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MECHANICAL CHARACTERIZATION AND HYSTERETIC BEHAVIOUR OF CLT PANELS MADE OF CHILEAN RADIATA PINE

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Abstract

The use of cross-laminated timber (CLT or XLAM) in the multi-storey buildings construction sector has been spreading in Europe and North America over the last twenty years. Considering that Chile has one of the largest radiata pine forest resources of the world, it is clearly possible to introduce this timber construction system in Chile. Therefore the mechanical characterization and seismic behaviour of 3-ply cross-laminated timber panels made of Chilean radiata pine were studied. The panels (2.5 m height, 1.2 m width and 0.12 m thickness) were manufactured in the Materials Research Laboratory of Civil Engineering Department at Universidad de Santiago de Chile (LIMUS-USACH) in accordance with the current Chilean standards, which are based on ASTM standards. The New Zealand standard (BRANZ P21) for cyclic tests was also applied. These panels are intended to be used for the design of earthquake-resistant systems in mid-rise buildings.

Keywords: Cross laminated timber; mechanical characterization; radiata pine panels.

1. Introduction

Cross Laminated Timber (CLT) is becoming an alternative building material in different parts of the world, and it is one of the most emblematic products derived from wood for the construction of mid-rise buildings. This system has been used for more than twenty years in Europe, and over the last decade in USA and Canada [1,2]. The excellent mechanical properties of CLT have allowed its use for the construction of different kinds of buildings, from low buildings with a large surface area to towers more than ten storeys high. Many of these buildings have been built in low seismicity areas, but nowadays there is a tendency to develop these kinds of projects in high seismicity zones, e.g., Italy and the west coast of Canada and USA [3]. CLT has the advantage of excellent heat and sound insulation characteristics that increase the well-being of the inhabitants and reduce energy expenses in heating systems [4]. This material allows the massive construction of medium sized housing solutions due to its high earthquake strength, and moreover it favours the reduction of atmospheric CO2.

This work has been backed up by a number of research projects that have included tests on components subjected to dynamic loads [5] and full scale tests in buildings [6]. These tests have allowed the use of CLT as the main earthquake resistant system in buildings, and the use of wood in tall buildings. Several guides have been developed on the design of wood and CLT buildings [7, 8], allowing architects and engineers to use CLT in construction.

In Chile there isn´t still enough information on the manufacture and use of CLT in buildings. In 2012 Materials Research Laboratory of the Civil Engineering Department (LIMUS-USACH) of Universidad de Santiago de Chile, with financial support from Corporación de Fomento, CORFO, took the initiative of introducing CLT in the national market through a pioneering research project whose objectives were: 1) to study the technical and economical feasibility of using CLT in buildings in Chile, and 2) to promote the use of CLT in Chile. Technical part of this project studies the use of local lumber (radiata pine) as the basis for CLT, testing CLT panels and their connections, the production and design of a building based on CLT for social housing in Santiago, Chile. [9-13]. The present document will be focused on the technical aspects of this project, with emphasis on the experimental program and its results. Therefore, a set of experimental tests that were carried out in order to characterize mechanically 3-ply CLT panels made of Chilean radiata pine is presented. Furthermore, fire resistance tests of structural CLT panels were made. The (2.5-m length, 2.2-m width and 0.12-m thickness) panels were manufactured entirely in the Materials Research Laboratory of the Civil Engineering Department of Universidad de Santiago de Chile (LIMUS-USACH). The experimental program was performed according to current Chilean standards, which in turn are based on ASTM standards. The New Zealand standard [14] for cyclic tests was also used. These panels are intended to be used for the design of earthquake-resistant systems in a mid-rise building in order to promote their use in Chile.

Finally, a value for the force modification factor (R) and a maximum storey drift limit is estimated for the seismic design of mid-rise buildings made of CLT panels manufactured with Chilean radiata pine. These values will be proposed to be included in the Chilean Seismic Design Code for buildings, NCh 433 [15].

2. Experimental program

2.1 Manufacture of CLT panels

The reference average density of Chilean radiata pine with 12% moisture content is 470 kg/m3 [16], and the average value of the elastic modulus is 10000 MPa for grade G1 quality (visual classification) and 10200 MPa for grade C24 (mechanical classification) [17]. The average density of wood used in this study was 445 kg/m3 with an average moisture content of 12.6%, and an average elastic modulus of 9920 MPa. Prefere structural adhesive was used (100 pp of resin 6151 and 15 pp of catalyst 6651) [12]. In manufacturing process, the lumber (138 mm width, 41 mm thickness and 4.0 m length) was classified visually and mechanically [18, 19] and then grouped according to its corresponding classification, as presented in Figure 1a. In order to achieve the required length, and to eliminate knots if desired, finger-joints were used, as shown in Figure 1b. Timber was planned to make thickness of pieces 40 mm and to smooth edges in order to reduce spaces between them.

Once the components were planned down, they were glued together on their lateral edges to form individual layers, as indicated in Figure 1c. Three layers were stuck crosswise on top of each other and glued together under high pressure using a frequency pressing machine (20 kW power) to form the final CLT panel as shown in Figure 1d. In the manufacture of each individual layer a vertical pressure of 25 MPa and a lateral pressure of 9 Mpa were applied. For the final panel a vertical pressure of 28 MPa and a lateral pressure of 3.5 Mpa were applied.

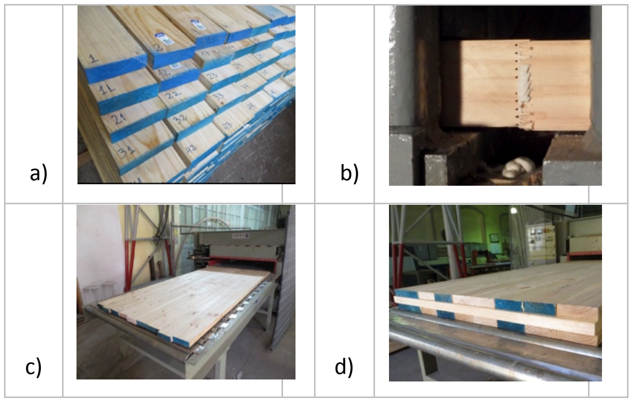

Figure 1 - Manufacturing process of a radiata pine cross laminated timber panel: a) a sample of sawn lumber used for the panel's layers; b) connections of sawn lumber (typical finger-joint); c) pressing of a layer; and d) final cross laminated timber panel.

2.2 Loading setups

Experimental tests on subjecting CLT panels from bending, compression, and in-plane shear loads were carried out. Chilean codes, which are based on ASTM standards, were followed. Loading and unloading cycles were applied during the in-plane shear tests in order to obtain lateral displacements under different load levels, residual displacements after each cycle, and hysteresis loops. The loading/unloading programme was adopted from the New Zealand standard [14]. Three samples of CLT panels were used in each type of test. Further details on these experimental tests can be found in [9, 20, 21]. Metal brackets (Simpson Strong Tie and Rothoblaas) and Anker nails (Rothoblaas) were used to connect the panels to the foundations. Dissipated energy, equivalent viscous damping, maximum lateral load, displacement at maximum lateral load, and yield displacements were obtained.

Fire resistance tests were performed according to Chilean standard NCh 935/1 [22].

2.3 Bending test

Figure 2 shows a CLT panel subjected to four-points-bending. Chilean standard NCh 803 [23] was adopted to establish the experimental procedure of the test. Figure 3 shows a typical failure due to bending.

Figure 2 - Bending test

Figure 3 - Failure caused by bending

2.4 Compression test

A typical compression test is shown in Figure 4. The details of the experimental procedure can be found in Chilean standard NCh 801 [24]. The maximum capacity of the equipment and measuring devices were used in order to apply the vertical load. The maximum vertical load applied was 700 N and no kind of failure occurred.

2.5 In-plane shear test

Chilean standard NCh 802 [25] was used to define the setup and experimental procedure. The lower edge of the panel was anchored firmly to the bottom of the testing frame by means of three metal angle connectors on each side of the panel in order to prevent lift and horizontal movements. The in-plane shear test was carried out by applying loading and unloading cycles in order to get the lateral displacements under different load levels, as well as the residual displacements produced by those loads. A total of eight loading and unloading cycles were applied, with load increments of 4.9 kN (500 kgf) in each cycle. Figure 5 shows a typical in-plane shear test of a CLT panel. In all the shear tests the hold-down connector failed, see Figure 6, showing the high strength of this kind of system. Hold-down (WHT540), shear bracket (TITAN TCN 240) and nails (Anker 4x60) were provided by Rothoblaas.

Figure 4 - Compression test

Figure 5 - In-plane shear test

Figure 6 - Failure in a hold-down

2.6 Cyclic test

Cyclic tests using the New Zealand standard (BRANZ P21) [14] were performed. A typical cyclic test is shown in Figure 7. Similarly to the in-plane shear tests, the lower edge of the panel was anchored firmly to the bottom of the testing frame by means of three metal angle connectors at each side of the panel in order to prevent lift and horizontal movements. Hold-down (HHDQ14) and SDS ¼" x 2 ½" screws were provided by Simpson Strong Tie [26]. The shear bracket (TITAN TCN 240) and nails (Anker 4 x 60 mm) were used [27]. In order to safeguard the integrity of the equipment and the measuring systems, the load protocol established by this standard was applied up to the maximum possible; in this way, on one of the tested panels the penultimate value of the horizontal displacement at the upper level was reached, which according to the panel's dimensions is 36 mm. In the other two panels that were tested the load was applied until a maximum horizontal displacement of 29 mm was reached, a value that corresponds to the fourth, of the six indicated in the protocol of the BRANZ P21 standard. No important failures appeared in any of the three panels, with only some small deformations of the screws found.

Figure 7 - Cyclic test

2.7 Fire resistance test

Figure 8 is a front view of one of the samples subjected to the fire resistance test, showing the face of the panel that was not exposed to the fire. Figure 9 shows a side view of the test. Test procedure for determining fire resistance of vertical construction elements and the dictations of Chilean standard NCh935 [22] were applied. The maximum temperature to which the samples were exposed was 900 °C on the side directly exposed to the fire. Each sample was prepared using two CLT panels 2.4 m length, 1.1 m width and 0.12 m thickness, which were joined by a vertical overlap with type WT-T screws diameter 6.5 mm and length 90 mm set every 0.4 m.

Figure 8 - Fire resistance test. Front view

Figure 9 - Fire resistance test. Lateral view

3. Graphical results

3.1 Bending test

Figure 10 shows the average load-deformation curve of the three tested panels (solid line). The dashed line is the average curve of the permanent deformations.

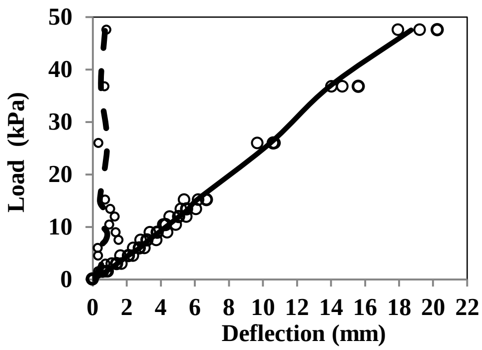

Figure 10 - Load-deflection curve of bending test

3.2 Compression test

Figure 11 shows the average vertical load-deformation of the three tests carried out (solid line). The dashed line is the curve of the average permanent deformations.

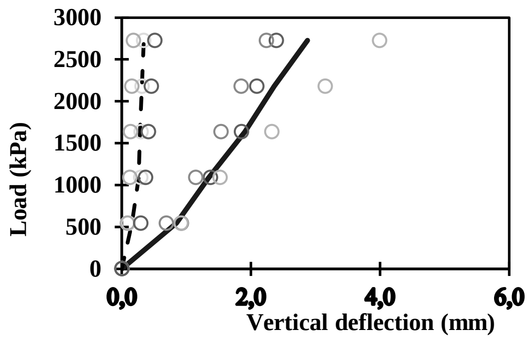

Figure 11 - Load-deformation curve of compression test

3.3 In-plane shear test

Figure 12 shows the loading protocol prescribed by Chilean Standard NCh 802 [25], and Figure 13 presents the average lateral load-deformation curve of the three tested panels (solid line). The dashed line represents the average of permanent horizontal deformations.

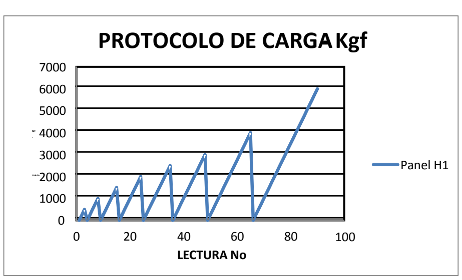

Figure 12 - Loading protocol for in-plane shear test according to NCh 802

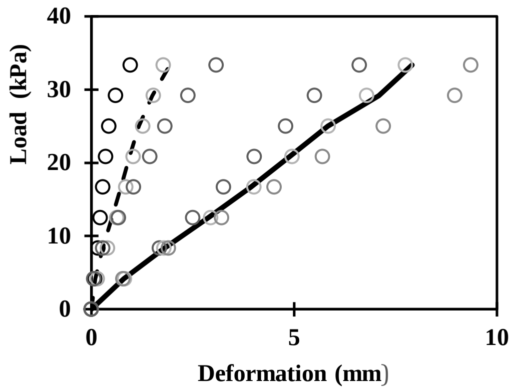

Figure 13 - Lateral load-deformation curve of the in-plane shear test

3.4 Cyclic test

Figure 14 shows the cyclic load protocol according to the New Zealand standard (BRANZ P21) [14] corresponding to the dimensions of the tested panels. Figure 15 presents the hysteresis curve of the panel in which a 36 mm deformation was reached.

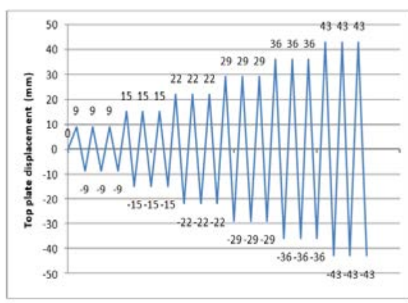

Figure 14 - Loading protocol for cyclic test according to BRANZ P21

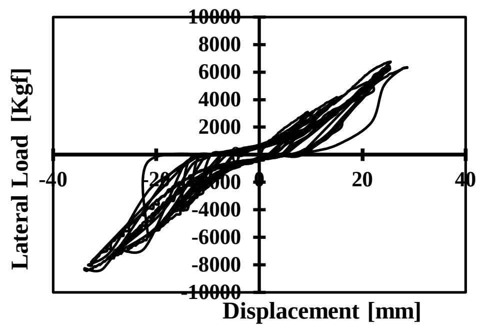

Figure 15 - Hysteresis loops of cyclic test

4. Numerical results

4.1 Static and monotonic tests

Table 1 shows average values of maximum forces applied and maximum average reference stresses determined in bending, compression, and in-plane shear tests. The stresses were calculated considering the linear elastic behaviour theory and a homogeneous material.

Table 1 –Test results

Test	Average max. force applied (kN)	Average max. stress (MPa)
Bending	227.9	22.25
Compression	718.8	5.00
In-plane shear	79.9	0.56

In the interpretation of the results shown in Table 1 it must be kept in mind that failure by breakage of the fibers under tension was achieved only in the bending test of the CLT panels. In the compression test there was no kind of failure, and in the in-plane shear test a brittle failure occurred due to the tension in the hold-down. Therefore, the CLT panel made of Chilean radiata pine, with the considered dimensions in the present study, is able of resisting greater compression stresses and greater shear stresses than those given in Table 1.

Table 2 shows the average values of the bending breakage stress. The bending stiffness was determined by the Gamma method, the K method, the Shear Analogy method, and the simplified method [8]. The average maximum force applied in the bending test, shown in Table 1, was used.

On the other hand, the North American standard [7] gives a value of 6.1 MPa for the allowable stress in bending of the CLT, grade V2, which has properties similar to those of radiata pine, with a modulus of elasticity of 9653 MPa. Therefore, the bending breakage stress of the radiata pine CLT panel is three times greater than the allowable stress of the North American CLT panel grade V2.

Table 2 – Bending tension

Method	Average maximum stress radiata pine (MPa)
Gamma	24.9
K	22.3
Shear analogy	23.1
Simplified	23.1

4.2 Cyclic test

The averages of the maximum lateral load and displacement at maximum lateral load of the three samples of CLT panels are shown in Table 3. The dissipated energy and equivalent viscous damping averages are also included.

The results of the cyclic tests show that the panel-connector system has a low energy dissipation capacity, yielding a 5% value for the equivalent viscous damping, a value lower than those obtained in other studies, where 11%, 14%, and 17% have been determined for this parameter [28, 29, 8,]. However, it agrees with the viscous damping value used in static and spectral methods, of seismic analysis according to Chilean Standard NCH 433 [15]. Therefore, for the seismic design of CLT buildings in Chile using Chilean radiata pine it would be valid to use any of the two methods contained in the standard mentioned above, with a parameter value R that must be determined for the CLT system.

Table 3 – Results of cyclic testing

Item	Average of results
Maximum lateral load (kN)	71.8
Maximum lateral load displacement (mm)	31.2
Dissipated energy (kJ)	4.2
Equivalent viscous damping (%)	5.3

4.3 Fire resistance test

Since there was no structural collapse of the panels, the fire resistance time was defined as that, from the beginning of the test, until smoke started going to the unexposed side of the panel through the vertical joint. That time was 39 minutes for one of the samples and 40 minutes for the other. These results are consistent with those reported elsewhere [30]. Furthermore, the resistance to fire time of CLT buildings can be increased by using gypsum boards [8].

5. R factor estimation

5.1 Considering in-plane shear test results

The average values of the horizontal displacements at the upper level of the panel obtained from the in-plane shear tests were 14.8 mm at the yielding point, and 35.7 mm for the system's failure caused by the breakage of the hold-downs, as shown in Figure 5 [9, 12]. Considering these results, a value of 2.4 was obtained for the ductility of the CLT panel-connector system. Then a conservative value of R = 2.0 is proposed, lower than 5.5 which is established by the Chilean standard for wooden structures [15].

5.2 Considering cyclic test results

In the cyclic tests the system's failure was not reached, since the methodology of the standard used [14] does not require it, and attention was placed on the protection of the equipment's integrity. But considering the numerical results obtained [21], a conservative value of 2.0 is also proposed for R.

6. Storey drift estimation

6.1 Considering test results

As already mentioned, the average value of the maximum horizontal displacements at the top level of the panel, obtained from the in-plane shear tests, was 35.7 mm for the system's failure caused by breakage of the hold-down, and 31.2 mm in the cyclic tests, as shown in Table 3. It was already mentioned that in the latter case the system did not fail any way.

Based on these results and on the values prescribed by the international standards for timber construction [31], a value of 1.0% can be proposed for Chilean standard NCh 433 for the maximum storey drift of mid-rise buildings made with radiata pine CLT.

6.2 Considering a mid-rise prototype

In a previous paper [11] a design was made of a mid-rise building prototype for a social housing solution in Chile. American and Canadian standards [7, 8] and guidelines were adopted [32], with some modifications for CLT based on typical Chilean radiata pine. A four-story building with a structure made of CLT panels was designed and used to demonstrate the technical feasibility of a building with CLT panels in Chile. An R factor of 3, and an over-strength factor of 2 for the connectors were used. With these R values it was possible to comply with the storey drift limit of 0.2% specified by the Chilean standard [15].

Considering these results and an R value of 2 proposed in the present study, it is possible to propose a value of 0.5% for the maximum storey drift to the Chilean standard, which is more conservative than those of international standards.

7. Conclusions

Mechanical characterization of three-ply cross-laminated timber panels made of Chilean radiata pine (2.5 m height, 1.2 m width and 0.12 m thickness) has been presented. Maximum bending strength values of the panel were obtained. In the case of in-plane shear strength test, the panel's strength could not be measured because the hold-down broke in tension, without the panel CLT undergoing any damage. This result could be expected because the strength of the construction system with CLT, and in general of wooden structures, is largely dependent on the strength of the connectors. No failures occurred in the compression tests because the CLT panels have a great resistance.

Resistance to fire, the results obtained were consistent with existing information on the CLT construction system at international level.

Concerning to seismic behaviour of the system, the results indicate an energy dissipation capacity lower than that reported in literature on the matter, with an equivalent viscous damping average of 5%, but it must be kept in mind that this capacity depends mainly on the connectors used. In Chile this value allows the use of the national standard for seismic design, because both, the calculating formulas for seismic coefficient and acceleration design spectrum have been determined for 5% damping.

Based on the results obtained, a conservative value of 2 is proposed for the seismic response reduction factor (R) to be incorporated into the Chilean Seismic Building Design Standard, NCh433, in the specific case of mid-rise buildings based on CLT wall structures. Furthermore, it is proposed to incorporate a value of 0.5% for storey drift for this kind of buildings.

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