warming while cleaning corer and hole, allowing a discontinuous drilling operation—although cutting speeds below 700 rpm gave no warming problems. Tests made on spruce beams showed increased smoothness of the core surface for increased density.

Fig. 2 Corer

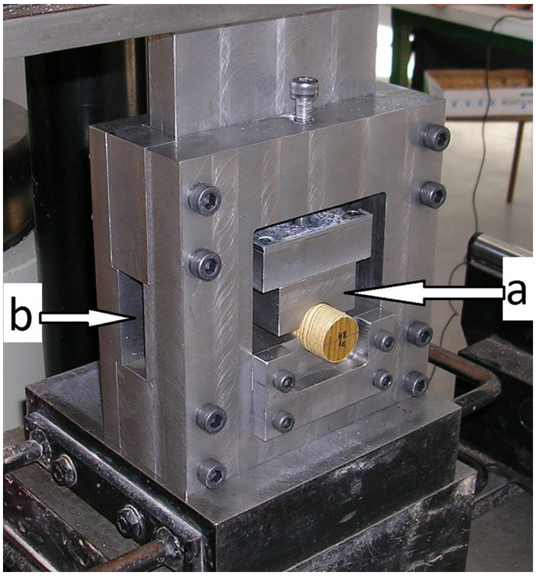

Fig. 3 Core shear testing device: **a** locking part, **b** visual access

Table 1 Block-shear specimen types extracted from the first group of beams

Specimen name	Shear area (mm × mm)	Number of specimens
B20	20 × 20	107
B35	35 × 35	74
B50	50 × 50	56

2.2.2 Shear device and testing method

A shearing device was developed to allow for testing cylindrical specimens, by having grooves of the same diameter of the core on both the loading and locking parts. Additionally, visual access to the shear plane was possible from the sides of the test device (Fig. 3), a necessary condition to ensure correct positioning of the specimen. In addition, the loading part of this device has a self-aligning cylindrical bearing so that the test piece is loaded at the end grain with a stress field uniform in the width direction, as stated in EN 14080 (2013). This shear device was also designed so that it could test block shear specimens, by removal of the locking parts with the cores shape.

Shear tests were performed according to EN 14080, for all specimen types, with mean test duration of about 60 s, complying with the minimum required 20 s. The glued line shear strength was measured by establishing the device shear plane at a maximum distance of 1 mm from the glued joint plane. The shear strength of the lamellas was also measured by establishing the shear plane approximately at half the thickness of each lamella. Specimens were conditioned until equilibrium prior to testing (20 °C, 65%RH).

When testing cylindrical specimens, the specimen diameter accuracy is of utmost importance, not only to compare test results, but also to guarantee fitting between the core and the shearing tool, needed for uniform pressure to be applied to the shear surface.

While the determination of wood failure percentage (WPF) of glued joints with phenol-resorcinol-formaldehyde (PRF) is facilitated by its distinct color, this is not easy for melamine-urea–formaldehyde (MUF). In the latter case, a pH indicator was used, which proved to be adequate for this purpose in glues of urea–formaldehyde, melamine–formaldehyde and melamine-urea–formaldehyde due to the different coloration obtained between wood and glue (Dibuz and Shelton 1967; Gibson and Krahmer 1980; Künniger 2008).

2.3 Extraction of block and core shear specimens

EN 14080 (2013) establishes a relationship to take into account the effect of the size of the specimen on the glued joint shear strength. For both types of specimens (blocks or cores extracted parallel to the glued joint - Fig. 1), the shear strength (f_v) shall be determined as follows:

$$f_v = k\frac{F_u}{A}, \tag{1}$$

where F_u is the failure load (N); A is the sheared area ($b \times t$ for a test block and $l \times t$ for a drill core, in mm^2); t is the thickness in the grain direction (mm); b and l are the dimensions of the sheared area perpendicular to the grain direction, for blocks and cores, respectively (mm); k is a modification factor for test pieces where the thickness in the grain direction of the sheared area is less than 50 mm: $k = 0.78 + 0.0044 \times t$.

The modification factor k is equal to the unit for specimens with thickness equal to 50 mm, decreasing for lower dimensions.

To study the influence of the block specimens' size on the shear strength (first group of beams) tests were made on block-shear specimens of three different shear areas mentioned in Table 1. Figure 4 shows how the specimens had been cut from each beam.

To compare the shear strength on block and core specimens (second group of beams), block and core shear specimens were extracted from each beam, as indicated in Table 2. Block shear specimen types B50 (Fig. 5a) and B20 were used, cores extracted perpendicular to the glue lines had final diameter of 25 mm (C25—Fig. 5b) and length equal to the height of the beam, and the cores parallel to the glued lines were 35 mm in diameter (C35—Fig. 5c) after extraction, as specified in EN 14080

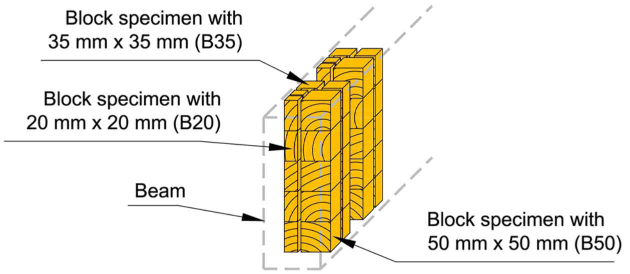

Fig. 4 Sampling plan for the first group of beams

Table 2 Block and core shear specimen types extracted from the second group of beams

Specimen name	Specimen type	Shear area		Number of specimens[a]
		Shape	Dimensions (mm)	
B20	Block	Square	20×20	2 or 3
B50	Block	Square	35×35	1 or 2
C35	Core	Square	26×55	2, 4 or 10
C25	Core	Circle	25	2 or 3

[a] Number of specimens by each beam part (2, 5 or 6 parts according to each beam length), depending on the size of the cross section

(2013), about 55 mm in length and had a shear area of 26 mm × 55 mm after the machining process.

Figure 6 shows a scheme of the extraction of shear specimens. The beams were divided into five or six parts (according to their length), and from each part, depending on the size of the cross section, the number of specimens were extracted as mentioned in Table 2. For the artificially aged beams the process was similar, but in this case the beams were divided in two parts, and the specimens were extracted as shown in Fig. 6, except for specimens B20 that were not considered in this case.

3 Results and discussion

3.1 Influence of the block specimens' size on the shear strength

Maritime pine glued lines exhibited higher shear strength than spruce glued lines (Table 3), agreeing with Frihart and Hunt (2010) who indicated a growing glued joint strength with wood density up to 0.7–0.8, decreasing for densities above this limit. For very high density, the low penetration of adhesive into the wood determines lower wood failure percentages and lower glued joint strength.

Regarding the preservative treatment effect, these results show that preservative treated maritime pine produced stronger glue lines than untreated maritime pine. This seems to be related to the higher wood shear strength in the case of preservative treated wood samples.

Regarding size effect, shear strength of both wood and glue lines was found to decrease with the increase of specimen dimensions, as could be expected from Eq. (1), and confirmed by the ANOVA test (at 5% level), accompanied by an increase in the dispersion of values due to reduced shear area (Table 3). The influence of specimen size on glued lines' shear strength is higher for untreated maritime pine wood, lower for treated maritime pine, and much lower for spruce, as the average modification factor (k—ratio between the glued lines' shear strength of B50 and the other specimen types (B35 or B20)) is significantly (at 5% level) different with the specimen dimension (Fig. 7). In the case of treated maritime pine, a lower correlation was found between glue line and wood shear strength (Table 3), together with a lower wood failure percentage than that obtained for the other wood types, suggesting a lower performance of the treated maritime pine glued lines.

The wood failure percentage is similar for the three specimen dimensions. The correlation between the strength of the glued joint and the average strength of the two adjacent lamellae is generally higher for smaller specimens

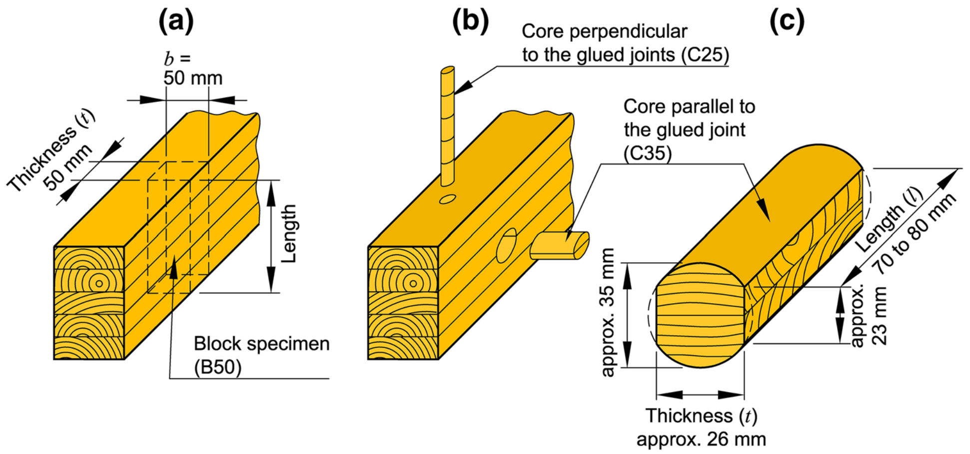

Fig. 5 Specimens used in the study: **a** block specimen, **b** cores (parallel and perpendicular to the *glued lines*), **c** preparation of 35 mm cores according to EN 14080

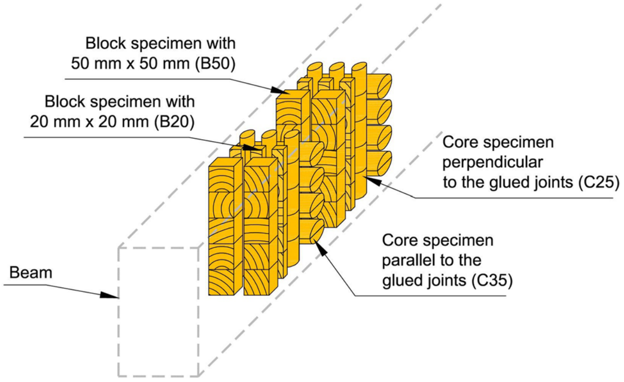

Fig. 6 Extraction of shear specimens from the beams

Table 3 Results of block-shear specimen tests

Glulam type	Specimen type	Glued line shear strength			Average wood failure percentage (%)	Wood shear strength			Correlation[a]
		No. of values	Average (MPa)	Standard deviation (MPa)		No. of values	Average (MPa)	Standard deviation (MPa)	
Untreated maritime pine	B20	104	15.9	2.2	89	133	16.5	2.5	0.41
	B35	49	14.4	1.7	91	60	15.9	2.3	0.21
	B50	41	12.7	1.3	86	64	13.3	2.1	0.31
Spruce with PRF	B20	106	11.3	1.8	87	163	12.4	2.6	0.30
	B35	60	10.8	1.2	88	99	11.8	2.4	0.09
	B50	43	9.8	0.9	90	68	10.8	2.0	0.23
Treated maritime pine	B20	72	16.5	2.3	78	103	17.5	2.1	0.12
	B35	36	14.6	2.3	73	79	16.8	1.9	0.10
	B50	30	13.5	2.1	72	51	16.4	1.4	0.03

[a] Correlation coefficient of the regression line between glue line shear strength and wood shear strength

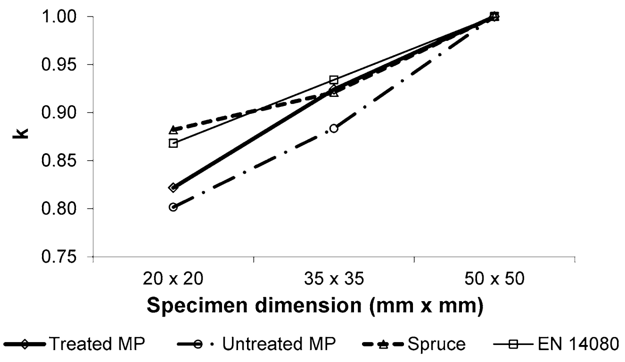

Fig. 7 Results of the average k factor for block-shear specimen tests

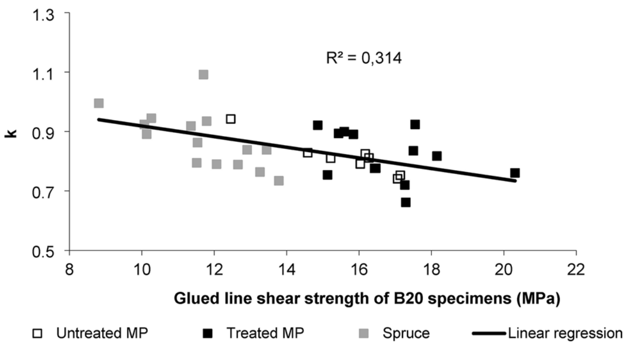

Fig. 8 Decrease of the modification factor k with the strength of the glued joint for 20×20 mm^2 specimens

(20×20 mm). The reason for this may reside in the largest number of results that are available for this size of specimen, as sample size affects the correlation coefficient as suggested by Green et al. (1984).The average increase of the modification factor (k) observed for spruce specimens seems to confirm the values proposed in EN 14080 (equal to 0.87 for 20 mm thickness specimens). However, for maritime pine the k values should be lower. For 20 mm thickness specimens the modification factor found was 0.82 and 0.80 for treated and untreated maritime pine, respectively, indicating that the influence of the size of the specimen is not constant over the entire strength range. In fact, the modification factor (ratio between the glued lines' mean shear strength of B50 and B20 specimen types for each glued joint of each beam) decreases with the increase of strength (Fig. 8), where a significant correlation was confirmed by the 2-tailed t test (at 5% level). For 35 mm specimens a similar trend was obtained.

3.2 Comparison of block and core specimens

The results obtained for the second group of (aged) beams are presented in Table 4.

Table 4 Shear strength test results for aged specimens

Glulam type	Specimen type	Glue line shear strength (SG)			Average wood failure percentage (%)	Wood shear strength (SW)		
		No. of values	Average (MPa)	Standard deviation (MPa)		No. of values	Average (MPa)	Standard deviation (MPa)
Untreated maritime pine	B20	301	15.4	1.9	84.6	327	15.5	2.2
	B50	408	13.8	1.5	84.7	345	13.8	1.9
	C35	296	14.5	1.6	78.5	–	–	–
	C25	522	13.9	2.3	82.3	579	14.9	2.3
Treated maritime pine	B20	165	14.0	1.9	77.5	210	14.1	2.5
	B50	291	12.4	1.5	77.5	335	13.6	2.3
	C35	216	12.8	2.1	70.3	–	–	–
	C25	420	11.8	2.6	70.7	518	14.4	2.4
Spruce with MUF	B20	189	10.8	1.8	82.1	227	11.4	2.0
	B50	288	9.9	1.6	77.8	277	11.3	1.6
	C35	185	9.0	1.8	79.2	–	–	–
	C25	363	10.0	1.7	83.6	447	11.6	1.7
Spruce with PRF	B20	108	10.0	2.2	81.1	167	10.3	2.3
	B50	115	9.3	1.5	83.9	154	10.6	2.2
	C35	93	9.5	1.5	76.6	–	–	–
	C25	174	8.8	2.0	77.8	230	10.6	2.2

For aged untreated maritime pine, the average wood strength of the specimen type B50 (13.8 MPa) is equal to the glued joint (Table 4), whereas in the unaged material (Table 3) the average glued joint strength (12.7 MPa) is lower than that of wood (13.3 MPa). These unaged beams were manufactured at variable curing temperatures (average of 18 °C) in a factory environment, while the second group of beams were produced in the laboratory for this study, where the curing temperature was kept constant (20 °C) and the procedure used to prepare and to apply the adhesive could lead to an improvement in the quality of the glued joint, as Gaspar et al. (2010b) obtained a beneficial effect of curing temperature on the glued line performance. In all the other glulam beams, the shear strength of wood is always higher than the shear strength of the corresponding glued joints.

For test specimens B20, B50 and C25, the higher shear strength obtained both in the wood and in the glued joint of spruce wood glued with MUF adhesive as compared to the spruce beams glued with the PRF adhesive, may be explained by the higher average density of spruce wood glued with MUF adhesive (473 kg/m^3) than in the case of spruce glued with the PRF adhesive (449 kg/m^3).

The wood failure percentage (WFP) is lower for the treated maritime pine than for the other beams, confirming the lower performance of this type of joints (Gaspar et al. 2010b). For both block type specimens tested, the WFP obtained on maritime pine (treated and untreated) are similar, whereas in spruce specimens, the WFP differences between B20 and B50 may be due to slight differences in the density of the specimens. No changes were identified in the WFP due to the type of specimen.

The strength of the glued joint is highest for the untreated maritime pine, followed by the treated maritime pine, spruce with MUF adhesive and spruce with FRP adhesive, following the trend of the wood strength, for all specimen types. The dispersion of the results is higher for specimens B20, C35 and C25 than for specimens type B50, similarly to that observed with the first group of beams (Table 3).

The correlation between the mean strength values for each specimen type and same glued joint of each beam gave significant values as was confirmed by the 2-tailed t test (at 5% level), appearing that core specimens perpendicular to the glued lines are suitable to measure the glue line strength (Table 5).

The observed decrease in the correlation coefficient, from 0.79 to 0.69 (Table 5) between the B50 specimens and the other three types (B20, C25 and C35), seems to be caused by the sampling method used (Fig. 6), because the correlation decreases as the distance between specimens increases as a consequence of the natural variability of the wood. However, the correlations are significant between specimen types, which means that a comparison between the different specimen types can be done to evaluate their relation, as will be done in the following sections.

Table 5 Correlation coefficient between the glued line shear strength of the various types of specimens

Type of specimen	Type of specimen			
	B50	B20	C25	C35
B50	1	0.79	0.75	0.69
B20		1	0.86	0.85
C25			1	0.83
C35				1

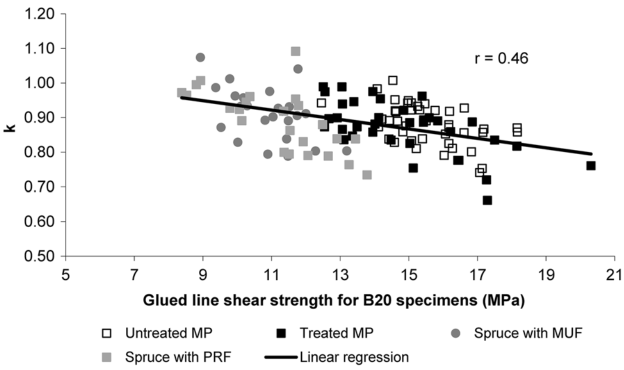

Fig. 9 Decrease of the modification factor k with the strength for B20 type specimens (aged and non-aged)

3.2.1 *Block specimens*

Similar to what was done for samples obtained from unaged beams, the comparison between the results obtained with both types of test block (B50 and B20) was performed using the average shear strength values of each joint of each glued beam (resulting from the five or six beam parts) for each specimen type. So the mean strength obtained is representative of the overall length of each beam. These results, together with those of the non-aged specimens (Fig. 8) are presented in Fig. 9, confirming that the modification factor (k—ratio between the glued lines' shear strength of B50 and B20 type specimens) decreases with increasing strength. Despite the modification factor proposed by EN 14080 (0.87 in this case—see respective line in Fig. 10) be, on average, acceptable, as confirmed in this work where a similar coefficient was found using linear regression analysis (0.8737—Fig. 10), it was concluded that, for a more precise analysis of the results, the k factor should be adapted to the level of strength.

Thus, the modification factor (k) would better reproduce the results by using a function of decreasing slope, as for example the quadratic function shown in Fig. 10 with which a significant and higher correlation coefficient was obtained (0.89) compared with the linear regression analysis (0.86).

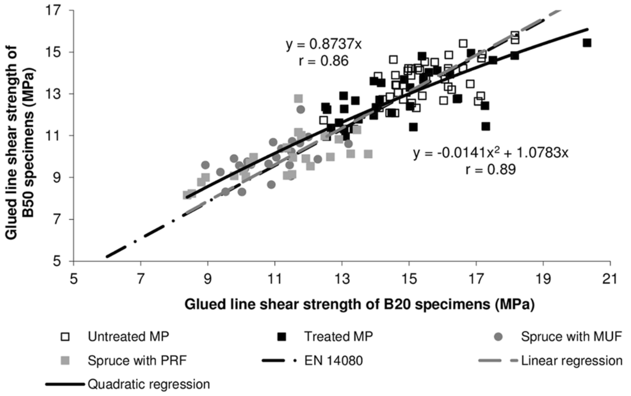

Fig. 10 Correlation between *glued line* shear strength for B50 and B20 specimens (aged and non-aged)

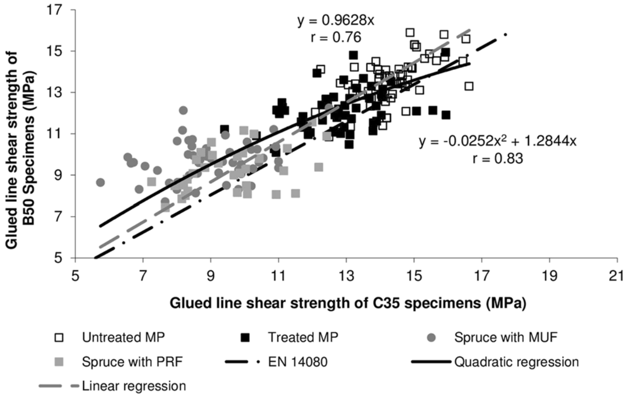

Fig. 11 Relation between *glued line* shear strength for B50 and C35 specimens

3.2.2 *Core specimens*

Similarly to the results obtained with test specimens B20, for C35 cores the modification factor (ratio between the glued lines' shear strength of B50 and C35 type specimens, in this case) also decreases with increasing strength. The quadratic function also provides a better fit to the results (correlation coefficient of 0.83, Fig. 11) than the linear regression. The modification factor proposed by EN 14080 (0.89 in this case—see respective line in Fig. 11) was not much different from the one obtained in this work using linear regression analysis (0.9628—Fig. 11). The adjustment of the quadratic function to group results separated by retention level and wood species (untreated maritime pine, treated maritime pine, spruce with MUF and PRF) showed that in all cases the amount of variance explained by the model is significant (at 5%, 2-tailed test), however the correlation coefficient is higher when adopting all results.

As observed in Table 4, the dispersion of strength and the difference between the wood and glue line shear strength for C25 specimens are always larger than for block specimens B50, and generally also larger than C35. The main cause for this could be the way specimens are obtained, as the C25 cores' surface quality after extraction is worse than that obtained in the other specimen types. Surface quality of C25 type cores is worse because they are obtained by drilling, although the other specimens types are obtained by sawing or machining that is expected to give better surface quality. During the experimental work it was also observed that core surface quality improves with increased drilling speed and for increased density. Besides, smaller specimens are also likely to give higher dispersion of test results.

The modification factor (k) for C25 shows the same trend as that found in the previous two types of test specimens (C35 and B20). The correlation coefficient obtained with the quadratic function between the glued line shear strength of specimens C25 and B50 is equal to 0.79 (Fig. 12), as significant as in the previous specimen types, whereas for the linear regression adjustment the correlation coefficient is 0.71.

The results obtained in this study for C25 type specimens give an average shear strength varying from −10 to +30% of B50 type specimens strength, using the quadratic function adjustment. Selbo (1962) used a core of the same diameter and compared the shear strength decrease with the standard block specimen of ASTM D 905 (1994) which has a lower shear area (50.8 mm × 38.1 mm) than B50, what seems to partially justify the decrease obtained (between 0 and 14%). In addition, problems were reported in obtaining pure shear attributed to the tolerance required in the shearing tool hole to insert the specimen, showing to significantly affect the tests, what would lead to a decrease in the shear strength. Outinen and Koponen (2001) obtained 30–70% higher strength than the results of traditional block specimens (B50). In this case, a 32 mm diameter drilled shear specimen was used that seems to justify the higher shear strength obtained.

The results obtained on C25 cores (perpendicular to the glued joint) show that these specimens are apparently suitable to evaluate the glue joint shear strength, given that the correlation with the results of the other types of cores is significant.

3.2.3 *Variability of the modification factor*

Figure 13 shows the variation of the modification factor (size effect) with the shear strength, for each specimen type, based on the quadratic regressions referred to above. It is observed that this variation is similar for core type specimens C25 and C35, and slightly less important for specimens B20. When shear strength is around 15 MPa, the values obtained for the modification factor are similar to the values given by the standard EN 14080 (0.89 for C35 specimens and 0.87 for B20 specimens). However, the difference between the modification factors obtained in this study and the one suggested by EN 14080 increases as much as the material shear strength differs from 15 MPa, leading to unsafe corrections in the case of stronger glued joints.

4 Conclusion

For a successful extraction of cores, appropriate corers should be used and drilling procedures should be adjusted, to provide samples with satisfactory surface quality.

As expected, the study carried out confirmed the influence of specimens shape and size on shear strength with modification factors (k) similar to that suggested by EN 14080 if a linear relation is considered between the

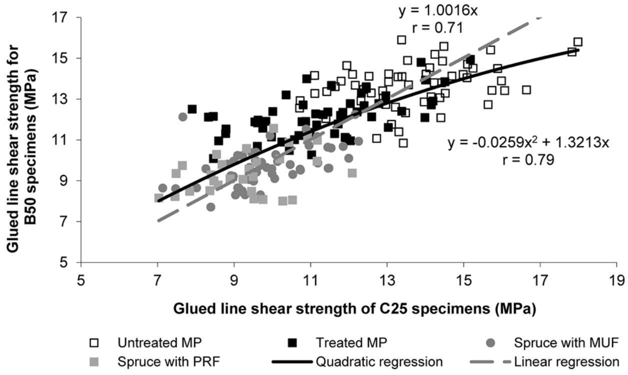

Fig. 12 Relation between *glued line* shear strength for B50 and C25 specimens

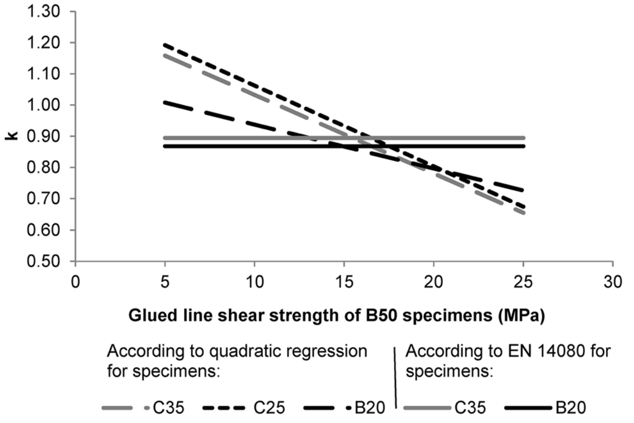

Fig. 13 Comparison between the k values variation obtained in this work and the one proposed in EN 14080

reference block specimen (50 mm × 50 mm shear area) and other specimen types considered (block specimen with 20 mm × 20 mm shear area and core specimen parallel to the glued line with 26 mm thickness). However, it was found that this influence varies with the material strength range. Therefore, the modification factor to account for specimens other than the reference block specimen should take the shear strength level into account. The results found in this work point out a decreasing modification factor with the increase of strength for all specimen types considered, including the core specimen perpendicular to the glued line with 25 mm diameter. When shear strength is around 15 MPa, the values obtained for the modification factor are similar to the values given by EN 14080. However, the difference between the modification factors obtained in this study and the ones suggested by EN 14080 increases as much as the material shear strength differs from 15 MPa, leading to unsafe corrections in the case of stronger glued joints.

The extraction of cores perpendicular to the glued joint provides an alternative way to measure the strength of glued joints and timber suitable for the health assessment of glued laminated timber members in service. In addition, the cores extracted perpendicular to the glued lines allow for testing more than one glue line with the same core, with a reduced amount of material removed from the element to be inspected.

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