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EFFECTS OF VARIABLE CLIMATE CONDITIONS ON THE BEHAVIOR OF POST-TENSIONED MASS TIMBER WALL PANELS

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ABSTRACT: Post-tensioned (PT) mass timber rocking walls are innovative lateral force-resisting systems used in resilient seismic design. The system relies on an initial tensioning of wall panels using high-strength steel rods. However, tension losses are known to occur in PT systems over time, especially when these systems are exposed to variable climate conditions. In mass timber rocking wall designs, existing creep models do not allow for reliable prediction of long-term PT losses. Thus, the purpose of this research is to characterize the long-term behaviour of PT mass-timber wall panels exposed to variable climate conditions and to develop a model for reliable prediction of the effects of such exposures. The mass timber panels consist of ANSI PRG 320 approved cross-laminated timber (CLT) and mass ply panels (MPP). The components of the complex effect of long-term variable climate exposure are isolated by comparing data collected on similar panel specimens exposed to controlled humidity cycles in post-tensioned and unloaded conditions with those collected on loaded specimens exposed to a constant environment. Panel in-plane deformations, loads, and moisture content in the tested systems are continuously monitored. These tests provide data for the development of an in-plane creep model for mass timber panels that will be validated on two monitored full-scale 9.1 m tall post-tensioned rocking walls, exposed to naturally varying indoor conditions in a large-scale structural testing laboratory for 12 months. This paper summarizes the experimental data collected from specimens in the environment with controlled humidity cycles and the constant environment and some lessons learned. The data shows the following trends: (1) it appears that, during the test time frame and under the imposed changing environmental conditions, the PT system's response is dominated by the in-plane shrinkage and swelling of the specimens, (2) the MC profiles of the PT panels have a significant effect on the panel's strain behaviour, and (3) under constant environmental conditions, the CLT panels experienced more viscoelastic creep compared to the MPP panels.

KEY WORDS: Creep, Mass timber panels, Post-tensioning

1 INTRODUCTION

Utilizing timber in large structures is a sustainable option for construction and is made possible with mass timber panels, such as cross-laminated timber (CLT) and mass ply panels (MPP) [1]. Post-tensioned (PT) mass timber rocking walls have been developed as an innovative lateral force-resisting system to allow for resilient, low-damage seismic designs [2-4]. However, substantial tension losses have been recorded in monitored mass timber panel PT systems [4]. Existing models do not allow for reliable prediction of long-term PT losses, due to sparse data and limited understanding of the complex mechanisms of in-plane deformations in loaded mass timber panels experiencing non-uniform moisture variations induced by variable climate conditions. There is a general understanding that such models must be able to account for dynamic moisture transfer through thick composite panels and contributions of resulting hygro-expansion as well as viscoelastic and mechano-sorptive creep and relaxation [4-8]. This paper presents the experimental study conducted to measure the components of strain resulting from these entangled phenomena. However, in the interest of brevity of this conference paper, the isolation of these components is not included

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herein. The presented study is part of a project carried out at Oregon State University, whose overall objective is to provide data and a functional model to allow engineers to confidently incorporate PT mass timber rocking walls in resilient seismic design.

2 METHODOLOGY

The experimental methodology provides for a comprehensive separation of the contribution of the effects of free hygro-expansion, viscoelastic creep, and mechano-sorption [9].

2.1 MEDIUM-SCALE SPECIMENS IN A CONTROLLED VARYING ENVIRONMENT

A total of twelve medium-scale panels have been tested in a climate chamber that has dimensions of 2.48 m x 2.44 m and can maintain temperatures ranging from -30 ℃ to +40 ℃ and relative humidities (RH) from 10% to 90% (Figure 1).

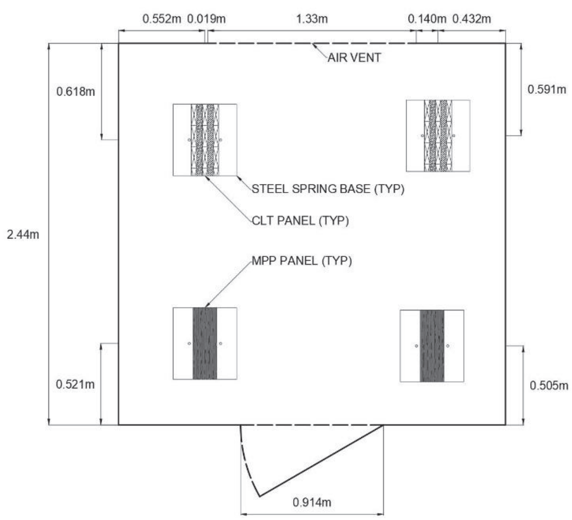

Figure 1: *Plan view of panel layout in climate chamber (approximate actual panel locations).*

Ten specimens are loaded with the tensioning of the PT rods and two are not loaded, designated here as unloaded specimens. One of the unloaded and five of the loaded panels were 5-ply Douglas fir-Larch CLT (1.52 m x 0.457 m x 0.174 m) while the remaining panels were 152.4 mm-thick Douglas fir MPP (1.52 m x 0.457 m x 0.152 m). Since full-scale applications of the mass timber PT wall systems generally have the edges of the walls concealed by other structural components, moisture flow is typically 1-dimensional through the face of the wall [8]. Therefore, in this test, each panel was edge-sealed such that moisture flow was perpendicular to the panel face. Due to the sizes of the panels and the geometry of the chamber, only four panels could be tested at a time thus, there was a total of three batches of specimens. Each test cycle consisted of an initial exposing of the panels to two weeks of uncontrolled environmental conditions to provide more time for the panels to creep under the applied load. Following the two-week period in uncontrolled conditions, three cycles of humidity ranging from 30% RH (two weeks) to 90% RH (two weeks) at constant temperature (20 ℃) were then applied to the panels to determine the complex deformation resulting from the superposition of viscoelastic and mechano-sorptive creep, shrinkage, and swelling [1,5].

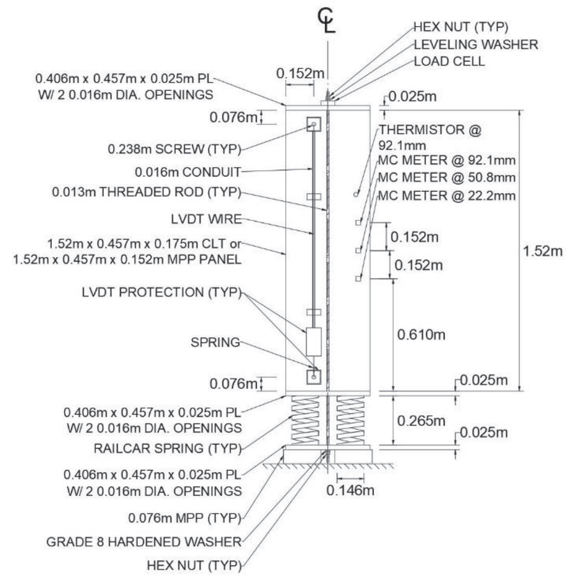

Figure 2: *Test setup for loaded specimens exposed to a controlled varying environment (frontal view).*

Each loaded panel is placed on steel spring bases to minimize the tension losses to less than 2% of the applied force (Figures 2-4). The load is transferred through two post-tensioned threaded steel rods running through holes in the top plate and the bottom of the spring base and monitored by two load cells placed at the end of each rod. The level of applied PT load was chosen to be approximately 7% of the compressive strength of each panel. The loading process was comprised of two phases: during phase 1, the panels were loaded to the chosen level of stress, and during phase 2, the spring bases maintained the applied load within 2% of the initially applied load for the remainder of the test.

The instrumentation setup includes a linear variable differential transformer (LVDT) which measures the vertical deformation of each timber panel. Electric resistance moisture sensors equipped with screws with insulated shafts monitor the moisture content (MC) over an approximate length of 13 mm within the first three plies of the CLT panels and the first, second, and forth plies of the MPP panels as indicated in Figure 5.

Two unloaded reference panels with a similar setup as the loaded panels were tested in the same climate conditions to determine the effect of free shrinkage and swelling [5]. When compared to the loaded panels shown in Figure 2, the unloaded panels did not have a top plate or PT rods installed (Figure 6). The instrumentation on the unloaded panels was similar to the instrumentation installed on the loaded panels except the unloaded panels did not include load cells.

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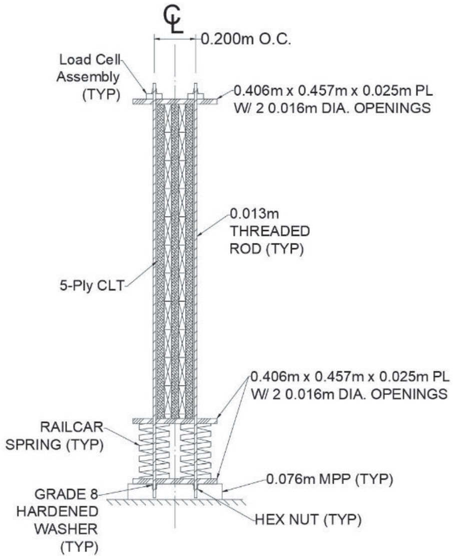

Figure 3: *Test setup for loaded CLT specimens exposed to controlled varying environment (profile cross-section).*

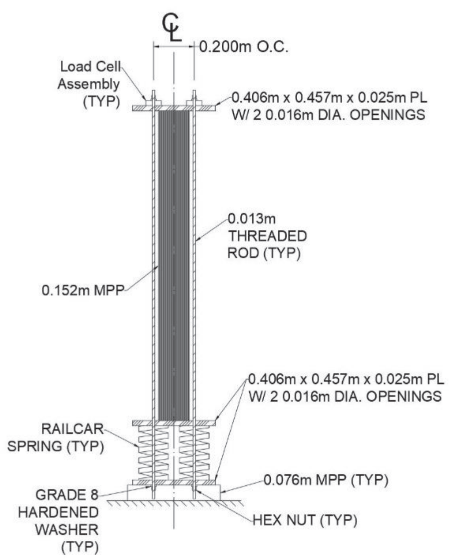

Figure 4: *Test setup for loaded MPP specimens exposed to controlled varying environment (profile cross-section).*

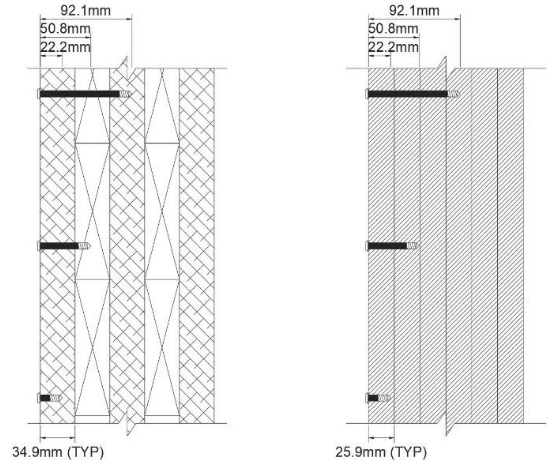

Figure 5: *Electric resistance moisture sensor depths (Left: CLT cross-section along panel height. Right: MPP cross-section along panel height).*

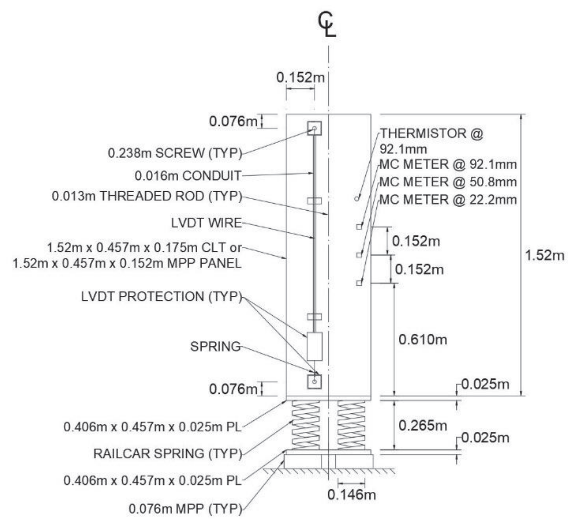

Figure 6: *Test setup for unloaded specimens exposed to controlled varying environment (frontal view).*

For safety reasons, panels were laterally braced with pins at the top of each panel to prevent any tipping motions. The pin connection between the lateral support system and the panels is used to not restrict any vertical deformation of the panels.

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Figure 7: *Test setup inside the climate chamber.*

2.2 MEDIUM-SCALE SPECIMENS IN CONSTANT ENVIRONMENT

Three CLT and three MPP panels of the same dimensions as the specimens described in 2.1 are tested in an environment with constant RH and temperature, to isolate the viscoelastic creep component within the panels [5]. The setup is as described in 2.1 except that the specimens are not instrumented with moisture sensors and are not edge sealed. The specimens are PT-loaded at the same level as specimens tested in variable climate conditions.

Figure 8: *Test setup inside constant climate conditions (sensors unattached).*

3 DATA ANALYSIS AND PRELIMINARY RESULTS

The preliminary results presented in this paper include the two unloaded specimens, and six of the ten PT specimens tested in the controlled and varying environment. Additionally, approximately 10.5 months of data from the six specimens in the constant environment are presented. Data processing consisted in three phases: (1) Offsetting, (2) Signal Processing, and (3) Calculations.

3.1 DATA OFFSETS

Prior to loading each specimen, the LVDTs were physically adjusted such that the output reading was approximately zero. However, the readings were not exactly zero, therefore, during post-processing, offsets were applied to the displacement readings of each sample. For consistency, the average of the first three data points prior to the beginning of the loading process was taken as zero displacements and then used as the offset for the respective specimen.

Additionally, the average percent MC (calculated as described in section 3.3.4) of the loaded MPP panel in the first batch of samples had a portion of data with unnatural changes in MC during the third dry cycle. Therefore, for this section of data only, the data line was smoothed to eliminate the obvious signal offsets.

Offsets to zero the load cells were not applied during post processing since at the beginning of the tests, offsets were initially programmed into the data acquisition system. However, for the panels in the constant environment, there were portions of data that had rapid changes in loads throughout the tests. Therefore, the data line was smoothed to eliminate the large erratic changes in measured load.

3.2 SIGNAL PROCESSING

Signal irregularities such as unexplained spikes were removed by means of a median filter with an overall window of 13 data points determined iteratively until all artifacts were removed. It should be noted that the median filter was applied once to the offset LVDT readings, the load cell readings, and the average moisture contents (calculated as described in section 3.3.4).

3.3 CALCULATIONS

The measured data were used to determine the following derived quantities: 1) panel displacement, 2) average strains in the panel, 3) average panel stress, and 4) average moisture content in the panel.

3.3.1 Panel-spring displacement

For the panels in the constant climate only, the LVDT signals were erratic and inconsistent with what would be physically expected. Therefore, the displacements of these panels during loading phase 2 were calculated using the corresponding phase 2 load cell data in combination with the stiffnesses of the spring bases following the general relationship:

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$$\delta = \frac{F}{k} \quad (1)$$

in which δ is the displacement of the spring base, F is the force applied to the system, and k is the stiffness of the spring base. At the start of loading phase 2, after the spring bases were compressed under the initially applied load, the displacements of the spring bases would be equal to the displacements of the panels. Therefore, the point at which each panel was fully loaded (beginning of phase 2) was assumed to be zero displacement within the panel.

3.3.2 Panel strain

Following typical convention, positive strains measured indicated panel growth while negative strains indicated panel contraction. Since the LVDTs on the panels in the climate chamber did not have erratic readings, the average longitudinal strains (ε) in the panels were calculated based on the readings from the LVDTs as:

$$\varepsilon = \frac{\delta_{LVDT}}{l_0} \quad (2)$$

where l_0 is the initial length of the specimen between the wood screws used to secure the LVDT wire to the sample (or 1371.6 mm), and δ_{LVDT} is the displacement reading from the LVDT.

For the panels in the constant climate, δ_{LVDT} in Equation 2 was substituted with δ calculated by Equation 1 and l_0 was assumed to be the panel's undeformed height (1524 mm). It should be noted that assuming l_0 to be equal to the panels' undeformed height is not entirely accurate since after loading, the panels would deform elastically and would therefore be shorter overall. However, this assumption gives a reasonable approximation.

3.3.3 Panel stress

The engineering stress (σ) in each panel was calculated using the readings from two load cells as:

$$\sigma = \frac{P_1 + P_2}{A_{panel}} \quad (3)$$

where P_1 and P_2 are the loads measured by the load cells applied at the two post-tensioned rods and A_{panel} is the cross-sectional area of the panels (CLT: 0.080 m^2, MPP: 0.070 m^2).

3.3.4 Average panel moisture content

The average MC in each panel was calculated using data from the resistance sensors embedded into each panel at the various depths shown in Figure 5. More specifically, the first three plies of the CLT panels were monitored while the first, second, and fourth plies of the MPP panels were monitored. Since the panels are symmetric, it was assumed that the moisture profile in the panels would also be symmetric around the centre thickness. Therefore, since the MPP panels have an even number of plies (i.e., six, 25.9 mm-thick plies), the average of the three percent MC readings of each panel can be taken to represent the overall average panel percent MC ($MC_{MPP\ avg}$):

$$MC_{MPP\ avg} = \frac{MC_{ply1} + MC_{ply2} + MC_{ply4}}{3} \quad (4)$$

where MC_{ply1}, MC_{ply2}, and MC_{ply4} are the percent MC readings of the 22 mm, 51 mm, and 92 mm long sensor pins in the MPP panel, respectively.

However, since the CLT has five plies, a weighted average percent MC ($MC_{CLT\ wavg}$) was calculated assuming the sensors capture the percent MC in ply one, ply two, and half of ply three. The equation is as follows:

$$MC_{CLT\ wavg} = \frac{MC_{ply1} + MC_{ply2} + 0.5MC_{ply3}}{2.5} \quad (5)$$

where MC_{ply1}, MC_{ply2}, and MC_{ply3} are the percent MC readings of the 22 mm, 51 mm, and 92 mm long sensor pins in the CLT panel, respectively.

3.3.5 Interpolation of data

Due to differing time steps for the data within both batches of samples tested, it was necessary to interpolate between data points so that displacements and MCs could be compared at specific points in time. Therefore, each data set was linearly interpolated between measured data points to get the displacement and MC readings every 30 seconds throughout the entirety of the tests.

3.3.6 Cumulative moisture content

Although the same humidity cycle program was applied to both batches of samples, the differences in initial MC in the panels, the first two-week period after loading in uncontrolled environments, and mechanical issues with the climate chamber resulted in variability of specimen initial conditions. Because of this, it is difficult to directly compare the deformations recorded on separate batches of panels tested with different humidity programs in the time domain. To facilitate a more meaningful comparison, the cumulative moisture content (CMC) in each panel was calculated (Equation 6) to present strains as a function of CMC rather than time [9], where the CMC is given by:

$$CMC = \sum_{0}^{i} |MC_{i+1} - MC_i| \quad (6)$$

where MC_i and MC_{i+1} is the i^{th} and i^{th}+1 average percent MC sensor readings of an individual panel, respectively.

Each CMC value aligns with a corresponding measured strain value thus allowing for convenient comparison.

3.3.7 Summary of data

Figures 9 and 10 summarize the environmental and moisture content data from the first and second batches of CLT and MPP samples tested in the climate chamber in the time domain. Additionally, Figures 11 and 12 summarize the strain and CMC data from the first and second batches of CLT and MPP samples tested in the climate chamber presented in the time domain. The first batch of samples included one loaded CLT and one loaded MPP panel and the two unloaded panels used to capture the free shrinkage and swelling. The second batch of

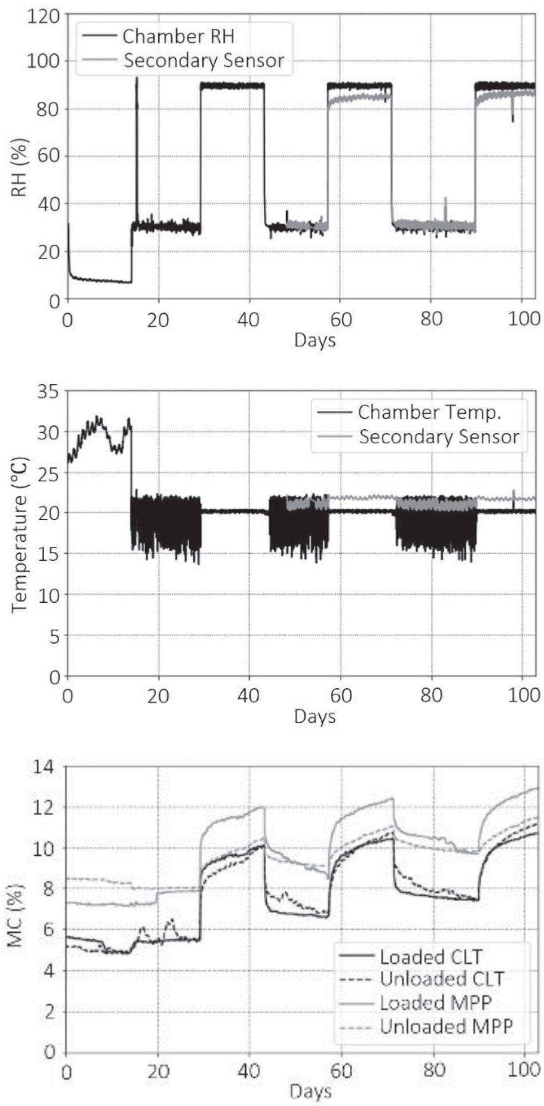

Figure 9: *Batch one environmental and MC data (top: RH over time, middle: temperature over time, bottom: weighted average percent MC over time).*

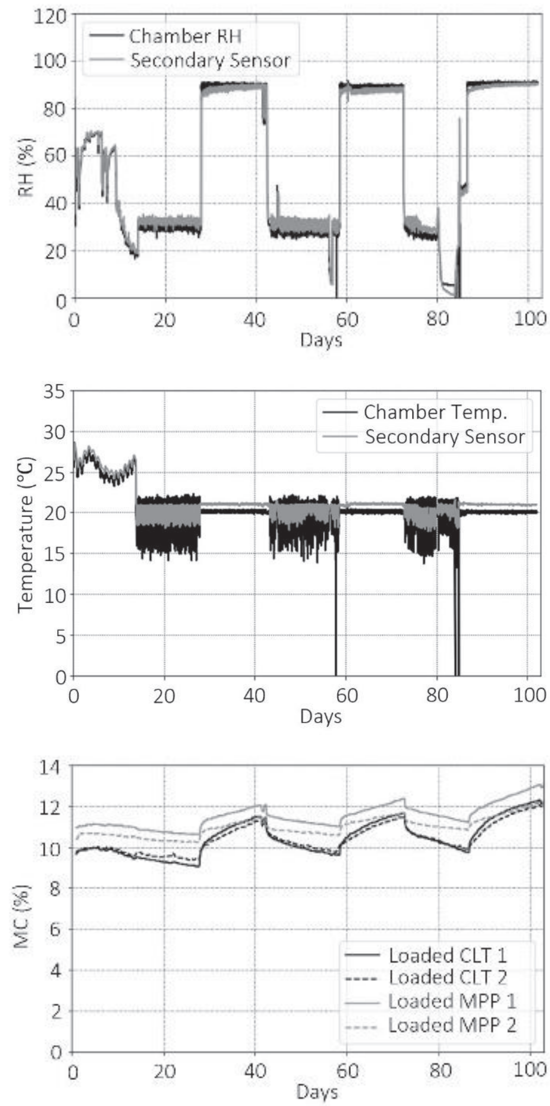

Figure 10: *Batch two environmental and MC data (top: RH over time, middle: temperature over time, bottom: weighted average percent MC over time).*

samples included two loaded CLT panels and two loaded MPP panels. It should be noted that during the second batch of tests, one of the MPP panels was unloaded and re-loaded approximately seven days into the test period in the uncontrolled environment. Therefore, the plots show data for this particular panel starting at the point in time just before the reloading. Throughout the tests, the spring bases were able to maintain the applied stresses within 2% of the initially applied stress. As seen in the strain vs. time plots in Figures 11 and 12, during the first 14 days after initial tensioning, the deformation in the panels was dominated by shrinkage and swelling due to the uncontrolled conditions in the chamber environment (approximately 6-10% RH and 26-32 ℃ for the first batch and 16-70% RH and 23-29 ℃ for the second batch). Following the commencement of the first dry cycle on day 14, a rapid increase in strain indicates a sudden expansion in the panels equilibrating to the 30% RH. As each dry and wet cycle commence, the rate of strain changes. During the dry cycles, the strain rates are negative indicating the effect of shrinkage due to a loss of moisture to the surrounding environment. During the wet cycles, the strain rates are positive indicating the effect of swelling induced by the gain of moisture from the ambient environment.

Unexpectedly, however, the overall trends in the strain of the first batch of samples indicated that the loaded CLT panel (and portions of the loaded MPP panel) experienced more elongation than the unloaded panels.

Based on the strain vs CMC plots, each of these described trends are reiterated; the panels from the second batch experienced less strain and less CMC compared to the first. After plotting the response of both batches of panels together in Figure 13, it can be seen that the free shrinkage

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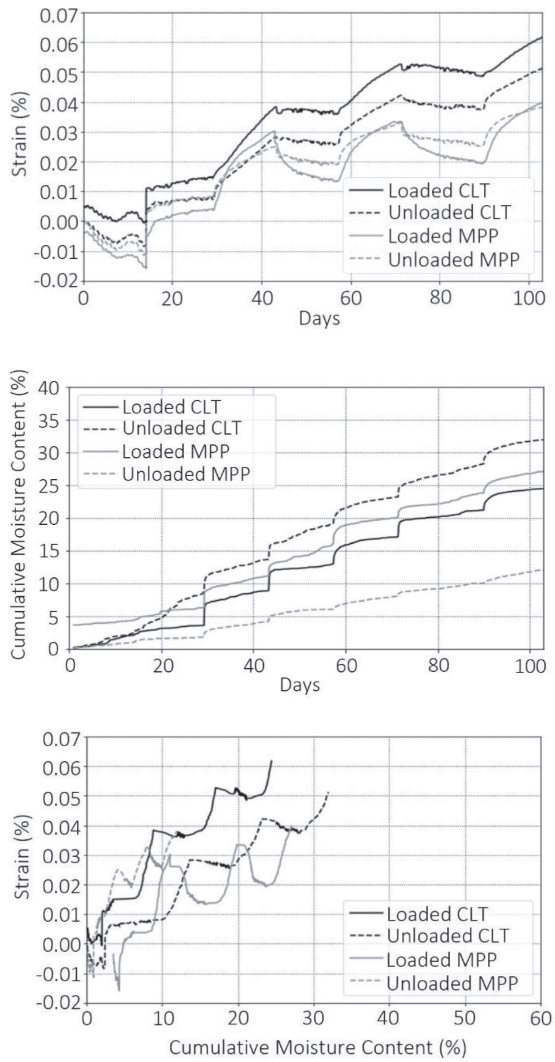

Figure 11: *Batch one specimen data (top: strain over time, middle: CMC over time, bottom: strain versus CMC).*

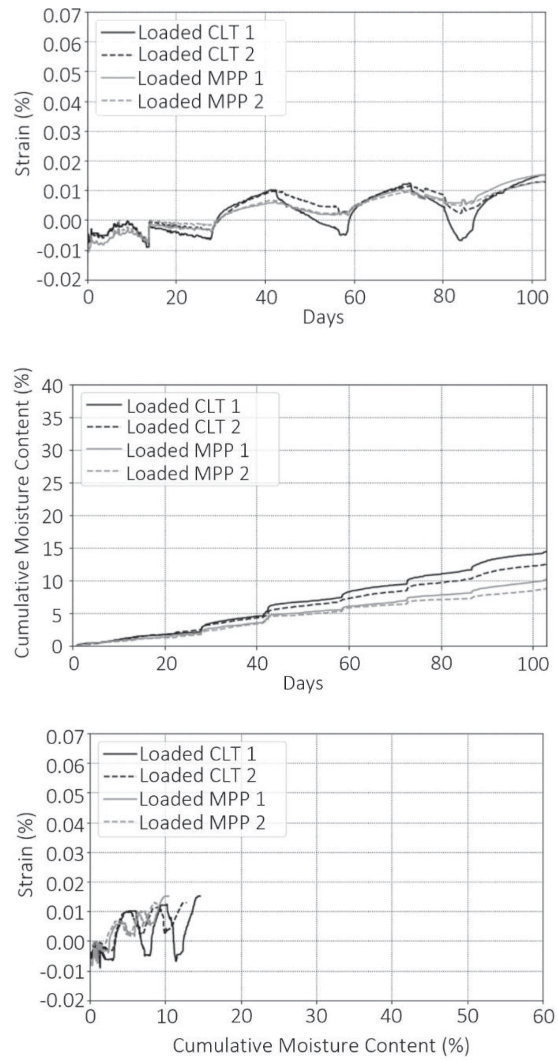

Figure 12: *Batch two specimen data (top: strain over time, middle: CMC over time, bottom: strain versus CMC).*

and swelling strains are in fact generally greater than the total strains of the loaded panels from the second batch (except for the CLT specimens from approximately 4% to 6.4% and from 7.8% to 10.4% CMC).

Figure 14 summarizes the test data from the panels in the constant environment over a period of approximately 10.5 months. It should be noted that the loading of the CLT panels occurred approximately one week after the loading of the MPP panels. Since the panels were close to each other, the loading of the CLT panels disrupted the MPP data around day 7. Additionally, it can be noticed that shortly after the loading of the CLT panels, a portion of data is missing. This data was removed due to an error with the data acquisition system.

As expected, based on the calculated displacements, the panels exhibit an overall shortening over time. In particular, the CLT panels displace more than the MPP panels even though both were loaded to the same percentage of their respective compressive strengths. When compared to the test data from the varying environment (Figure 15) over the same time domain, it can be seen that the panel behaviour between the tests in the different environments nearly mirror each other (excluding the cyclic behaviours from the changing RH). Strains of the panels in the changing environment increase with time to a maximum strain between approximately 0.0004 mm/mm to 0.0006 mm/mm while strains in the constant environment decrease with time to a minimum strain between approximately -0.0003 mm/mm to -0.0007 mm/mm.

4 DISCUSSION

The unusual trend observed in both batches of specimens tested in the climate chamber could be attributed to differences in moisture profiles between the panels as each panel had different initial MCs. It could also be attributed to layup differences between panels which in turn could affect the diffusion coefficients. Another possibility could be caused by inaccurate sensor readings.

For example, as seen at day 0 of the test for the first batch of panels (Figure 11), the loaded CLT panel increases in strain as it is loaded whereas the loaded MPP panel decreases in strain. This would mean that the CLT panel elongates as it is loaded which is not reasonable.

Overall, the second batch of specimens (Figure 12) experienced significantly less amounts of strains which may in part be due to the overall differences in CMC between the panels. It is also important to point out the initial MCs between both batches. The first batch of samples had more dispersed MC levels between approximately 5% and 10% while the second batch of samples had more consistent MC levels of approximately 10% or more. The causes leading to the differences in initial MCs between batches of specimens stems from the storage conditions of the panels. For example, the first batch of panels were left in the chamber powered off for several months prior to testing while the second batch of panels were left outside of the chamber in an uncontrolled indoor environment. Additionally, the first batch of panels began testing in May of 2022 while the second batch of panels began testing at the end of the summer in September of 2022. As might be expected, the higher temperatures and likely higher humidities in the unconditioned indoor environment at the end of the summer likely led to the second batch of samples equilibrating to the larger initial MC levels measured at the beginning of the tests. Since changes in MC inherently affects strains due to shrinkage, swelling and mechano-sorptive creep in timber, it would be expected that more drastic CMC curves would result in more drastic strains. This is evident between the two tests as the first batch of specimens have more CMC and more strain contrary to the second batch of specimens which have less CMC and therefore less strain (Figures 11 and 12). Additionally, beginning at a higher moisture content may mean that the panels have more dimensional stability when exposed to changing MC as they are further along in the moisture sorption isotherm curves.

Another important detail is the relative position of each specimen in the chamber. As seen in Figure 1, for both rounds, the CLT panels were arranged such that they were closest to the chamber vents from which the dry and wet air and temperature were controlled. Therefore, these panels would be the first to experience MC changes which can generally be seen in the data from Figures 11 and 12; most of the MPP panels had less CMC. This observation concerning lower CMC levels in the MPP panels could also be attributed to the larger number of layers of adhesives within the MPP panels which may affect the moisture diffusion properties.

The larger amounts of strain observed in the CLT panels compared to the MPP panels in the constant environment is likely due to differences in the mechanical properties of the panels. Although the wood in both panel types are similar species, the difference in the general layup will affect the overall panel properties.

Another possible contributor to the differences in overall strain between both panel types could stem from differences in the moisture profiles of the panels. While all panels were placed in the constant environment and allowed to react with the environmental conditions, it is

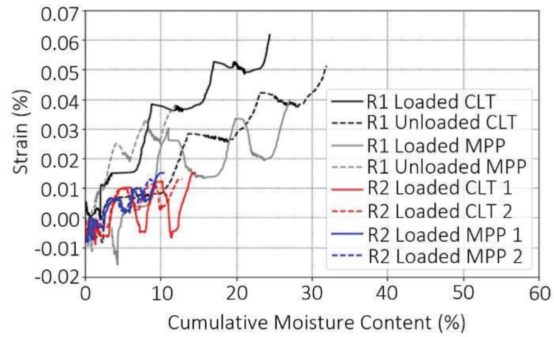

Figure 13: *Batches one (R1) and two (R2) specimen strain verses CMC data comparison.*

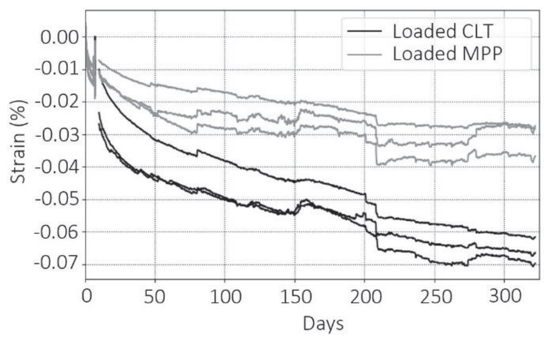

Figure 14: *Specimen strain data in constant environmental conditions.*

possible that the panels did not all reach equilibrium by the start of the test. Based on the observations from the specimens tested in the changing environment, it would be reasonable to suspect that if the initial MC profiles of the specimens are different, then there would likely be large variations in the measured strains.

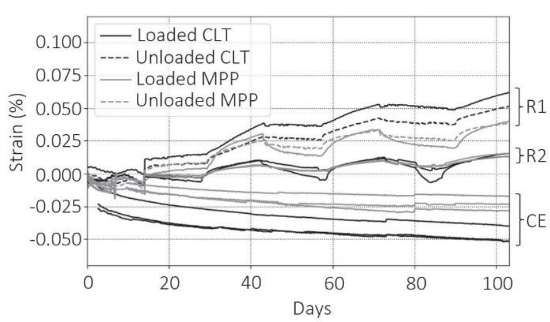

Figure 15: *Batches one (R1), two (R2), and specimens in constant environment (CE) strain data.*

5 PRELIMINARY CONCLUSIONS

This paper presents a preliminary analysis of data of medium-scale PT CLT and MPP systems with the objective of providing data and a functional model to allow engineers to confidently incorporate PT mass

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timber rocking walls in resilient seismic design. The data shows the following trends: (1) it appears that, during the test time frame and under the imposed changing environmental conditions, the PT system's response is dominated by the in-plane shrinkage and swelling of the specimens, (2) the MC profiles of the PT panels have a significant effect on the panel's strain behaviour, and (3) under constant environmental conditions, the CLT panels experienced more viscoelastic creep compared to the MPP panels, which is likely due to differences in the material properties of the panels and or differences in panel moisture profiles. The data also allows for the isolation of the viscoelastic and mechano-sorptive creep which will facilitate model development in future works.

The difference in responses of the panels between the two test batches exposed to cyclic climates may be explained by different initial MCs. A practical conclusion for future testing is that prior to testing all panels should be equilibrated to the same MC and that the environment during the two-week period prior to the launching of humidity cycles should be replicated for each batch so that all panels will start the humidity cycles with the same MCs. The MC of panels in the constant environment should be checked prior to testing as well.

In the current study, the CLT panels were located closest to the climate chamber vents in each batch of tests involving cyclic climate conditions and were observed to absorb more moisture. Therefore, in the future work, the effect of panel location in the chamber on the moisture absorbed into the CLT and MPP specimens should be determined.

REFERENCES

[1] J. Cover. Mass timber: The new sustainable choice for tall buildings. International Journal of High-Rise Buildings, 9(1):87-93, 2020.

[2] Granello G., Palermo A., Pampanin S., Pei S., van de Lint J. W.: Pres-Lam buildings: state of the art. Journal of Structural Engineering, 146(6): 04020085, 2020.

[3] Pei S., van de Lindt J. W., Barbosa A. R., Berman J., McDonnell E., Dolan J. D., Blomgren H., Zimmerman E., Huang D., Wichman S.: Experimental seismic response of a resilient 2-story mass-timber building with post-tensioned rocking walls. Journal of Structural Engineering, 145(11): 04019120, 2019.

[4] Baas E. J., Granello G., Barbosa A. R., Riggio M.: Post-tensioned timber wall building: lessons learned from design and construction practice in New Zealand and United States. In: 2021 World Conference on Timber Engineering, 2021.

[5] R. P. Longman. In-plane creep behavior of cross-laminated timber and mass plywood panels: A methodology to evaluate the long-term performance of post-tensioned mass timber walls. Oregon State University, 2021.

[6] Zheng X., He M., Li Z., Luo Q.: Long-term performance of post-tensioned cross-laminated timber (CLT) shear walls: hygro-mechanical model validation and parametric analysis. Archives of Civil and Mechanical Engineering, 22(2):1-18, 2022.

[7] He M., Zheng X., Lam F., Li Z.: Potential loss in prestressing tendon forces under long-term service conditions: cross-laminated timber shear wall applications. Journal of Structural Engineering, 148(3):04021284, 2022.

[8] Nguyen T. T., Dao T. N., Aaleti S., Hossain K., Fridley K. J.: Numerical model for creep behavior of axially loaded CLT panels. Journal of Structural Engineering, 145(1):04018224, 2019.

[9] Muszyński L., Lagaňa R., Davids W., Shaler S. M.: Comments on the experimental methodology for quantitative determination of the hygro-mechanical properties of wood. Holzforschung, 59(2):232-239, 2005.

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