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EXPERIMENTAL AND NUMERICAL EVALUATION OF CROSS-LAMINATED TIMBER (CLT) PANELS PRODUCED WITH PINE TIMBER FROM THINNINGS IN URUGUAY

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ABSTRACT:

Due to the high volume of timber required for manufacturing, the production of cross-laminated timber (CLT) panels could be an appropriate destiny for the existing surplus of pinewood presently available in Uruguay. Although wood construction is uncommon in this country, there are some companies with the capacity to adapt their production to new products such as CLT. This work evaluates the properties of CLT panels manufactured in Uruguay with local pine (*Pinus taeda* and *Pinus elliiottii*) from forest plantation thinning, which typically present low mechanical properties. Boards and panels were mechanically tested and the mechanical properties were determined, showing a strength class lower than C14. A numerical model, using the finite element method, was developed and the numerical results were compared with the experimental values. The results provided a first approach to the conditions and limitations of the use of CLT panels for building floors, produced under the current manufacturing conditions in Uruguay.

KEYWORDS: CLT, *Pinus taeda*, *Pinus elliotii*, experimental tests, numerical simulation, Uruguay

1 INTRODUCTION

The pulp and timber industry is the second in relevance in Uruguay, after the food industry, and, in 2014, represented 2.5% of GDP [1]. Currently there is approximately 1 million ha of forest plantations of fast-growing species, mainly pine and eucalyptus [2]. The average annual production of pine wood (mainly *Pinus taeda* and *Pinus elliottii*), for the period between 2010 and 2030, is estimated in 2.9 million m^3. From this volume, 1.7 million m^3 have no industrial destiny, of which 1.4 million m^3 come from silvicultural thinning [3]. In addition, the Action Plan of the Wood-Forest Sector Council (CSFM) has the objective of promoting the investments that increases the local wood consumption and the diversification of wood products production [4].

Uruguay does not have a timber design code or standards about the mechanical properties of the local species. However, timber building is increasing, usually associated to single family houses for second residence or social houses [5, 6]. Currently, the visual grading of *Pinus elliottii/taeda* is on-going research; the first results [7, 8] shows that, for plantation cycles between 15 and 25 years, the maximum strength class reached is C14 [9].

Because of the high volume of timber required in the cross-laminated timber production, this article proposes a first evaluation of CLT panels manufactured in Uruguay using pine wood from thinning, which has mechanical properties lower than C14.

In the last years, a significant increase in the development and expansion of CLT panels has been produced over the world [10], [11]. This is due to its structural advantages, such as versatility of use, high level of prefabrication and easy fastening of the panels during the building construction. There are different commercial alternatives for CLT panels, varying the species, the mechanical properties, the thickness, the adhesive, etc. Some companies offers its own structural calculation software designed to the mechanical properties and manufacturing conditions of its CLT panels (e.g. KLH, Stora Enso, Binderholz, etc.). A European Standard about the requirements of the manufacture and tests of CLT was recently published [12]. Some works about CLT with fast-grown species in South America are being developed [13,14], although the manufacturing requirements are not standardized and CLT panels are not a commercial wood-engineered product yet.

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The structural validation of CLT panels depends on the timber properties, the gluing quality, the manufacture process, etc. Static tests, non-destructive testing [15] or numerical simulations [16] are tools commonly used to estimate its structural properties.

The objective of this work is the experimental and numerical evaluation of the first CLT panels prototypes manufactured in Uruguay using pine timber from thinnings and define the applications and limitations of using it as flooring elements in buildings.

2 MATERIAL AND METHODOLOGY

2.1 CLT MANUFACTURING

The country does not have a specialized industry in the production of CLT, so the manufacture process is summarized below. At the timber yard of a local sawmill located in Northern Uruguay, dried boards obtained from thinning logs and without finger-joints were visually graded according to own criteria (not standardised grading). The boards were attached by the edges with non-structural adhesive (in order to facilitate the manufacturing) and structural Emulsion Polymer Isocyanate adhesive (EPI) was applied between layers before the vertical pressing, Figure 1.

Figure 1. *Manufacturing process of a 5-layers prototype of CLT panel*

Four panel prototypes of 2.4 m length and 1.2 m of width were manufactured, combining different number of layers (3 and 5) and layer thickness (33 mm and 45 mm), varying the total thickness between 99 mm and 177 mm.

According to [12], manufactured panels had the layup code (thickness in mm/orientation) shows in Table 1 and in Figure 2.

Table 1: *Layup code for manufactured CLT panels*

Prototype	Layers	Layup (thickness mm/orientation)
P1	3	33l-33w-33l
L1-L2	5	33l-33w-33l-33w-33l
L3	5	33l-33w-45l-33w-33l

l: lontigudinal orientation
w: transversal orientation

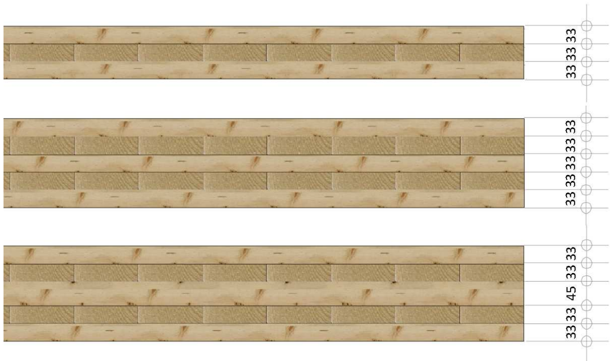

Figure 2. *Layer thickness of CLT panels*

2.2 EXPERIMENTAL SAWN TIMBER TESTING

From the visually graded timber used for manufacturing CLT panels, 24 specimens (mean cross-section 37x127 mm and 2.4 m length, with moisture content between 10.5 and 13.2%) were tested in bending according to the standard EN 408 [17]. Modulus of elasticity and bending strength were estimated for each specimen. The results were used as input data in the numerical FE model.

Bending test configuration and dimensions of sawn timber are presented in Figure 3 and Table 2.

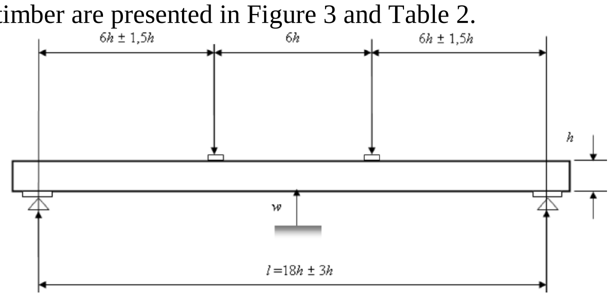

Figure 3. *Bending test configuration for sawn timber*

Table 2: *Number and dimensions of evaluated samples*

	n	**Dimensions**
Sawn timber	24	37x127x2400 mm^3
CLT panels	1	99x360x2400 mm^3
	2	165x360x2400 mm^3
	1	177x360x2400 mm^3

2.3 EXPERIMENTAL CLT PANELS TESTING

Four-point bending tests were made until rupture on 2.4 m-long and 360 mm-wide CLT panels, Figure 4.

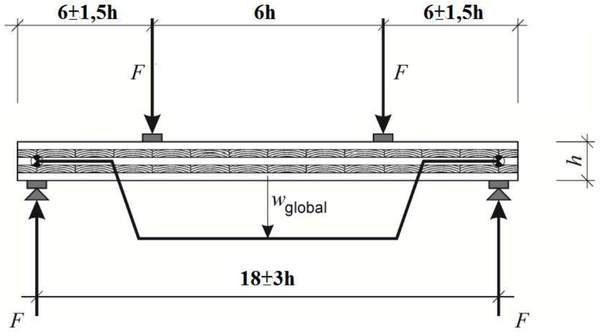

Figure 4. *Bending test configuration for CLT prototypes panels*

Deflection was measured using linear variable differential transformer (LVDT), located on both two sides of the panel at the middle of the span. Total deflection was calculated as the mean value of both measurements and the failure load was registered.

Figure 5. *Bending test of CLT panels*

2.4 NUMERICAL SIMULATION

Numerical models, using the finite elements method, were developed in the software *COMSOL Multiphysics* to study the structural behaviour of CLT panels.

Physical and mechanical properties obtained from sawn timber tests (see *5.1.Experimental results*) were used as input data in the FEM model, Table 3. Modulus of elasticity perpendicular to the grain (E_{90}) and shear modulus (G) were estimated according to [18], Equations (1) and (2).

$$E_{90} = E_0 / 30 \quad (1)$$

$$G = E_0 / 16 \quad (2)$$

Table 3: *Input data for FE model*

Parameter	Value
E_0 (N/mm^2)	6328
E_{90} (N/mm^2)	211
G (N/mm^2)	396
ν	0.3
ρ (kg/m^3)	440

E_0: modulus of elasticity parallel to the grain; E90: modulus of elasticity perpendicular to the grain; G: shear modulus; ν: Poisson coefficient; and ρ: density.

A 3D FE model was developed to simulate the experimental bending test of the prototypes CLT panels. The dimensions of the three different prototypes and test configuration (span and loads) were modelled. Timber was considered as a linear and orthotropic material; in addition, a tethraedrical meshing was used, Figure 6.

Adhesive properties (EPI) were obtained from [19]. The adhesive surface was modelled through the *Thin Elastic Layer* complement of *Comsol* software, using the elastic parameters of the adhesive: k_n and k_t (normal and tangential) according to Equations (3) and (4).

$$k_n = \frac{E_{ad}(1 - \nu_{ad})}{t(1 + \nu_{ad})(1 - 2 \cdot \nu_{ad})} \quad (3)$$

$$k_t = \frac{G_{ad}}{t} \quad (4)$$

where, ν_{ad} = 0.37 is the Poisson coefficient of the adhesive, E_{ad} = 4 GPa and G_{ad} =1.54 GPa are Young´s modulus and shear modulus of the adhesive, respectively; and t = 0.5 mm is the glue line thickness.

Adhesive interaction was modelled in contacts between layers. Contacts between the edges of the boards were considered as free contact, and no adhesive parameters were used.

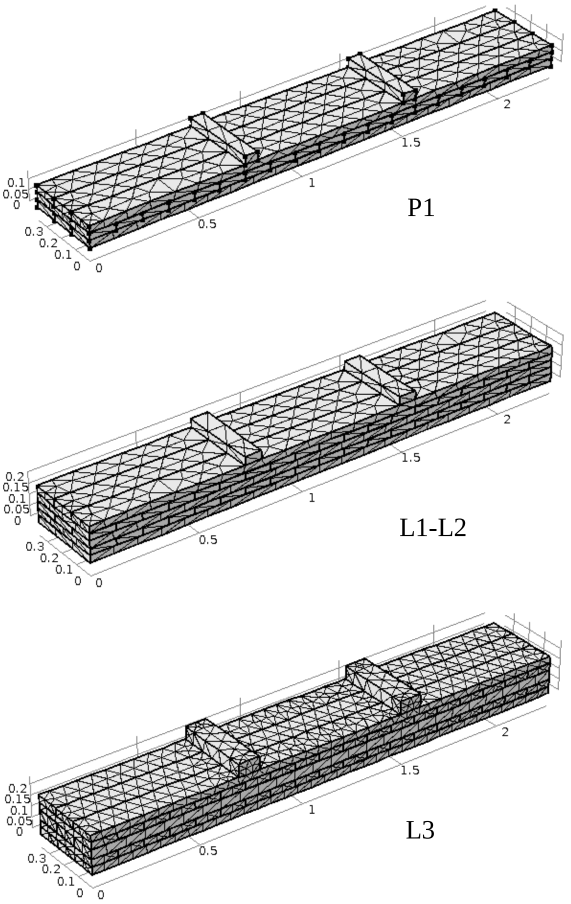

Figure 6. FE model of CLT prototypes

3 RESULTS AND DISCUSSION

3.1 EXPERIMENTAL RESULTS

Some physical and mechanical properties from the experimental bending test of sawn timber specimens are presented in Table 4.

***Table 4:** Mechanical and physical properties of sawn timber*

Properties	Mean value	CoV
E_0 (N/mm^2)	6328	22%
f_m (N/mm^2)	25.80	43%
ρ (kg/m^3)	440	11%
	5th percentile	
f_{05} (N/mm^2)	12,80	-

The modulus of elasticity and bending strength are low because the specimens were obtained from silvicultural thinning, which includes a high percentage of juvenile wood.

Load-deflection results from bending tests were obtained for the four prototypes of CLT panels manufactured, Table 5, being L1 the 3-layers panel and P1, P2 and P3 the 5-layers panels.

***Table 5:** Load and middle span deflection for CLT panels tested in bending*

	Middle span deflection (mm)			
	h = 99 (mm)	h = 165 (mm)	h = 165 (mm)	h = 177 (mm)
Load (kN)	Panel P1	Panel L1	Panel L2	Panel L3
10	11.20	3.25	3.81	2.59
20	23.31	6.54	6.91	4.72
30	34.85	10.03	9.97	6.94
40	--	13.52	13.04	9.17
50	--	17.10	16.08	11.41
60	--	20.62	19.12	13.73
70	--	24.27	22.34	16.07

3.2 FE MODELLING

The load-deflection relationship in elastic behavior of the CLT panels was numerically evaluated. Figure 7 shows the longitudinal stress distribution and deflections for the loads 20, 50 and 80 kN.

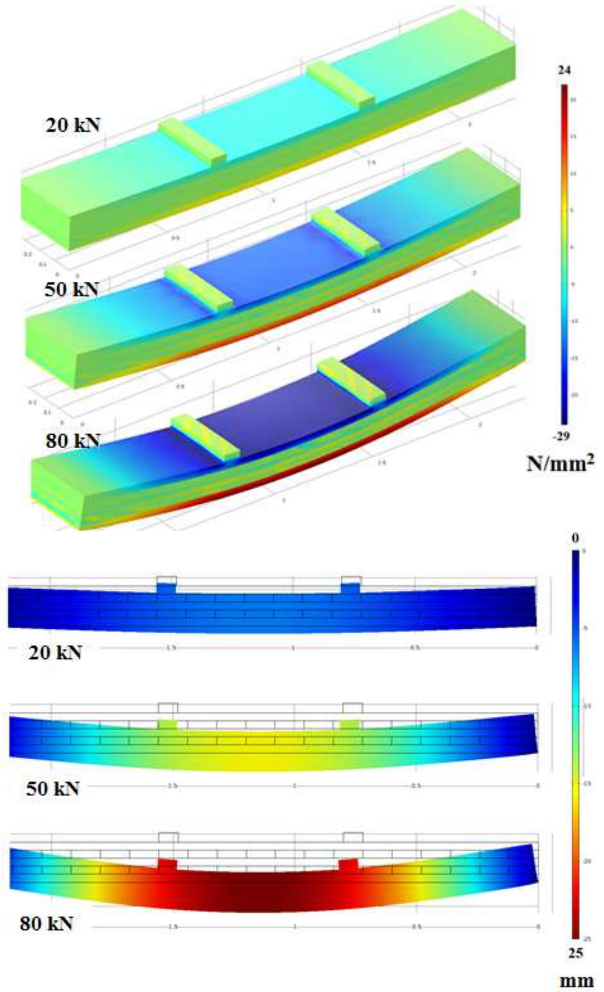

Figure 7. Longitudinal stresses (upper side) and deflections (down side) in the FE model

The results of the numerical deflection obtained were in agreement with the experimental values for all the CLT panels studied. Figure 8 shows that relative error of the numerical deflection was lower for small loads, varying between 4.0 and 8.5% for loads close to the failure (30 kN for 3-layer panel and 80 kN for 5 layer panels).

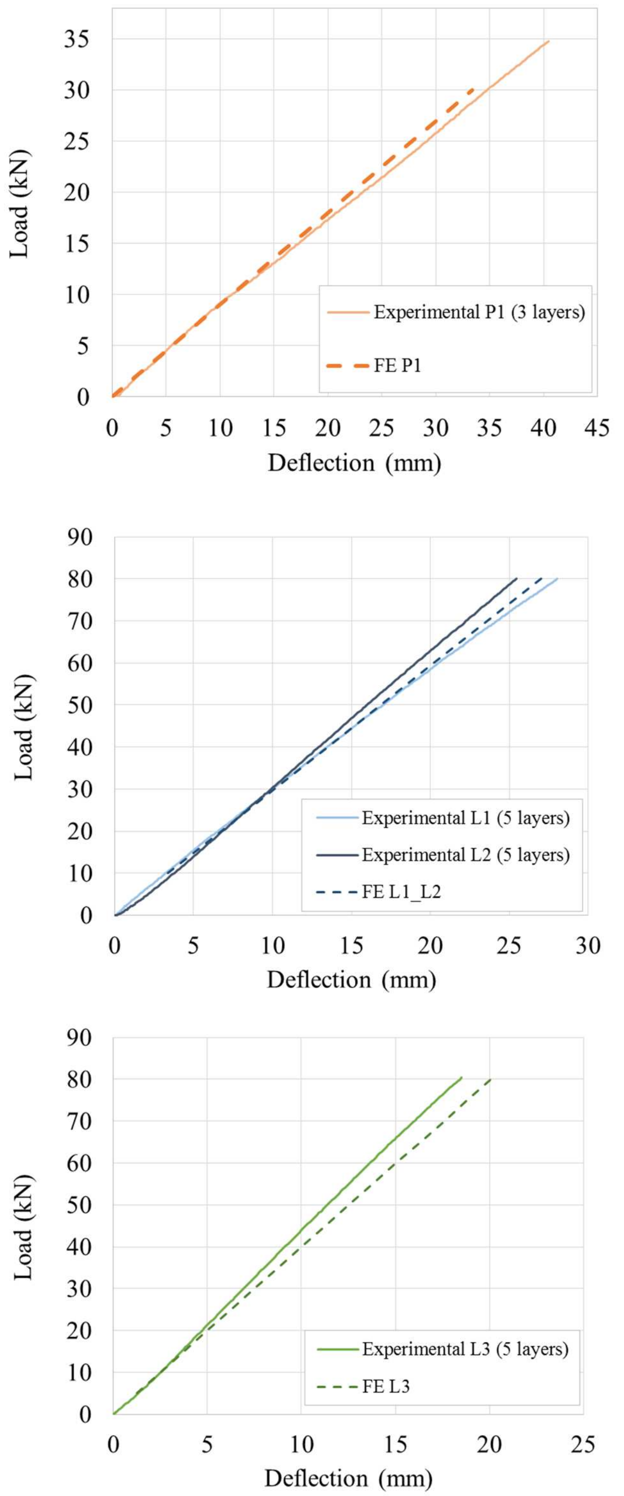

***Figure 8**. Load-deflection curves for experimental and numerical results*

Analysis of new layer configurations

Four new different layer configurations were designed and numerically modelled in order to study the influence of the number and orientation of boards in the deflection (Figure 9).

***Figure 9**. Alternative layer configuration evaluated through FE numerical modelling*

Different layer thicknesses were studied for the models M1, M2 and M3, and different layer orientation was evaluated in model M4. In all cases, the total height of the CLT panel was constant (99 mm for 3-layer panel and 165 mm for 5-layer panel). Table 6 presents the configuration of the new CLT panel models, considering different thickness and orientation of layers.

***Table 6:** Configuration of the new CLT panels numerically analysed*

Model	Layers	Configuration
M1	3	37l-25w-37l
M2	5	39l-29w-29l-29w-39l
M3	5	39l-24w-39l-24w-39l
M4	5	33l-33l-33w-33l-33l

Figure 10 shows the numerical load-deflection diagrams for the new 3-layer panel (M1) versus the 3-layer panel P1.

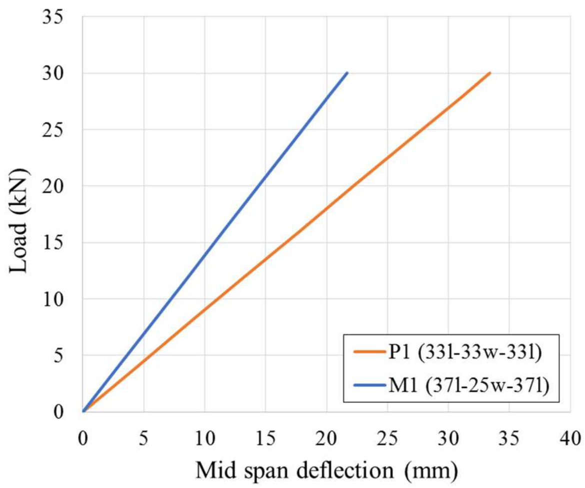

Figure 10. *Load-deflection diagram for numerical results of different 3-layer panel configurations (M1 and P1).*

An increase of 11% of the outer layers thickness and a decrease of 24% of the inner layer thickness implies a lower deflection for the same load and, therefore, an increase of the global stiffness of the CLT panel.

Figure 11 shows the load-deflection diagrams numerically obtained for 5-layer M2, M3 and M4 panels versus for 5-layer L1 panel.

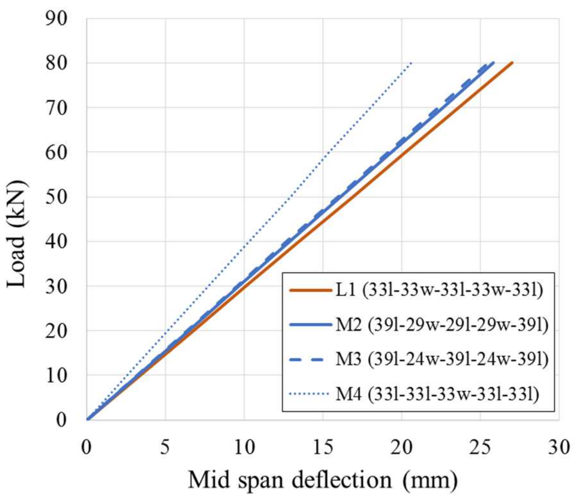

Figure 11. *Load-deflection diagram for numerical results of different 5-layer panel configurations (M2, M3, M4 and L1).*

Models M2 and M3 show similar behavior than L1. However, model M4, which were designed with the two external layers in the longitudinal direction, shows, for the same load applied, lower deflections than L1

These results introduced the study of different layer configurations, using the same timber volume, in order to improve the stiffness of the panels.

3.3 EXPERIMENTAL VS. COMMERCIAL PROPERTIES

The cost of the prototypes built for this study was estimated as an addition of the cost of every process (board production, gluing, pressing, etc.), performed by different companies, which were collaborating for the first time. Therefore, the prototypes are naturally more expensive than an established industrial product. Table 7 shows the mechanical properties of the timber used for the manufacture of CLT panels for different companies and countries and an estimation of the final cost compared with the manufacturing in the currently conditions in Uruguay.

Table 7: *Mechanical properties of layers and estimated cost of CLT panels*

Companies and countries	**Mechanical properties (N/mm^2)**		**Cost (€/m^2)**	
	$E_{0,m}$	**$f_{m,k}$**	**3-layers**	**5-layers**
Company 1 (EU)	8000	16.0	35-49	72-74
Company 2 (EU)	12000	24.0		
Wood from thinning (Uruguay)	6328[1]	12.8[2]	83[3]	108[3]

[1] Mean value from 24 experimental data
[2] Characteristic value from 1 sample and 24 specimens
[3] Cost of the Uruguayan prototypes, which does not corresponds with the cost of industrial manufacturing

Modulus of elasticity of the sawn timber used in the international commercial CLT panels varies between 8000 and 12000 N/mm^2, while the sawn timber from thinning in Uruguay reaches a mean value close to 6000 N/mm^2. This is because the wood from thinning usually contains a large fraction of juvenile wood. The characteristic bending strength of Uruguayan pinewood is close to the 13 N/mm^2, lower than the minimum strength class (C14) defined in EN 338.

Currently, in Uruguay the installed industrial capacity can manufacture panels with maximum dimensions of 3.00 x 1.20 m. Although it can be increased in the future, the low modulus of elasticity is a limiting factor in the structural design for the serviceability limit state. For example, in a calculation, according to Eurocode 5 [20], of simply supported 5-layers CLT panels for use in housing and offices, the maximum span results in 4 and 4.5 m respectively, limited by vibration and deflection values. This span is in accordance with the usual modulations for the rooms in offices and housing. In Table 8, other combinations of span and loads for different uses are presented. V, D and B represent the limiting value for vibrations, deflections or bending, respectively.

Uruguay has the higher building cost of Latin America [21] due, mainly, to the low efficiency and high costs of the labor. The costs of CLT building in Uruguay, considering the CLT prototypes costs, are 25% and 35%

higher than the conventional building (using concrete and masonry) for floors and walls, respectively.

In a comparison with the costs of the sawn timber used for the configuration of CLT panels, the price of Uruguayan commercial wood is higher than the European wood in relation with its strength and stiffness, and similar to USA, Table 9. This price corresponds with Uruguayan no-graded wood and the price of wood from thinning is unknown because currently there is no market for it. It is estimated that the development of the local timber market would bring down the cost of pinewood.

Table 8: *Uruguayan CLT floors design for different span and use loads*

Span (m)		imposed loads (kN/m²)			
		2	3	4	5
	Cat.	**A**	**B**	**C/D**	**C/D**
2.4		✔	✔	✔	✔
3.0		✔	✔	✔	✔
3.5		✔	✔	✔	✔
4.0		✔	✔ V	✔ V	✔ V / D
4.5		✔ V	x	x D	x
5.0		x D	x D	x	x
5.5		x	x	x B	x B
6.0		x	x B	x	x
6.5		x B	x	x	x

V: vibrational limiting value; B: bending limiting value; D: deflection limiting value; ✗*: Non-structural use*

Table 9: *Exportation costs of coniferous sawn timber* [22]

Country	Sawn timber Cost (€/m³)
Germany	226
Austria	242
USA	340
Uruguay	294[1]

[1] Commercial no-graded wood

4 CONCLUSSIONS

- Four CLT prototypes made with Uruguayan pine timber from selvicultural thinning were manufactured and tested in bending in order to study their structural behavior.

- Numerical models were developed to simulate the experimental tests. The results of the numerical models were in agreement with the experimental results, with a maximum relative error of 8.5% predicting the deflections of the panels.

- New CLT configurations were studied from the FEM model. Results showed that stiffness of CLT panels could be improved, without increase of timber volume, modifying the layer configuration (thickness and orientation).
- Pinewood obtained from plantation thinning could be used as raw material to construct CLT.
- According to Eurocode 5, current CLT Uruguayan panels for flooring are valid for maximum span of 4.5 m for category A (housing) and 4 m for category B (offices).

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