World Conference on Timber Engineering Oslo 2023

DIMENSIONAL VARIATIONS MONITORING OF RADIATA PINE CLT PANELS: A CASE STUDY IN CONCEPCIÓN, CHILE

Víctor Rosales[1], Fernanda Pascal[2], Franco Benedetti[3], Pedro Rebolledo[4], Alan Jara-Cisterna[5], Mauricio Vargas[6]

ABSTRACT: Variations in wood moisture content lead to changes in virtually all physical and mechanical properties of timber. Besides, the damage to building elements is usually associated with unfavorable changes in material properties, support conditions, geometry, or load variations that can influence the structure's performance or durability. This research is oriented to monitoring the behavior of a CLT module prototype under the action of humidity, simulating the possible changes resulting from its use as a habitable space. With these field measurements, we study the dimensional variation of wall elements and moisture content in the structural panels in order to explore the possible behavior of the PymeLAB experimental building PymeLAB, a 5-story living laboratory that was installed on campus from the University of Bío-Bío during 2022. In this study, a prototype has been manufactured with conditioned 3-layer Radiata pine CLT panels with an initial moisture content of 11.6%. Dimensional changes caused by different humidification cycles were measured. The change in the moisture content of the internal face of the CLT panels exposed to the indoor climate showed increases in deformations of up to 1.74 mm/m.

KEYWORDS: Monitorig CLT, Moisture expansion, hydrothermal performance, CLT Radiata pine.

1 INTRODUCTION

Since the climate of Chile is quite varied, the moisture content of the wood in service varies from one region to another according to the differences in temperature and humidity. Consequently, there are 9 climatic zones, from the desert north to the extreme south [1].

Each building must be subject to a site assessment that considers the impact of seasonal weather conditions associated with the location, the structure, and its behavior in use. Its conditions of use will also have repercussions on the behavior of the building. For example, structures with exposed CLT are not usually used due to construction regulations associated with fire. However, knowing the behavior of uncovered CLT panels allows us to propose its behavior for combination with other interior and exterior cladding materials.

Hygroscopic materials can absorb moisture from the air when its relative humidity rises and release moisture into the air when it falls. These humidity variations result in dimensional variations in the wooden elements, which can cause problems in their connections or sheathings [2], resulting in post-sale costs in the buildings. The damp-absorbing effect of building materials can greatly influence the indoor hygrothermal environment [3]. Moisture absorption/release by hygroscopic materials can be calculated with the basic MBV factor, where the density and porosity of the materials are essential properties in the theoretical calculation of moisture buffering because these factors are likely to influence moisture transport. In addition, air velocity plays a relevant role in the sorption performance of materials. To obtain comparable results, various humidity buffering protocols require that the air velocity be constant and around 0.1 m/s during the tests [4]. Humidity and buffering capacity depend on several factors, from which porosity and temperature are influential; therefore, the moisture buffer values for bio-based materials have been measured at a constant temperature of 23°C [5].

One of the performance demands for buildings is durability, which in the case of wood can be greatly affected by prolonged exposure to moisture [6]. Moisture changes in wood are accompanied by deformations such as shrinkage and swelling. In particular, the prolonged exposure of wooden constructions to the effects of

[1] Victor Rosales, University of Bio Bio, Chile, vrosaleg@ubiobio.cl Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile.
[2] Fernanda Pascal, University of Bio Bio, Chile, fernanda.pascal1801@alumnos.ubiobio.cl
[3] Franco Benedetti, University of Bio Bio, Chile, fbenedet@ubiobio.cl
[4] Pedro Rebolledo, University of Bio Bio, Chile, prebolle@ubiobio.cl
[5] Alan Jara-Cisternas, University of Bio Bio, Chile, afjara@ubiobio.cl
[6] Mauricio Vargas, University of Bio Bio, Chile, mvargas@ubiobio.cl

https://doi.org/10.52202/069179-0070

humidity affects the durability and safety of the constructions [7].

Wang et al. (2018) point out that dimensional changes [8], moisture damage and microbial growth must be considered. These can eventually occur with short-term wetting or high relative humidity (RH) (80% to 95%), where the cycles of contraction and swelling of the wood can compromise the mechanical connections due to the degree of humidity exposure. On the other hand, it is pointed out that cracks are attributed to seasonal variations influenced by the internal climate that occurred in the buildings, which is associated with the process of contraction and swelling of the wooden elements. Also, shrinkage and swelling can affect the durability and stiffness of the connections [9].

Sung & Gi (2019) studied the swelling and contraction behavior of Larix kaempferi and Pinus koraiensis, analyzing CLT boards in a controlled environment [10]. From the results, they were able to distinguish that larger deformations were observed in the "y axis" (radial axis, perpendicular to the growth of the fibers) with respect to those perceived in the "x" and "z" axes. They also discriminated that the thickness does not lead to a tendency in the swelling and contraction behavior. However, the combination of the layers is of great relevance since the layers in the longitudinal direction of the panel give it dimensional stability in the x and z axes. According to the research carried out by the authors Schmidt et al. (2017), it is possible to accelerate or stimulate the wetting process to evaluate the performance of CLT panels against deformationsn using a multi-chamber modular environmental conditioning method.

Authors as McClung et al., Wang, Lepage et al., Kordziel and Schmidt et al., cited in the work of Schmidt et al. [6], carried out laboratory-scale experiments emphasizing the monitoring of the wetting and drying behaviors of large CLT samples, thought as the effect of water attacking the faces of the panels (rain). In addition, McClung et al. found that 5-layer CLT samples soaked by immersion for one week with epoxy-sealed edges and subsequently integrated into assemblies of variable permeability were generally within acceptable MC ranges (<26%) after one month, and most of them were dry after 4 to 6 months [6].
According to EN16351 [11], Service Class (SC) 1 is characterized by a moisture content in materials corresponding to a temperature of 20°C, and the relative humidity of the surrounding air only exceeds 65% for a few weeks in a year. In SC 1, the average moisture content in most softwoods will not exceed 12%. Service class 2 is characterized by a moisture content in the materials corresponding to a temperature of 20 °C, and the relative humidity of the surrounding air only exceeds 85% for a few weeks of the year. In SC 2, the average moisture content in most softwoods will not exceed 20%. For its part, SC 3 is characterized by climatic conditions that lead to higher moisture content than in SC 2. Additionally, the standard propose values for the adjustment of the in-plane moisture deformation (0.0002) and perpendicular to the plane (0.0024). These parameters are considered in an expression for the correction of the size for moisture contents within the range from 6% to 25% in the species recognized in the standard. The existing formula in the EN standard predicts CLT contraction and expansion as a function of the CLT coefficient. The limitation of this approach is that the dimensional change of CLT cannot be estimated before measuring the actual CLT coefficient. CLTs of various layer combinations can be manufactured, thus, the dimensional characteristics would differ depending on the layer combinations [10].
A study on moisture in edge-glued wood panels found that a 1 percent change in moisture in White Pine will change the width of a 75mm wide board by 0.05 to 0.15mm. In addition, the study showed that boards gain or lose moisture 10 to 15 times faster from the ends than from the faces and sides of the panel. In contrast, for CLT panels, this is less due to the element's configuration, but a different behavior is expected at the ends of the pieces.

Han et al. [7] used samples with different moisture contents in the layers that make up the CLT elements to study the effect of the moisture difference. The humidification processes were carried out within a period of 3 weeks. After humidification, the changes in width and thickness of the samples were measured during drying under two conditions (80% and 40% relative humidity). The results showed that the dimensional changes of the CLT samples tended to be repeated in shrinkage and swelling, which depended on the humidity variation. Both the shrinkage and the swelling in the width of each sample varied from 0.492 to 2.145 % and from 0.459 to 2.542 %, respectively [7]. For the samples made with a similar moisture content between the inner and outer layers (difference less than 1.6%), the variation in shrinkage and swelling were less than 1.5%.

Schwab et al. [12] investigated the swelling coefficient for a thickness of 20 mm in sheets of European spruce CLT. They found that in the X,Y,Z directions the swelling ceofficient was from 0.00031 to 0.00038, respectively. For their part, Gereke et al. [13] investigated the swelling coefficient for a 30 mm sheet thickness Fagus sylvatica CLT. The swelling coefficient found for the X,Y,Z direction was 0.00011, 0.0023, and 0.00009, respectively. The swelling shrinkage coefficient in the Y direction was approximately 21 and 26 times higher than in the X and Z directions, respectively.
3-layer panels (90 mm thick) of Korean larch (larix kaempferi, 500 kg/m3) and Korean pine (pinus koraiensis, 410 kg/m3) were investigated to predict the dimensional change of CLT from the dimensional change of the sheets. In order to know the swelling, small samples were conditioned at 7.7% moisture

https://doi.org/10.52202/069179-0070

content, which were then brought to 19% and later to a saturated state. For this type of panels of the Korean larch species, in the x direction, a swelling and contraction value of 0.000217 and 0.000507 respectively was achieved; for the z direction 0.000150 and 0.000223 respectively. Using the same CLT panel configuration, but of the Korean pine species, in the x-direction, a swelling and contraction value of 0.000216 and 0.000467 respectively was achieved; for the z direction 0.000117 and 0.000183 respectively. [10]

Given the lack of knowledge about the moisture-deformation behavior of Radiata pine CLT boards subjected to temperature and humidity variations under operation conditions, this work studies the dimensional variation of a full-scale CLT module located in the University of Bio-Bio (Concepción, Chile).

2 MATERIALS AND METHODS

This work focuses on the behavior of a CLT prototype against inner climate variation by monitoring the variation in the in-plane CLT climate response. The workflow considered five humidity cycles of 3 weeks long each.

During the entire test period, the University of Bío-Bío on-site weather station recorded the outdoor weather data, and monitoring equipment recorded the indoor weather. A daily humidity production cycle was chosen, whose maximums are short but intense depending on the relative humidity level necessary to reach the value established by the control equipment.

Sensors were installed in the prototype to continuously record the following parameters: temperature and relative humidity in the center of the module. Here only the measurement parameters temperature and relative humidity are considered.

The interior temperature is maintained at 20°C by a control regulating an electric radiator. The relative humidity is measured in the center of the room at a height of 1.2 m. In addition, the air from the fans is kept at 0.1 m/s.

The ambient temperature remained constant at 20 °C except for a few days, in which this temperature was exceeded for some hours due to intense solar radiation. The damping effect on humidity is more important over 50% in relative air humidity, an environment in which fungal growth is favored. According to the type of panels used in this research, those with no treatment, sealing, or sheathing, are defined as open type, which is not always the case employed in common practice.

2.1 PROTOTYPE DESCRIPTION

The CLT panels were manufactured in the Wood Design and Technology Laboratory facilities of the University of Bío-Bío, Concepción. Kiln-dried radiata pine lumber having a 12% (+/-2%) moisture contente were used. The average density of the lumber boards was 398 kg/m^3, and were mechanically classifiedas C16 according to EN338 [14]. Boards were planed to 18 x 130 and 33 x 130 mm thicknesses, and then edge and face glued with PU-1 K polyurethane adhesive. For the curing of the adhesive, a hydraulic press was employed, applaying a pressure of 0.8MPa. The final dimensions of the CLT panles was 99 x 1200 x 1960 mm (33 x + 33 y + 33 x) for the walls and 84 x 850 x 3600 mm (33 x + 18 y + 33 x) for the floor and ceiling. In one of the panels, electrodes were installed to measure and monitor the moisture content from the beginning of the process.

In order to make the joints, a half-wood milling process is carried out on the edges of the CLT panels, with a dimension of 33 x 60 mm. A C16 Radiata Pine board of 33x119mm was employed to produce the joint between panels, fastened with screws arranged every 70 mm. The elements are assembled using the traditional techniques for this type of construction system, which is based on the use of screws in the corners for the wall-wall connection, angle bracket for the wall-floor connection, and screws for the wall-ceiling connection. Figure 1 presents general views of the module used for the study.

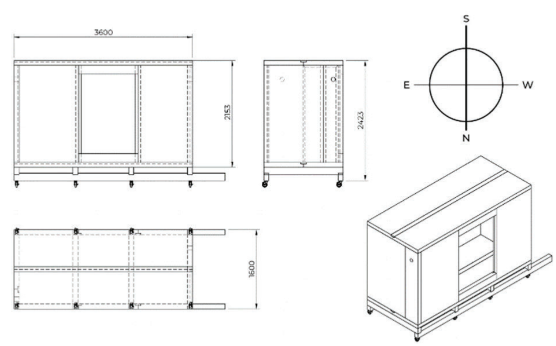


Figure 1: *Floors and elevation plan (left) and 3D view of prototype.*

After the assembly, the sealing tasks were carried out with tapes and membranes that reduce the infiltration and transfer of steam. The edges of the CLT panels were not sealed. Besides, thermal insulation and sheathings were installed on the exterior face. The module has an access door of 42 x 600 x 2300 mm and windows of 500 x 1600 mm located on the north side, which use a thermopanel with a U value of 1.8 W/m^{2}K. The thermal transmittance value of the envelope for the wall is U=0.46 W/m^{2}K, which is obtained from the constructive conformation of the wall (99 mm CLT of Radiata Pine with 50 mm of mineral wool).

On the outside and at the height of 2500 mm, a temperature and relative humidity recorder was located in the shade, which captures the climate data of the surrounding zone. Inside, two Yowexa-Japan temperature and relative humidity recorders were installed, located at the same interior height (1200 mm) but in 2 different positions. To regulate the indoor climate, a climate unit and a series of humidifiers are installed and connected to an automatic temperature and humidity control system, which was set to control each cycle.

2.2 INSTRUMENTATION

The panels were coded as N, S, E, O (North, South, East, and West), gridded every 300 mm, and in selected zones of the grid, humidity sensors (electrodes) and digital transducers were installed on a Whittemore-type device. The humidity sensors were installed at different depths (P1=21 mm, P2=27 mm, and P3=32 mm), completing a thickness of 1 lamina constituting the CLT, as shown in Figure 2.

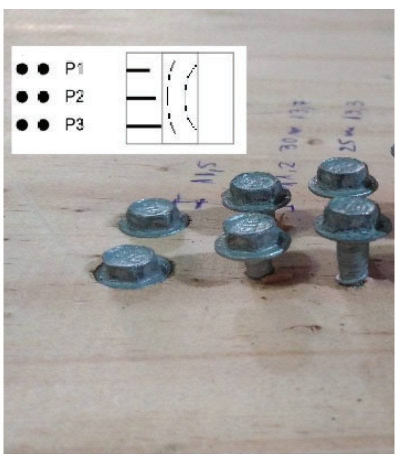


***Figure 2**: Installation of the moisture monitoring electrodes at different depths (P1, P2 y P3)*

Displacement transducers were installed in the area close to the moisture measurement points to evaluate the in-plane deformations of the panel (X, Z plane). Two measurement zones were considered to evaluate the horizontal deformations in the same panel (SX1, SX2), one to measure the complete deformation of the panel plus one joint (SX3), and one for the evaluation of the vertical deformation (SZ3). Depending on the sensor installed, the distance between these two points is around 500 mm to 600 mm. and 1085 mm for SZ3. The layout of the instruments is schematized in Figure 3.

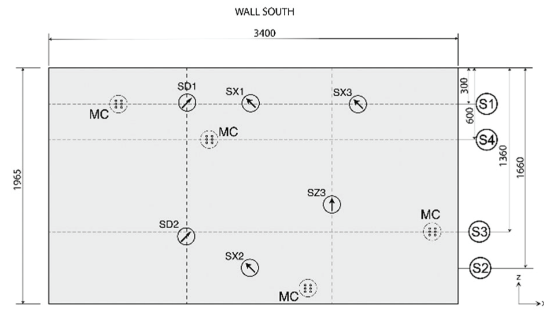


***Figure 3:** Layout for moisture (MC) and displacement metering (S X and SZ) metering.*

2.3 CLIMATE CONDITIONS

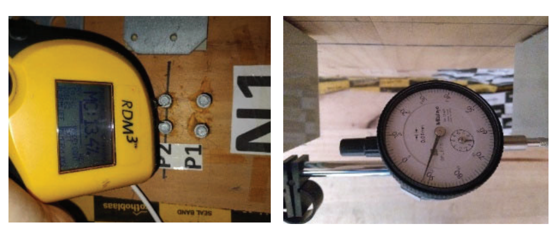
The climate used to develop of the experiment considers a temperature of 20 ° (+/- 2°C), and relative humidity (RH) that varies by stages, increasing from 60% to 90% (+/- 3%). Consequently, five stages of indoor climate conditions were defined (Table 1), distinguishing Stage 1: (conditioning) 60% RH; Stage 2: 65% RH; Stage 3: 75% RH; Stage 4: 85% RH and Stage 5: 90% RH. The measurements began on November 2, 2021, and ended on February 3, 2022. The module's external weather conditions corresponded to the Nonguén area's climate (Concepción, Chile) during spring 2021 and summer 2022.

***Table 1:** Climate conditions during the experiment*

Cycle	Days	Inside		Outside	
		Mean RH (%)	Mean temp (°C)	Mean RH (%)	Mean temp (°C)
Stage 1	0-20	59,6	20,5	64,6	16,3
Stage 2	21-43	66,0	21,0	65,3	16,8
Stage 3	44-62	77,1	21,7	68,2	17,7
Stage 4	63-78	84,7	21,7	70,4	18,1
Stage 5	79-94	90,6	21,4	70,1	17,2

2.4 MONITORING SETUP

The deformations in the CLT panels were recorded at constant intervals (two times a day) using Mitutoyo instruments. In addition, the moisture content of the different panels was recorded three times a week, through a RDM^3 Delmhorst resistive xylohygrometer (Figure 4). Additionally, it was necessary to measure the interior climate of the module (Temperature and Relative Humidity) at 30 min intervals, measuring the room temperature at two different points.



https://doi.org/10.52202/069179-0070

Figure 4: Moisture content (left) and displacement (right) measurement instrument.

Critical aspects of installing the moisture content electrodes and the measurements included: (1) avoiding gaps and knots between electrodes, (2) using guides for exact electrode spacing, (3) drilling holes to the exact length of the insulated casing used for the electrode, (4) insert the screws at the same speed and leaving the insulated base leveled with the wood, and (5) ensuring communication with the manual system [15].
The analog displacement gauge has a measuring range of 12mm with a resolution of 0.01mm. However, Huston et al. suggest that electronic instruments are more practical for long-term measurements [16].
The instrumentation arrangement on the wall was intended to monitor the displacements and moisture content of the wood in the nearby area (Figure N°5).

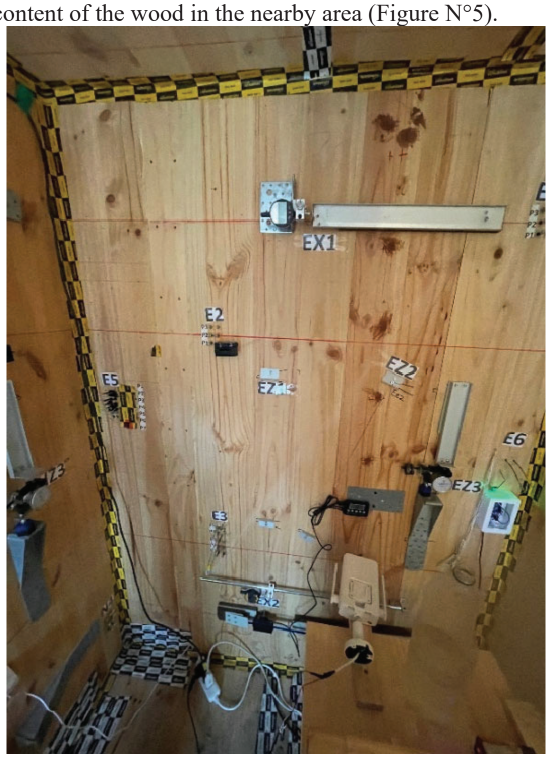


Figure 5: Instrumentation and monitoring system arrangement for the East Wall.

2.5 DIMENSIONAL CHANGE IN CLT WALLS

The expression proposed in the EN16351 standard was used to determine the dimensional change, which establishes a coefficient that depends on the direction (in-plane or out of plane).

$$a_{cor} = a_a \; x \; (1 + K_{cor,\propto} x \left(H_{ref} - \; H_a\right)) \qquad (1)$$

Where a_{cor} = effective dimension (mm); a_a = actual dimension (mm); $K_{cor,\alpha}$ can be either $K_{cor,90}$ = stability coefficient perpendicular to the fiber or $K_{cor,0}$ = stability coefficient in the plane, both expressed for to 1% variation in moisture content between 6% and 28%; H_{ref} = 12%, reference moisture content; and H_a = actual moisture content (%).

3 RESULTS AND DISCUSSION

3.1 POST PROCESAMIENTO DE DATOS Y LA INCERTIDUMBRE DE MEDICIÓN

The literature provides estimates of measurement uncertainty for moisture content based on wood strength, biological variability within a given wood species, and at different moisture contents [15]. In this study, the discontinuous readings were not corrected for the radiate pine CLT given the calibration of the instrument manufacturer for this specie. Moreover, the data collected during the assessments suggest that most of the time, local moisture content fluctuations were clearly correlated with internal weather conditions and the depth of masurement in the CLT panels.

To keep under control the uncertainty, two pieces of 100 x 300 x 450 mm of radiata pine CLT were placed inside the monitored module, and the moisture content was controlled through the instrument and in the laboratory. The moisture content sensors' performance in the CLT module's different positions during the 90 days of the evaluation was consistent with the data obtained from the control samples.

For their part, the instruments that captured the module's temperature and relative humidity were permanently contrasted. Their measurements resulted in being consistent.

The obtained data consist of discontinuous readings for the moisture contents in different positions (North, South, East, and West walls) and depths (P1, P2, and P3), for the deformation of the panel on its corresponding X or Z position. On the other hand, the internal and exterior climate values were recorded continuously.

Both the moisture content data and displacements in the CLT walls are presented in the tables in the following sections. The indoor climate data, as well as the exterior climate data (temperature and relative humidity) are shown as 1-day central moving averages.

3.2 MOISTURE CONTENT MEASUREMENTS

The increase in moisture content inside the prototype module induces an increase in the moisture content of the different panels that set up the walls. Figure 6 shows a comparison of the increases in moisture content at depth P1in the different positions of the module walls (North, South, East, and West).

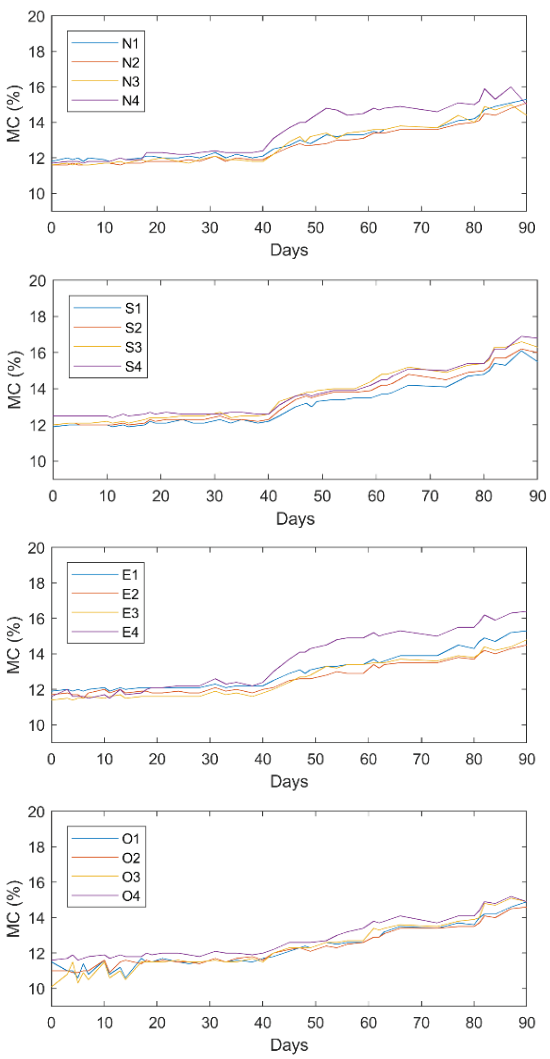


Figure 6: Moisture content variations at P1 depth in walls North, South, East, and West.

In cycle 1 with a temperature of 20 °C and 60% relative humidity (days 1 to 20), the values of moisture content in position P1 have an average value of 11.6 %; which is very similar to the averages at depths P2 and P3 (11.7% and 11.5%, respectively). Besides, for cycle 2 with a temperature of 20°C and 65% relative humidity (days 21 to 43), the moisture content in position P1 is 11.8% on average. In contrast, the moisture contents increase in the other two depths (P2 and P3).

In cycle 3 (days 44 to 62, temperature of 20°C and 75% relative humidity), the moisture content average in the three depths tends to be 12%. For cycle 4 (days 63 to 78, temperature of 20°C and 85% relative humidity), once again, the three depths showed similar average values equal to 13.5%. Finally, in cycle 5 (days 79 to 94, temperature of 20°C and 90% relative humidity), the average moisture content in position P1 are slightly higher than P2 and P3, with values of 14%, 13.7%, and 13.3%, respevctively. The different data are shown in Table 2.

***Table 2:** Moisture content mena values in the CLT walls for each climate cycle and measurement depth*

Stage	RH (%)	Measurement Depth	Initial MC (%)		Final MC (%)	
			Mean	SD	Mean	SD
1	60	P1	11.6	2.11	11.8	0.78
2	65		11.8	0.78	12.0	0.79
3	75		12.0	0.79	13.5	0.65
4	85		13.5	0.65	14.0	0.82
5	90		14.0	0.82	15.4	1.15
1	60	P2	11.7	2.13	11.9	0.81
2	65		11.9	0.81	12,0	0.81
3	75		12,0	0.81	13,0	0.89
4	85		13,0	0.89	13.7	0.84
5	90		13.7	0.84	14.7	1.16
1	60	P3	11.5	2.15	11.8	0.84
2	65		11.8	0.84	11.9	0.82
3	75		11.9	0.82	12.8	0.89
4	85		12.8	0.89	13.3	0.84
5	90		13.3	0.84	14.2	1.17

The results show an important moisture content gradient for cycle 5 in the three measurement depths. The percentage variations of the moisture contents are 15.4% for P1, 14.7% for P2, and 14.2% for P3. These increasings are related to moisture content increments of 3.8%, 3%, and 2.7% for P1, P2, and P3, respectively.

The moisture content measurements also highlighted the trend of the moisture to concentrate at the interface of the first two CLT layers rather than just on the surface. A recent Morrell et al. [17] study also showed this trend. In the results obtained, the damping effect of the CLT without protection can be noticed since the temperature and relative humidity of the environment should have induced an equilibrium moisture content close to 18 %. However, this value is closer to some measurements of the wall panels on the module's south side, as seen in Figure 7.

https://doi.org/10.52202/069179-0070

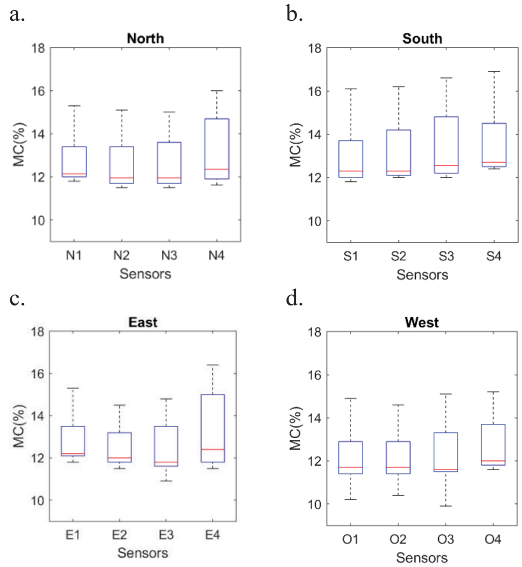


Figure 7: *P1 depth moisture content box plots for walls a) North; b) South; c) East; and d) West.*

The difference between the moisture content measured the north and east wall, appears to be related to the overheating of the wall due to solar exposure in the summer season.

3.3 DIMENSIONAL STABILITY

The dimensional variation suffered by the CLT module during the experiment is presented in Figure 8, which presents the south side wall results. The expressed values correspond to the differentials that happened in the measurement zone (from 500 to 600 mm) detected by the Whittemore gauge system.

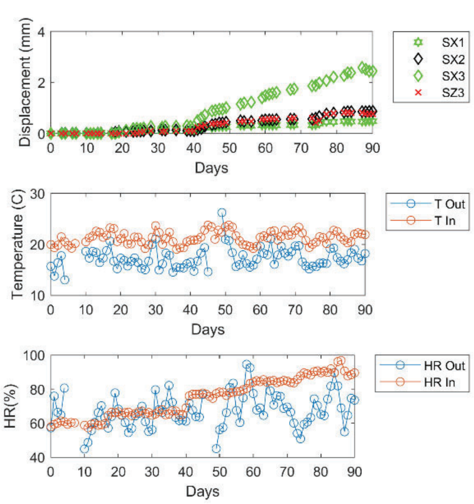


Figure 8: *In-plane dimensional change of South panel (top), interior and exterior average temperature (middle) and relative humidity (RH, bottom).*

The results of absolute experimental dimensional variations for the different walls are shown in Table 3 for the North, East, and South walls. It is noticed that the total displacement values fluctuate from 0.45 mm to 1.59 mm (SX1 and NX2, respectively), depending on the CLT panel and its orientation. The value measured by the SX3 sensor is not considered for mean value, since it is an evaluation that takes the entire width of one panel and half of the connection with the other panel, having an evaluation length of 1085 mm. Besides, the nominal value is determined considering the experimental dimensional variation evaluated in one meter of length.

Table 3: *Total dimensional* ***v****ariation in the different analysis directions in each sensor position and orientation.*

Direction	Sensor	Instrumental value (mm)		Total dimensional Variation	
		Initial	Final	Experimental (mm)	Nominal (mm/m)
X	NX1	0.12	1.29	1.17	2.34
	NX2	0.27	1.86	1.59	3.18
	EX1	10.51	11.37	0.86	1.72
	EX2	-0.06	-0.56	0.50	1,00
	SX1	-0.03	-0.48	0.45	0.76
	SX2	-0.01	-0.87	0.86	1.45
	SX3	0,00	2.45	2.45	2.26
Z	NZ3	-0.02	0.52	0.54	1.03
	EZ3	0.00	0.39	0.39	0.73
	SZ3	0.00	0.77	0.77	1.43

For the X direction (wall width) the average results variate 60% more than in the Z direction (wall height), as presented in Table 4. Besides, it is observed that the nominal displacement that would occur in the panels of 1 meter width (1.74 mm/m) should be considered in the gaps or construction tolerances in order to avoid problems in the connections or differences with the interior sheathings, particularly in wet areas.

Table 4: *Mean total dimensional variation for X and Z directions*

Climate Variation	Direction - Axis	Mean total dimensional variation	
		Experimental (mm)	Nominal (mm/m)
20 °C; RH 60 to 90 (%)	Z	0,57	1,06
	X	0,91	1,74

Due to the constraining action of the cross laminations, CLT has (relative to uniaxial glulam products) more stable in-plane dimensions when it interacts with the environment. The wall samples tested expanded a maximum of 1.59 mm in width (measured transverse to the surface layers) and 0.77 mm in length (measured longitudinally to the surface layers) during all wetting cycles. These deformations are still notably smaller than the nominal calculated values using recommended standard rates that do not take into account the intrinsic characteristics of the Radiata Pine employed.

3.5 STABILITY COEFFICIENT FOR RADIATA PINE CLT PANELS

Using the moisture content data at depth P1 in the area near the displacement measurement zones, it is possible to calculate the experimental stability coefficients through equation (1). These results are presented in Table 5.

Table 5: *Stability coefficient (swelling) calculated per each measuring sensor.*

Direction	Sensor	Total dimensional Variation		Delta MC	K cor,0	Mean Kcor,0
		Experimental (mm)	Nominal (mm/m)			
X	NX1	1.17	2.34	3.5	0.00067	0.00048
	NX2	1.59	3.18	3.3	0.00096	
	EX1	0.86	1.72	3.5	0.00049	
	EX2	0.50	1,00	4.8	0.00021	
	SX1	0.45	0.76	3.7	0.00020	
	SX2	0.86	1.45	4.3	0.00034	
	SX3	2.45	2.26	4.4	0.00051	0.00051
Z	NZ3	0.54	1.03	3.2	0.00032	0.00029
	EZ3	0.39	0.73	3.4	0.00021	
	SZ3	0.77	1.43	4.2	0.00034	

The average value achieved for the plane in the X direction of the CLT walls is 0.00048, 2.4 times higher than the coefficient recommended in the EN16351 standard for the Radiata Pine species. Moreover, the value of the SX3 sensor, which has a longer evaluation length, is close to the mean coefficient calculated, being 0.00051. In the other direction of the plane, Z or longitudinal direction, the average value is 0.00029.

Figure 9 presents a graphical comparison of the experimental stability coefficients with respect to the recommended values of the EN16351 standard.

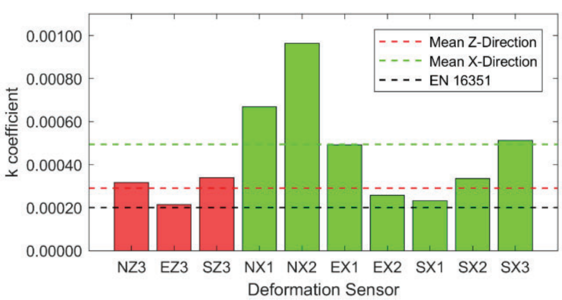


Figure 9: *Comparison of the experimental and recommended stability coefficient values for Radiara Pine CLT panels.*

Finally, in Table 6 is possible to appreciate the values of the swelling coefficient that different authors have achieved.

Table 6: *Comparison of experimental stability coefficient values recommended in different studies.*

Author	Specie	Swelling Value	
		X	Z
Pang S. & Jeang G.	Korean larch	0,000217	0,000150
	Korean pine	0,000216	0,000117
Gereke et al.	Fagus sylvatica	0,000110	0,000090
EN16351	Radiata pine	0,000200	0,000200
Experimental	Radiata pine	0,000479	0,000290

4 CONCLUSIONS

This research monitored the moisture content and dimensional variation based on the relative humidity of the internal climate of a conditioned CLT module, aiming to evaluate if the dimensional changes are within the parameters established in the EN 16351 standard: 2016.

The deformation of the CLT elements under humidity cycles was measured. The in-plane deformations of the CLT increase as the relative humidity of the environment increases in the experimental module. The most important deformations appear when the relative humidity of the environment rises above 75%. After these cycles, the deformations continue to increase.

The Radiata Pine CLT wall panels appear to be dimensionally stable during the development of the experiment. The observed zones expanded on mean 0.91 mm in width and 0.57 mm in height during the conditioning cycles. During the conditioning, the CLT moisture content increased 5.1% at a depth of 21 mm from the surface. The experiment was carried out considering potential conditions of short and long periods of climatic exposure. Even though the construction configuration of the prototype CLT module is atypical (no lining or sheathings were used), this type of test revealed the most critical behavior that the system could have in service. Therefore, it provides relevant information for the variety of climates existing in Chile.

The experience only considered the increase in humidity in the interior climate; thus, only the swelling coefficient was studied to stablish stability. It is suggested to develop experimets to study the behavior of Radiata Pine CLT panels under contraction cycles.

In the tested configuration, the direction of the outer most layer produces a distortion of the CLT laminations on the surface. Those points in which the outer layers of the CLT have pith or central wood suffered larger displacements, especially in the north wall.

Regarding the in-plane dimensional change that the CLT elements of the prototype module experienced, it was observed that these were greater than the values determined using the coefficient recommended in the

https://doi.org/10.52202/069179-0070

EN16351 standard, especially in the direction which is related to the direction of the cut of the wood.

ACKNOWLEDGEMENT

Collaborations of SIMPSON Strong-Tie, CMPC Maderas, Alto Horizonte, Promaest, Forestal Tricahue, JMS Ingenieros, Premad, Cortelima, Constructora IMB, Oxiquim S.A., Láminas Chile, Lemu Products, EBCO, as well as the funding and support provided by MacroFacultad, CIPYCS, and CORFO are deeply acknowledged. Finally, we also thank ANID BASAL FB210015 for their ongoing scientific collaboration with our academic departments.

REFERENCES

[1] Instituto Nacional de Normalización (2008): Nch1079:2008: Arquitectura y construcción - Zonificación climático habitacional para Chile y recomendaciones para el diseño arquitectónico. Santiago, C.

[2] Riggio M., Schmidt E., and Mustapha G.: Moisture Monitoring Data of Mass Timber Elements During Prolonged Construction Exposure: The Case of the Forest Science Complex (Peavy Hall) at Oregon State University. Front. Built Environ. 5:98. 2019 hile:INN

[3] M. Zhang, M. Qin, Z. Chen Moisture buffer effect and its impact on indoor environment IERI Procedia, 2005 (2017), pp. 1123-1129.

[4] Cascione, V.; Cavone, E.; Maskell, D.; Shea, A.; Walker, P. The effect of air velocity on moisture buffering. In MATEC Web of Conferences; EDP Sciences: Les Ulis, France, 2019; Volume 282, p. 02007.

[5] Igue, F.D.; Tran Le, A.D.; Bourdot, A.; Promis, G.; Nguyen, S.T.; Douzane, O.; Lahoche, L.; Langlet, T. Impact of Temperature on the Moisture Buffering Performance of Palm and Sunflower Concretes. *Appl. Sci.* 2021, *11*, 5420.

[6] Schmidt E., Riggio M., Barbosa A., and Mugabo I.: Environmental response of a CLT floor panel: Lessons for moisture management and monitoring of mass timber buildings. Building and Environment Volume 148, January 15 2019, Pages 609-622

[7] Han, Y., Park, Y., Yang, S.-Y., Chung, H., Chang, Y.-S., and Yeo, H. (2019). "Dimensional changes of cross-laminated specimens produced under different conditions due to humidity variation," BioRes. 14(2), 4035-4046

[8] Wang J.Y., Stirling R., Morris P.I., Taylor A., Lloyd J., Kirker G., Lebow S., Mankowski M.E., Barnes H.M., and Morrell, J.J. 2018. Durability of Mass Timber Structures: A review of the biological risks. Wood and Fiber Science. 50: 110-127

[9] Silva C., Ringhofer A., Branco J., Lourenço P., and Schickhofer G.: Influence of moisture content and gaps on the withdrawal resistance of self tapping screws in CLT. In 9º Congresso Nacional de Mecânica Experimental Aveiro, 15-17 de Out., 2014

[10] S.-J. Pang, G.Y. Jeong 2020. Swelling and shrinkage behaviors of cross-laminated timber made of different species with various lamina thickness and combinations Constr. Build. Mater., 240 (2020), Article 117924

[11] EN 16351, Timber structures, cross laminated timber, requirements, European standard, 2016.

[12] E. Schwab, A. Steffen, C. Korte In-plane swelling and shrinkage of wood-based panels Holz Als Roh-Und Werkst, 55 (4) (1997), pp. 227-233

[13] Gereke T, Schnider T, Niemz HA P (2009) Identification of moisture-induced stresses in crosslaminated wood panels from beech wood (Fagus sylvatica L). Wood Sci Technol 43(3):301–315

[14] EN338: Structural timber Strength classes; CEN. 2016

[15] Schmidt, E.; Riggio, M. Monitoring Moisture Performance of Cross-Laminated Timber Building Elements during Construction. *Buildings* 2019, *9*, 144.

[16] Huston, D., Structural sensing, health monitoring, and performance evaluation. 2010: CRC Press.

[17]J. Morrell, I. Morrell, A. Sinha, D. Trebelhorn Moisture intrusion in cross laminated timber and the potential for fungal attack Proc. WCTE 2018 World Conf. Timber Eng. Seoul/S. Korea (2018)