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Grading of Sardinian Pine for use as Cross Laminated Timber

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Abstract

In Italy, timber and wood-based products are increasingly used in construction due to their outstanding physical and mechanical properties. Design codes require the use of graded wood. This paper presents the preliminary results of an experimental programme aimed to explore the possible use of Sardinian timber as structural material. For this purpose, locally grown Maritime Pine boards were visually graded and tested to destruction. Physical (density, knots, grain deviation, annual ring width, moisture content, etc.) and mechanical (modulus of elasticity, tensile strength, ultrasonic velocity) properties were measured and are reported in this paper. Four-point bending tests were also carried out on Cross Laminated Timber panels made of the previously tested wood. The results demonstrate that it is possible to use Maritime Pine locally-grown in Sardinia to produce Cross Laminated Timber panels for use in construction.

Notation

A	is the knot parameter of the boards
ω	is the annual rings width of the boards
V	is the ultrasonic velocity of longitudinal stress waves through the boards
ρ	is the density of the boards
u	is the moisture content of the boards
E_{dyn}	is the dynamic modulus of elasticity of the boards
$E_{t,0}$	is the modulus of elasticity in tension of the boards
E_{glob}	is the global static modulus of elasticity of the boards
E_{loc}	is the local static modulus of elasticity of the boards
f_t	is the experimental tensile strength of the boards of the boards
F_{max}	is the failure load of the CLT panels
f_m	is the experimental bending strength of the CLT panels
$f_{m,CLT,k}$	is the characteristic bending strength of CLT panels
$f_{t,0,l,k}$	is the characteristic tensile strength of the boards

1. Introduction

Timber is a renewable and sustainable material and it is being increasingly used in construction due to its outstanding mechanical properties, including low density and high strength-to-weight ratio. The possibility of prefabrication, the reduced environmental footprint due to the segregation of CO_2 from the atmosphere, and the affordable construction are further advantages for using timber (Buchanan and Honey, 1994). Moreover, timber has the advantage of being aesthetically pleasing, and therefore it is often chosen for creating a warm and pleasant living environment. In Italy, the development of timber structural systems has also been fostered by the introduction of timber as building material in the new Italian Building Code (Technical Rules for Construction, 2008). However, most of the timber currently used in Italy and around the Mediterranean is imported from outside this area, often from countries which are far away (Austria, Germany, Russia).

In this framework, the idea of a short procurement chain based on the use of locally-grown timber would certainly meet the need of sustainability. The reduction of energy consumption due to transportation, the increase in CO_2 sequestration, the improvement of landscape and the reduction of hydro geological hazard would all contribute to a better environment. Furthermore, it would positively bring ecological, social and cultural advantages, such as a better forest management and new job opportunities related to timber production, processing and construction. These aspects are crucial in underdeveloped regions such as Sardinia (Italy), and this is one of the main reasons why Sardinian public agencies are funding some research projects aimed to explore the possibility of using locally grown timber as structural material (Fragiacomo et al., 2015).

Sardinian traditional buildings have been long characterized by the use of stone and masonry for the walls. Timber was generally used in roofs and finishes. However, local administrations are now promoting its use in construction due to its environmental benefits. In particular, Sardinian local governments have already started the construction of some housing blocks in Cross Laminated Timber (CLT) panels made of wood imported from abroad.

Sardinian wood is generally characterized by low quality due to the presence of defects (knots, clusters of knots, resin pockets, grain deviation etc.), thus its use in some wood-based products such as Glue Laminated Timber (GLT) would be not technically viable. The goal of this research is to produce structural elements of medium quality starting from a low quality timber, and GLT does not satisfy this criterion. Conversely, CLT meets this requirement due to its manufacturing process and specific layout. CLT is a wood-based product formed using small sections of timber boards finger jointed and glued together and arranged in orthogonal layers. One of the main advantages of this production process is that the lamination effect reduces the scatter of the board properties, and therefore the negative influence of their defects. The crosswise orientation of the board layers results in a composite plate element with similar in-plane mechanical properties, unlike GLT which has excellent mechanical properties in the board direction and poor mechanical properties in the other directions. With this technique, medium/high quality structural members can be produced using low/normal quality timber. As an example, Smith (2011) proposed a prefabricated cross laminated solid wood wall and roof panel made of 2-7 layers of alternating direction pine stock milled from waste wood. Since the type of wood used in the CLT affects the panel strength in bending and shear, Design Codes require the use of wood previously graded according to UNI EN 338 (2009), UNI EN 14081-1 (2011) and UNI EN 16351 (2015).

This paper presents the preliminary results of a research project aimed to explore the possible use of Sardinian timber as structural material in CLT panels. The project is founded by Sardinian local administration and involves an experimental programme carried out on Sardinian Maritime Pine (Pinus Pinaster), which is a widely spread and relatively fast growing conifer available in Sardinia, in the rest of Italy and also in several Mediterranean regions. Maritime Pine has never been considered as a structural material in Sardinia while several researches (Morgado et al. 2008 and 2010, Carballo et. al 2009) have been carried out on Spanish and Portuguese Maritime Pine in order to establish its structural performance and stated that, despite its defectiveness, the material exhibited a great structural capacity.

In the experimental programme a number of boards were tested to destruction with the aim of identifying a strength class profile of Sardinian Maritime Pine according to UNI 11035-1 (2010) and UNI 11035-2 (2010). Firstly, several physical and morphological parameters such as density, presence of defects (knots, clusters of knots, resin pockets, grain deviation), warping, annual ring width, position of the board with respect to the pith, and moisture content were measured and analysed from full-size specimens according to UNI EN 384 (2010) and UNI EN 408 (2010). Then, non-destructive (ultrasonic velocity and dynamic modulus of elasticity) and mechanical properties (tensile strength and modulus of elasticity in tension) were measured and analysed in order to obtain information on the base material. In addition, a regression analysis was carried out by studying the correlation between non-destructive and mechanical parameters with the aim of defining a criterion for predicting the strength class of the base material from non-destructive testing. Finally, four-point bending tests were carried out on 5-layer CLT panels made of the same wood. The modulus of elasticity, both local and global, and the characteristic bending strength were measured, and the collapse mechanisms detected.

2. Materials

2.1 Boards

The boards were sawn from Maritime Pine trees growing at about 650m above sea level from three different areas of Sardinia (Figure1): Olia Mountain (1), in the north-west; Lanusei area (2), in the centre; and Sette Fratelli Mountain (3), in the south-east. These areas are characterized by a Mediterranean climate, with rainfalls mostly in wintertime and autumn, and high temperatures in summertime. The prevailing winds are westerly and mistral, and represent a cause of warping of the trees. For the experimental programme, about 300 boards, 3.00m long, 0.035m thick and 0.125m wide, were used. All tests and measurements were carried out after an oven drying process. The boards were progressively dried in a climatic chamber, exposed to a relative humidity of 65% and 20ºC of temperature until constant mass (weight) was achieved (Pommier et al., 2013, Morgado et al., 2010).An alpha-numerical coloured code (black, red and green for areas 1, 2, and 3 respectively) identified the origin place and the board position in the log and stump (Figure 2).

2.2 CLT panels

CLT panels typically consist of an odd number of wood layers oriented at right angles to one another and glued together (Figure 3). For the experimental programme, 15 CLT panels (5 for each area) were produced by using the boards previously visually graded. Better quality boards were used for the outer layers, while inner layers were made by worse quality boards (Concu et al., 2013). As illustrated in the following section 4, the board quality was defined after a visual grading procedure which sorted the boards into three classes, S1, S2 and S3, according to UNI 11035-2 (2010). Better boards belong to classes S1 and S2 while worse boards belong to class S3. The panels were 2.80m long, 0.150m thick and 0.480m wide, and were made of 5 layers (Figure 4). The board moisture content was measured (13%) to make sure it was inside the limits of 8% to 18% to ensure an effective gluing process. A commercial polyurethane adhesive Jowapur® 686.60 produced by Jowat was used. Rollers and glue dispenser were used for panels production (Figure 5). Layers mutual adhesion was ensured by applying on the panels a pressure of 0.4 N/mm^2 for three hours at a temperature of 20°C. The panels were fabricated in the Laboratory of the Technical University of Graz, Austria.

3. Strength grading of boards

There are two methods of strength grading: machine and visual grading. With machine strength grading, one or more properties which are related to the strength of the timber are physically tested. In this way, timber pieces can be assigned to an established strength class. Visual strength grading defines grading classes of the base material by using physical parameters such as density and moisture content, and other mainly visually identifiable features, such as knots parameters, annual rings width, board warping, etc. Characteristic values of strength, stiffness and density are used in order to sort timber pieces into grade classes (UNI EN 14081-1, 2011). Visual grading can be applied simply and implemented without special measuring equipment. In a first step of the experimental programme, a visual grading method was used. Visual grading was performed according to UNI 11035-1 and 2 (2010). UNI 11035-1 provides reference for: (i) moisture content measurement; (ii) direct or indirect evaluation of density, which is performed by measuring the number of growth rings contained in a reference line (UNI EN 14081-1,2011); (iii) limits to defects reducing the strength (knots, slope of grain, checks, splits, shakes); (iv) limits to geometrical features representing growth defects (wane and warp); and (vi) decay. UNI 11035-2 (2010) provides visual strength grading rules and characteristic values for Italian structural timber. In detail, the following parameters were analysed in order to define the board strength grade.

Density. Density is defined as the weight divided by the volume of the entire board.

Knots. The knot parameter A (UNI EN 14081-1, 2011, UNI 11035-1, 2010, DIN 4074-1, 2009)shall be measured over the entire length of the board as the ratio between the smaller radius of the greatest knot and the surface width related to the cross-section where the knot appears (Figure 6).

Annual ring width. Annual rings width ω shall be measured in the radial direction as reported in Equation 1:

$$\omega = \frac{z}{N} [mm] \qquad 1.$$

where N signifies the number of annual rings along the distance z (Figure 7).
If the board contains the pith, the measurement of the distance z will be taken outside a circle of 25mm radius centred in the pith.

Warping. Four different types of warping were measured (UNI EN 14081-1, 2011, UNI 11035-1, 2010, Fowler and Ashmore, 2006): bow, cup, spring and twist (Figure 8). In the timber boards of this experimental programme, cup never occurred.

In a second step of the experimental programme, some other properties (modulus of elasticity, tensile strength, ultrasonic velocity) were measured via non-destructive ultrasonic testing and destructive tensile tests, in order to identify the timber mechanical performance.

Ultrasonic testing. Ultrasonic testing is a non-destructive testing method based on measurements of the velocity V of longitudinal stress waves propagating through the material. The wave is transmitted by a transducer through the board and received by a second transducer on the opposite side of the board. In this way, the time t needed for the wave to travel through the board, from the emitter to the receiver, along its entire length L, is measured. The average velocity of the wave V is then obtained from Equation2:

$$V = \frac{L}{t} [m/s] \qquad 2.$$

Measurements were performed in the center of the boards by using the Sylvatest® device, which allows the user to send and receive longitudinal ultrasound waves using two piezoelectric probes (Sylvatest user’s manual, 1991). Coupling problems were partially solved using conical penetrating probes. For prismatic, homogeneous and isotropic elements with a section width smaller than the stress wavelength, the dynamic modulus of elasticity E_{dyn} can be calculated as

$$E_{dyn} = \rho \cdot V^2 [N/mm^2] \qquad 3.$$

where V signifies the velocity of a longitudinal stress travelling in a board of density ρ and length L. The ultrasonic propagation time depends on the temperature and wood moisture content (Sandoz, 1993, Schickhofer and Augustin, 2001), thus the wave velocity and dynamic modulus of elasticity were corrected with respect to the reference moisture content u = 12% and wood temperature T = 20°C.

Tensile tests. Tensile tests were carried out according to UNI EN 408 (2010) to determine the static modulus of elasticity and the failure load. The load was applied up to approximately 1/3rd of the estimated failure load, and force and displacement were recorded in order to obtain data needed for determining the static modulus of elasticity. The test was then stopped, the displacement measuring devices removed, and finally the test was continued until the collapse of the board. The test set up is shown in Figure 9, where L_{ref} signifies the gauge length for the determination of the modulus of elasticity in tension $E_{t,0}$.

4. Results of strength grading

A wood board can be assigned to a specific strength class, according to UNI 11035-1and 2 (2010), only if the measured parameters comply with all the limit values for that specific strength class, otherwise it must be rejected. Therefore, a specific strength class is determined by the worst defect, wherever it is located on the surface of the board, and by the minimum mechanical property. Table 1 reports a statistical summary of measurements of morphological, physical and mechanical properties performed for timber strength grading.

It can be noticed the high scatter of the morphological parameters. As shown in Figure 10, about 50% of the boards were rejected for structural use due to their defects.

The very high values of twist warping, spring warping and knot parameters are the main causes for rejection. The strength classes of the remaining boards are governed by twist, therefore boards have been mainly included in S3 and S2 classes, according to Italian standards UNI 11035-1 and 2 (2010). European Standard UNI EN 338 (2009) provides a classification for wood boards based on strength, stiffness, or density properties. According to this standard, due to the low values of strength and modulus of elasticity, the boards do not fit into any of the strength classes.

The timber strength can be predicted by measuring properties that have a clear effect on the strength itself, or properties that do not directly affect strength but are good indicators of it. For example, as assumed in UNI 11035-1 (2010), morphological parameters are known to be among the key factors that define strength. The modulus of elasticity, on the other hand, is not a direct factor for defining strength, but it depends on the same variables affecting strength, hence it can be assumed as a good indicator of strength. Therefore, both types of properties can be considered as predictors of strength. However, the greatest emphasis should be given to the non-invasively measurable parameters with the greatest ability to predict strength.

The basis of strength grading with non-destructive measurements is the existence of a relationship between strength and one or more predictor parameters. In general, a deterministic relationship cannot be derived due to its complexity, but it can be established from empirical observations using statistical methods. The so called coefficient of determination r^2 indicates the portion of the total variation of the predicted variable which is explained by the predictor. In this paper, according to the approach proposed by Hanhijärvi et al. (2005), the parameters measured for visual grading were evaluated by regression analysis. The aim was to observe the coefficient of determination r^2 between each predictor and both the tensile strength f_t and the modulus of elasticity in tension $E_{t,0}$. A simple linear regression analysis was carried out and the coefficient of determination was used as a measure of the ability of the parameter to predict the grade determining properties. Results are shown in Table 2.

It can be seen that none of the parameters, with the exception of the ultrasonic velocity and dynamic modulus of elasticity, has a r^2 value higher than approximately 0.5. The best predictor of both tensile strength and static modulus of elasticity is the dynamic modulus of elasticity, obtained by the ultrasonic velocity.

As previously mentioned, visual strength grading is based mainly on morphological parameters such as knots. However, in this experimental work the correlation between knots and mechanical parameters is rather low, being r^2 less than 0.2. This does not necessarily mean that knots are not an important factor to determine timber mechanical properties. As suggested by Hanhijärvi et al. (2005), low r^2 may indicate that the rather simple definitions of knot effect quantity in the visual grading rules are not good enough to properly describe the complex effect of knots on strength. Therefore, the visual grading rules have to be rather conservative. Wood density is generally assumed to be a good predictor for timber strength in case of clear and defect-free wood. In this experimental work, density can account for approximately 44% of tensile strength variation and 48% of static modulus of elasticity variation.

5. Tests on CLT panels

The structural performance of CLT products depends upon the properties of the single layers and boards. The external loads are carried by the longitudinal (parallel) layers, whereas the transversal (perpendicular) layers have very low strength and stiffness in the main panel direction since the stresses are perpendicular to the grains (Figure 11). The so-called rolling shear (shear in the radial-tangential-plane) in the transversal layers leads to relatively low load-carrying capacities.

Four-point bending test was carried out on the panels. Figure 12 shows the testing setup according to UNI EN 408(2010). Four-point bending test results are summarized in Table 3. Panel failure was triggered by defects such as knots, aligned knots and slope of grain, as shown in figure 13.

According to UNI EN 14358 (2007) the bending strength characteristic value for CLT panel can be calculated as:

$$f_{m,CLT,k} = exp\left(\overline{f_m} - k_s \cdot s_f\right) \qquad 4.$$

where $\overline{f_m} = \frac{1}{n} \cdot \ln f_{m,i}$and $s_f = \sqrt{\frac{1}{n-1}\sum\left(\ln f_{m,i} - \overline{f_m}\right)^2}$ are respectively the mean value and the standard deviation for the stochastic variable $\ln f_m$, being f_m the bending strength and n the number of the tested panels. For n = 15, according to UNI EN 14358 (2007) the coefficient k_s is equal to 1.99.

By using Equation 4 the following values are achieved:
$\overline{f_m}$= 3.27N/mm^2
s_f = 0.15N/mm^2
so that the characteristic bending strength of CLT panels is $f_{m,CLT,k}$ = 19.76N/mm^2. This value is significantly higher than the experimental characteristic tensile strength of the boards used, which is $f_{t,0,l,k}$ = 10.10N/mm^2, demonstrating the effectiveness of CLT to attain medium quality products even when using low-quality wood.

The calculation model developed by Jöbstl et al. (2006)on the basis of UNI EN 1995-1-1 (2014) formulations and properly described by Unterwieser and Schickhofer (2013) predicts the CLT bending strength on the basis of the tensile strength of the base material (boards), according to the following Equation 5:

$$f_{m,CLT,k} = k_{m,CLT} \cdot f_{t,01,k}^{0.8} \qquad 5.$$

where

$f_{t,0,l,k}$ is the characteristic tensile strength of the boards, $k_{m,CLT} = k_{sys,CLT} \cdot k_{CLT/GLT} \cdot k_{h,CLT}$ is a coefficient that takes into consideration various effects (Hanhijärvi et al., 2005): (a) $k_{sys,CLT}$ considers the system effect of parallel laminations in longitudinal direction ($k_{sys,CLT}$ = 1.1 if the number of boards within the top layer is at least 4); (b) $k_{CLT/GLT}$ is a factor which considers the influence of the layers perpendicular to span on the homogenization of CLT in comparison to glued laminated timber (GLT), for which Jöbstl et al. (2006) suggest a value of 0.94; (c) $k_{h,CLT} = \left(\frac{h_{ref,GLT}}{h_{ref,CLT}}\right)^{0.1}$=1.15 is a height factor based on the reference height $h_{GLT,ref}$ = 600mm and $h_{CLT,ref}$ = 150mm for GLT and CLT respectively. The coefficient $k_{m,CLT}$ depends also on the coefficient of variation CV($f_{t,0,l}$) of the tensile strength of the base material as illustrated in Table 4.

This calculation model can be used for homogenous CLT elements with 5 layers of the same thickness, at least four lamellas running parallel in the top layers and a reference thickness of 150mm.According to this calculation model and being $f_{t,0,1,k}$ = 10.10N/mm^2 and CV($f_{t,01,k}$) = 27%, the predicted bending strength for Sardinian Maritime Pine CLT panels is $f_{m,CLT,k}$ = 19.08N/mm^2.This result fits well with the same parameter evaluated by experimental tests.

6. Conclusions

A research project was carried out in Sardinia (Italy), in cooperation with the Local Forestry Agency, with the aim of exploring the possibility of using locally grown timber as structural material. The experimental programme started by testing Sardinian Maritime Pine, a widely spread and relatively fast growing conifer that has not yet been considered as a structural material. This wood was first graded and then used for manufacturing CLT panels.

Firstly, Sardinian Maritime Pine boards were cut and strength graded. Various morphological, physical and mechanical properties were measured. The primary conclusions are:

- the dynamic modulus of elasticity, obtained from ultrasonic velocity measurements, is the best predictor for both stiffness and tensile strength of the material;
- according to Italian standards, Sardinian Maritime Pine boards can be clustered into three quality groups corresponding to strength classes S1, S2 and S3 respectively;
- European Standard UNI EN 338 (2009) provides a classification for wood boards based on strength, stiffness, or density properties. Due to the low values of static modulus of elasticity and tensile strength, Sardinian Maritime Pine boards do not fit into any of the classes.

In a second phase, four-point bending tests were carried out on the CLT panels made of the same Maritime Pine boards to measure the mechanical properties. The main observations are that:

- the failure is triggered by defects of the boards such as knots, aligned knots and slope of grain;
- the experimental characteristic bending strength of the CLT panels (19.76N/mm^2) is significantly higher than the experimental characteristic tensile strength of the component boards (10.10N/mm^2), confirming the possibility to attain medium-quality CLT products even when using low-quality timber boards;

- the experimental bending strength is quite similar to the value provided by the calculation model proposed by Jöbstl et al. (2006) based on the tensile strength of the component boards;
- despite the significant scatter of the board properties, Sardinian Maritime Pine CLT panels can be produced for use as horizontal and vertical members in civil engineering structures.

Future research will include the durability analysis of Sardinian Maritime Pine CLT panels, with special attention to biological attack including termites, moisture effect and long-term performance, with reference to related standards (UNI EN 15228, 2009). Then, the possibility of grading other timber species and testing different configurations of CLT panels, for example made of different timber species, will be considered.

It is worth noting that a lot of boards had to be rejected due to the excessive amount of defects. This defectiveness on one hand is an intrinsic factor of the wood species, on the other hand strongly depends on a forest management not oriented to a productive chain. The lack of an appropriate forest management has thus affected board quality and number, representing therefore a limitation to the present research. The production of CLT panels made of Sardinian timber is thus closely related to the idea of developing a timber short procurement chain. This idea involves the start-up of an industrial plant for the CLT production, and an accurate forest inventory and planning to ensure the volume of wood needed for running the plant is continuously available over time.

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Figure captions

Figure 1. Selected area (left) and Sardinian Maritime Pines(right)

Figure 2. Boards with alpha-numerical coloured codes

Figure 3. CLT panel

Figure 4. CLT panels made of Sardinian Maritime Pine boards

Figure 5. CLT panels production machine

Figure 6. Knot parameter definition

Figure 7. Annual ring width measurement

Figure 8. Boards warping. Reference length = 2m

Figure 9. Tensile test set up

Figure 10. Distribution of strength classes based on visual grading for all boards

Figure 11. Stress distributions along the depth of a CLT panel subjected out-of-plane bending and shear

Figure 12. Bending test: setup of the test with dimensions in mm (left) and photo of a specimen (right)

Figure 13. Failure mode of CLT panel in correspondence of knots (left) and aligned knots (right)

Table captions

Table 1. Statistical summary of measurements for timber strength grading. AV and CoV signify average and coefficient of variation, respectively.

Table 2. Coefficient of determination r^2 of individual visual grading parameters to mechanically determined properties.

Table 3. Four-point bending test results. F_{max} = failure load, E_{glob} = global static modulus of elasticity, E_{loc} = local static modulus of elasticity, f_m = bending strength.

Table 4. Parameters of the calculation model of CLT in bending (Unterwieser and Schickhofer, 2013).

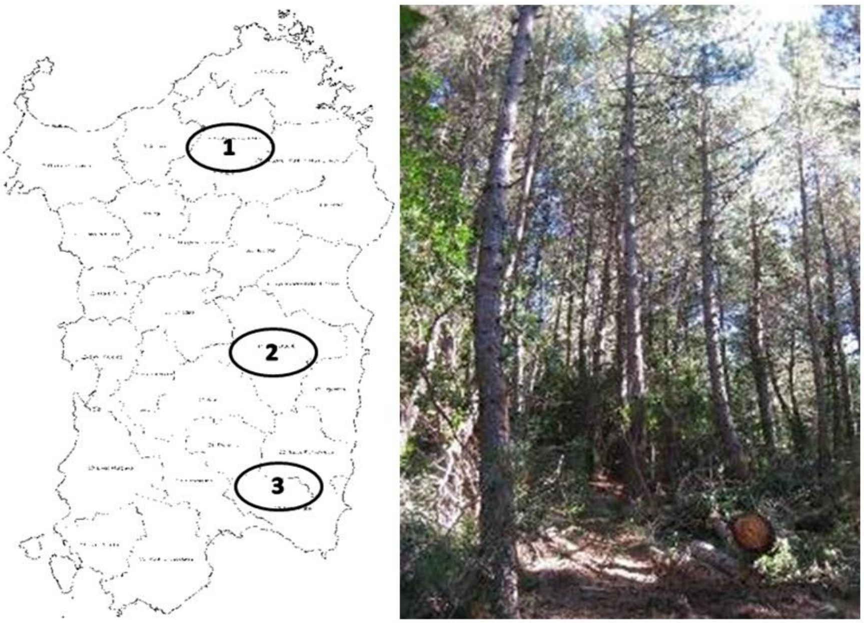


FIGURE 1

FIGURE 2

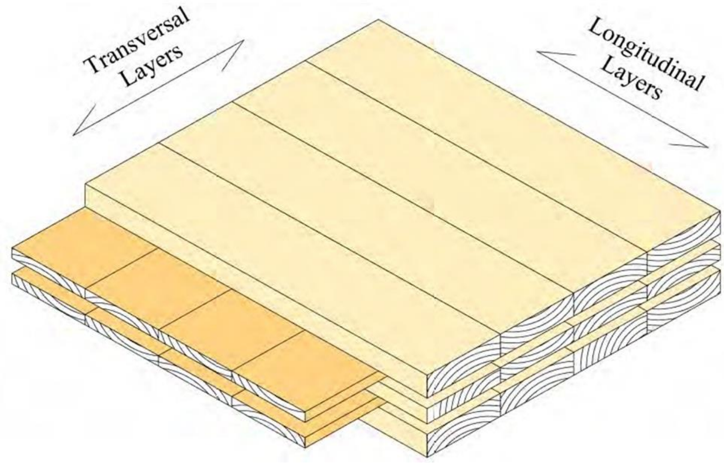
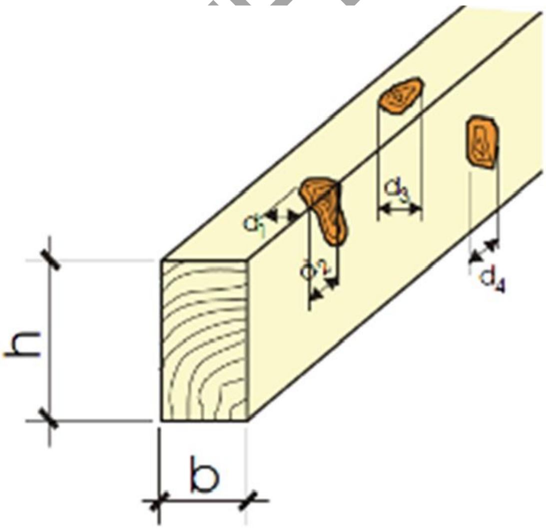


FIGURE 3

FIGURE 4

FIGURE 5



$$A = \frac{d_1}{b} \quad or \quad \frac{d_3}{b} \quad or \quad \frac{d_2}{h} \quad or \quad \frac{d_4}{h}$$

FIGURE 6

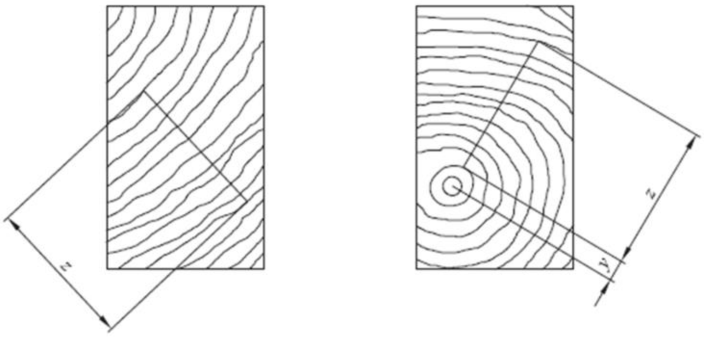


FIGURE 7

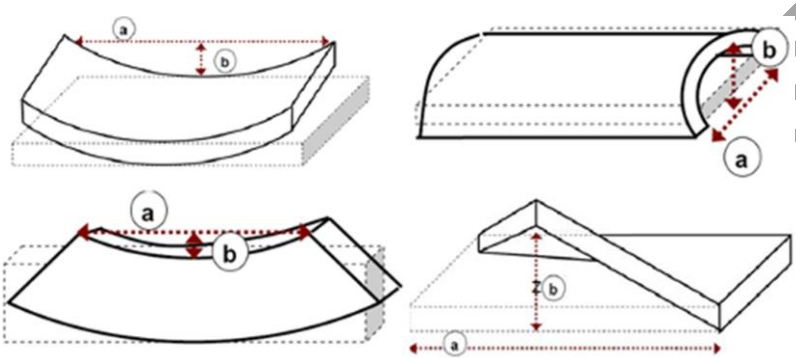


FIGURE 8

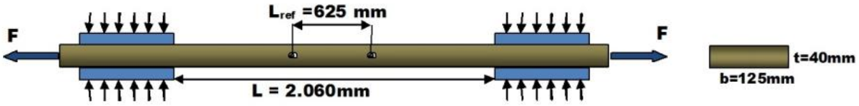


FIGURE 9

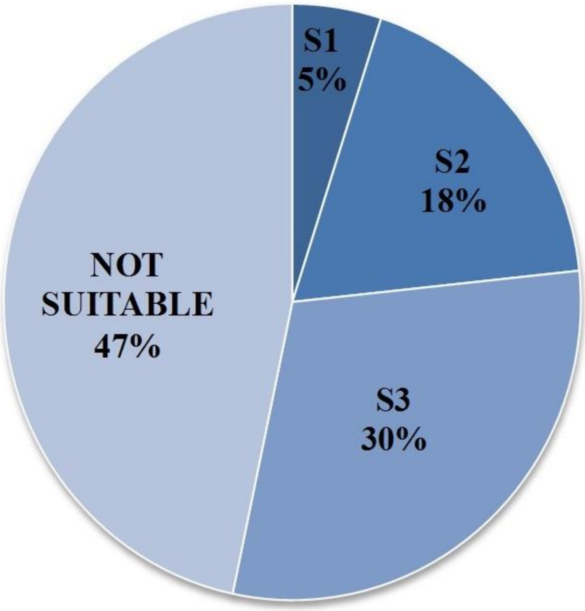


FIGURE 10

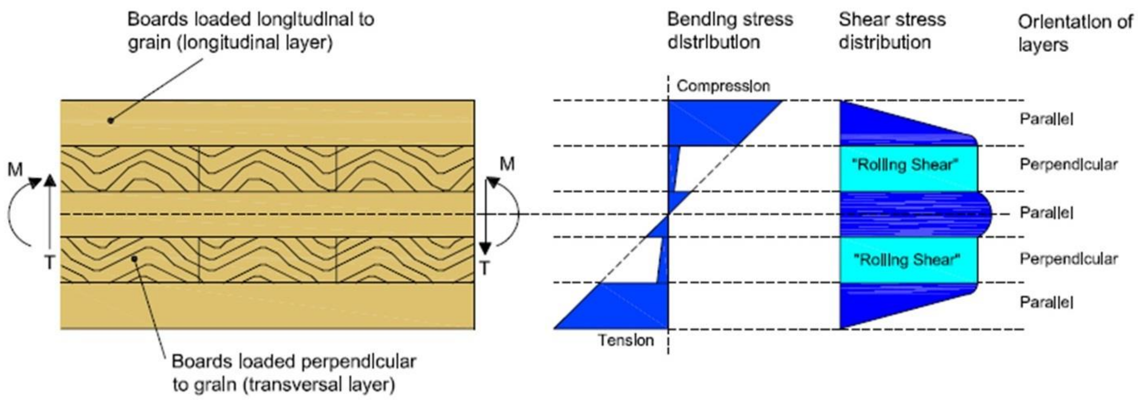
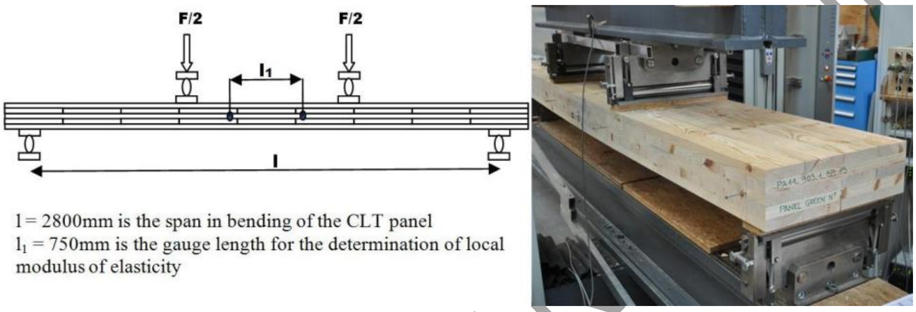


FIGURE 11



l = 2800mm is the span in bending of the CLT panel
l_1 = 750mm is the gauge length for the determination of local modulus of elasticity

FIGURE 12

FIGURE 13

Parameter		Black boards (from Olia Mountain)	Red boards (from Lanusei area)	Green boards (from Sette Fratelli Mountain)	Overall sample
density	AV [kg/m^3]	497.88	512.62	494.57	501.69
	CoV [%]	2.34	8.72	4.78	5.31
knots	AV	0.76	0.61	0.68	0.68
	CoV [%]	26.32	34.43	23.53	27.8
annual rings width	AV [mm]	7.24	5.64	4.42	5.77
	CoV [%]	24.45	23.4	22.85	23.7
twist	AV [mm]	16.45	17.54	17.66	17.22
	CoV [%]	48.33	73.77	48.36	56.98
bow	AV [mm]	7.94	8.35	6.31	7.53
	CoV [%]	78.97	52.1	37.24	57.39
spring	AV [mm]	6.04	5.40	4.57	5.34
	CoV [%]	76.66	66.11	48.58	65.08
moisture content	AV [%]	12.85	12.28	11.88	12.34
	CoV [%]	5.68	6.84	3.28	5.3
ultrasonic velocity	AV [m/s]	4105.22	3929	4006	4013
	CoV [%]	9.48	8.73	8.69	8.97
dynamic modulus of elasticity	AV [N/mm^2]	8377.79	8047.84	8063.37	8163.01
	CoV [%]	18.75	15.12	19.91	17.94
modulus of elasticity in tension	AV [N/mm^2]	5873.68	5803.79	5089.91	5589.13
	CoV [%]	24.19	17.53	21.17	20.97
tensile strength	AV [N/mm^2]	11.19	12.31	11.65	11.72
	CoV [%]	24.75	16.98	30.64	23.98

TABLE 1

r^2	f_t	$E_{t,0}$
Density	0.438	0.484
Knots	0.190	0.001
Annual rings width	0.490	0.001
Twist	0.040	0.015
Bow	0.050	0.010
Spring	0.040	0.013
Moisture content	0.410	0.046
Ultrasonic velocity	0.521	0.555
Dynamic modulus of elasticity	0.585	0.615

TABLE 2

Parameter	Average	Standard deviation
Mass [kg]	105.15	3.57
F_{max} [kN]	83.80	13.68
E_{glob} [N/mm^2]	5973.17	593.87
E_{loc} [N/mm^2]	7913.25	1158.35
f_m [N/mm^2]	26.10	4.30

TABLE 3

	$CV(f_{t,0,l})$	
	25% ± 5%	35% ± 5%
$k_{m,CLT}$	3	3.5

TABLE 4