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EVALUATING THE EFFECT OF COASTAL DETERIORATION ON STRUCTURAL INTEGRITY OF CROSS-LAMINATED TIMBER

Shaghayegh Kurzinski [1], Issa Ramaji [2], Molly York [3]

ABSTRACT: Cross-laminated Timber (CLT) is a sustainable building Mass Timber (MT) material made of a biological origin; wood. Since its introduction to North America, the biological durability of the material has been challenged due to the lack of investigation in different climates and deterioration zones. Almost all parts of the Pacific Northwest and most parts of the North Eastern regions of the United States have a high (4 out of 5) coastal deterioration zoning for wooden materials. Therefore, studying the effects of coastal deterioration such as salt-spray effects on the MT products' properties would provide helpful information and job-site measures for using these products. This work investigates the coastal deterioration of MT by measuring the effect of continuous salt spray exposure on the dimensional and mechanical properties of CLT panel samples with and without any industry-standard coating. The CLT specimens' initial density, dimensions, and bending stiffness are compared with the ones acquired after being tested and exposed to the continuous salt spray and controlled simulated moisture content, humidity, and temperature for two weeks. This work presents preliminary predictions for how much CLT deterioration and mass loss due to exposure to coastal salt spray could result in loss of mechanical properties.

KEYWORDS: Mass Timber, Cross-laminated Timber, Salt spray effect, Coastal climates, Structural integrity.

1 – INTRODUCTION

Since the adoption of Mass Timber (MT) from Europe in the North American market and the building codes, many efforts have been made to modify the products for the best performance in this region. Cross-laminated timber (CLT) is a sustainable MT material that has gained popularity in North America due to its environmental benefits and structural performance [1]. However, the biological durability of CLT in various climates, particularly in coastal regions, remains a critical area of investigation. Coastal environments, characterized by high humidity, salt spray, and extreme weather conditions, pose significant challenges to the longevity and structural integrity of wooden materials. The research on the coastal climate environmental risks of MT products is very limited, with most of the literature done on moisture intrusion, fungi, and termite deterioration. Moisture as the first insidious factor in wood deterioration can move rapidly through wood gaps. Moisture from precipitation or the installation of a concrete topping in the construction can be stored and stand on the floor assembly due to the significant storage capacity and the physical characteristics of CLT. This moisture can also seep between the cracks and joints in the outer plies of the CLT thereby penetrating deep into the core and taking years for it to fully diffuse through the thickness of the panels. [2]. The biodegradation due to the moisture penetration in CLT leads to a permanent loss in properties not only due to the fiber and mass loss but also because of disrupting the adhesive bond between the lamina. [3]. Another impact of moisture intrusion that has been studied before is the decay fungi that can affect the physical and structural properties of the CLT panels over time. [4].

Previous research has extensively documented the impact of moisture on the deterioration of wooden materials. Moisture intrusion is a primary factor in wood degradation, leading to issues such as the decay of fungi and loss of mechanical properties. Cappellazzi et al. [2] highlighted the risks of moisture penetration in mass timber elements, noting that moisture can rapidly move through wood gaps and accumulate in floor assemblies,

[1] Shaghayegh Kurzinski, Assistant Professor of Construction Management, School of Engineering, Computing, and Construction Management, Roger Williams University, Bristol, Rhode Island, USA.

[2] Issa Ramaji, Associate Professor of Construction Management, School of Engineering, Computing, and Construction Management, Roger Williams University, Bristol, Rhode Island, USA.

[3] Molly York, Undergraduate Student of Civil Engineering, School of Engineering, Computing, and Construction Management, Roger Williams University, Bristol, Rhode Island, USA.

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leading to prolonged wet conditions that promote biodegradation. Their study found that prolonged exposure to moisture can lead to significant structural damage, emphasizing the need for effective moisture management strategies in timber construction. Wang et al. [5] further emphasized the biological risks associated with moisture, including the disruption of adhesive bonds between lamina and the subsequent loss of structural integrity. Their review of mass timber structures identified key factors contributing to biological degradation, such as fungal growth and insect infestation, and recommended the use of protective coatings and treatments to enhance durability addition to moisture, coastal environments introduce the challenge of salt spray, which can corrode and deteriorate both the surface and core of wooden structures. Sinha et al. [4] discussed the potential for biological degradation in mass timber connections exposed to harsh environmental conditions, underscoring the need for protective measures. Their research demonstrated that untreated timber connections are particularly vulnerable to degradation, leading to reduced load-bearing capacity and increased maintenance costs.

Marine environments, in particular, are known for their harsh conditions that accelerate wood deterioration through processes such as biocorrosion, biofouling, and bioboring. These processes are exacerbated by the presence of fungi and other microorganisms that thrive in moist, saline conditions. Recent studies have provided new insights into the mechanisms of wood degradation in marine environments. Rao and Kuppusamy [6] detailed the biodeterioration of wood in seawater, highlighting the roles of biocorrosion, biofouling, and bioboring in the rapid decay of wooden structures. Their study emphasized the importance of selecting appropriate timber species and applying protective treatments to mitigate these effects. Goodell et al. [7] reviewed the emerging data on fungal degradation of wood, noting that advances in biochemical analyses have significantly altered our understanding of how fungi degrade wood and overcome protective coatings. Their findings suggest that traditional wood preservatives may not be sufficient to protect against modern fungal threats, highlighting the need for innovative solutions. Sivrikaya et al. [8] studied the weathering performance of wood treated with copper azole in combination with water repellents, demonstrating improved resistance to leaching and color change. Their research provided valuable insights into the effectiveness of combining chemical treatments with physical barriers to enhance wood durability in outdoor environments. Furthermore, research by Brischke and Meyer-Veltrup [9] explored the long-term performance of wood in outdoor environments, emphasizing the importance of protective treatments to mitigate the effects of weathering and biological attacks. Their findings support the need for ongoing research into effective preservation methods for wood used in coastal and marine applications. Additionally, another study by Singh [10] has shown that the application of nanomaterials can enhance the durability of wood by providing a barrier against moisture and microbial attack. Their study demonstrated that nanomaterial coatings significantly reduce water absorption and improve resistance to fungal decay, offering a promising approach for extending the service life of timber structures. Another significant contribution to the field is the work by Evans et al. [11], who investigated the use of bio-based coatings to protect wood from fungal decay and UV degradation. Their research demonstrated that bio-based coatings could provide effective protection while being environmentally friendly, making them a viable alternative to traditional chemical preservatives. Similarly, research by Schultz and Nicholas [12] focused on the development of environmentally benign wood preservatives that offer protection against decay fungi and termites without the use of toxic chemicals. Their study highlighted the potential of using natural extracts and biocides to achieve effective wood preservation with minimal environmental impact.

Despite these known risks, there is limited research on the specific effects of salt spray on CLT panels, particularly in the context of North American coastal climates. This study addresses this gap by investigating the structural integrity and mass loss of CLT panels subjected to continuous salt spray exposure. By comparing panels with and without industry-standard coatings, the research aims to provide insights into the effectiveness of protective treatments in mitigating coastal deterioration. The findings will contribute to the development of guidelines and best practices for the use of CLT in coastal regions, ensuring the long-term durability and performance of mass timber structures.

The extreme environmental events in the coastal regions such as the salt spray effect in New England regions in the USA are currently challenging the construction industry to adopt MT products as structural members of the building. Exposure to saltwater spray in coastal climates has the potential to deteriorate and corrode the surface and core of the MT structures. The long-term durability and service life of mass timber products needs further understanding of their performance when exposed to the coastal environment. To aid this understanding, this study investigates the structural integrity and mass loss of CLT panels with and without a layer of factory coating after two weeks of exposure to a simulated and continuous salt fog environment. In the following sections, first, the similar literature and then the project layout and expected results have been discussed. This study aims to evaluate the effects of coastal deterioration, specifically salt spray exposure, on the mechanical properties and structural integrity of CLT panels.

2 – MATERIALS AND METHODOLOGY

2.1 Panel Fabrication

A total of 60 Spruce-Pine-Fir (SPF) boards with nominal dimensions of 25.4 mm thickness, 50.8 mm width, and 2.5 m length, were purchased from a local lumber yard near Bristol, Rhode Island, USA. The boards were already Kiln-dried but were surfaced (S4S) and planed to the desired thickness of 12.6 mm. Before the fabrication, the boards' moisture content (MC%) at an ambient temperature was measured by a pin-typed moisture meter to ensure an equilibrium moisture content of approximately 9-11%. Then, the boards were face-glued using Henkel 1C-PUR (one component purbond) Loctile® HB X602 adhesive with the recommended Loctile® PR 3105 purbond primer and the spread rate of 180 g/m^2. A full 3-ply 38 mm CLT slab with 120 cm length and 80 cm width was fabricated using a vacuum press set to maintain a negative pressure of 0.82 MPa (24 in Hg) to apply sufficient pressure for the gluing process. This pressure was found to be sufficient based on previously tested specimens showing no glue failures. The boards were under pressure for 42 hours meeting the minimum requirement of 24 hours before being released. Afterward, 10 CLT replicas were cut from the slab to the dimensions of 60 cm length and 16 cm width. Five panels were coated with an industry-standard waterproofing polyurethane wood sealer while the other five panels remained without any coating finish.

Figure 1. Specimen Fabrication Process by the Vaccum Press

2.2 Center-Point Bending Test

First, the initial density of each panel was recorded by measuring the weight and the exact dimensions of each specimen. Then the panels were tested under a non-destructive center-point bending test per ASTM D198 [13]. Using a universal testing machine (Admet eXpert 2600) to record the load over deflection in the elastic range (proportional limit) to find out the initial stiffness of the specimens before any biodegradation using **Equation 1**. The width-to-depth ratio of 4:1 and span-to-depth ratio of 16:1 followed the standard recommendations to limit the impact of shear during the tests. The density of each specimen once again was recorded after taking out of the chamber when the panels reached their initial equilibrium MC% of approximately 9-11%. Then each specimens were tested at this final stage under a destructive center-point bending. Two structural integrity properties of post-test bending stiffness and the final bending Strength were measured again using **Equation 1** and **Equation 2** respectively.

$$\boldsymbol{E_{app}} = \frac{\boldsymbol{l^3}}{\boldsymbol{4 \times b \times h^3}} \times \frac{\boldsymbol{P}}{\boldsymbol{\Delta}} \quad \text{Equation 1}$$

$$\boldsymbol{\sigma} = \frac{\boldsymbol{3 \times P_{max} \times L}}{\boldsymbol{2 \times b \times h^3}} \quad \text{Equation 2}$$

where, E_{app} is apparent bending stiffness, P/Δ is the slope of the linear range of the load-deformation curve below the proportional limit with P and Δ accordingly being the maximum load and deflection at the proportional limit, l is the span length, b, and h are the width and the thickness of the specimen, $\boldsymbol{\sigma}$ is the bending strength, P_{max} is the maximum load that the panel

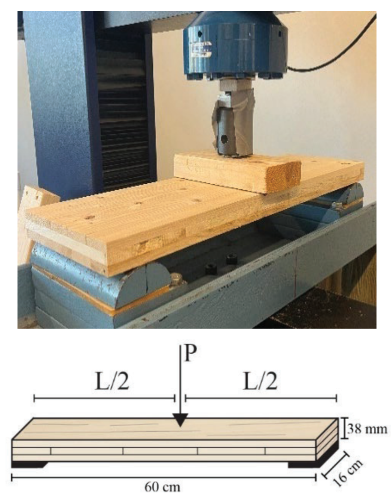

Figure 2. Demonstration of the Experimental BendingTesting

The acquired bending stiffness pre and post-salt-spray tests were compared to provide insights on the integrity loss due to the exposure. However, the bending strength needed to acquire after the destructive test and therefore the bending strength of the coated specimens was compared to the uncoated to provide insight into how the coating can assist in the retention of the structural integrity of the panels.

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2.3 Salt Spray Chamber Test

The salt spray test was conducted to evaluate the effects of coastal deterioration on the mechanical properties and structural integrity of cross-laminated timber (CLT) panels. The test was performed in accordance with ASTM B117 [14], which specifies the standard practice for operating salt spray (fog) apparatus. The specimens used in this study comprised ten CLT panels, with five panels coated with an industry-standard waterproofing polyurethane wood sealer and five panels left uncoated. The panels were subjected to a total of 110 hours of salt spray exposure over a period of 14 days, averaging 8 hours of exposure per day. The panels were placed in a salt spray chamber, with the chamber and spray tower temperatures set to 35 ± 2°C and 47°C, respectively. The salt solution used for the test was prepared by mixing ocean salt at a concentration of 5% with 95% deionized water. This brine mixture was poured into the chamber container connected to the spray tower. Additionally, the chamber required Type 4 water for certain operations, and after research, it was determined that the local water supply in Bristol closely met this requirement.

The test was conducted in three batches. In the first two batches, three specimens were placed in the chamber for the 110-hour exposure period. In the third batch, four specimens were placed in the chamber. This approach ensured that all ten panels were subjected to the same total duration of salt spray exposure. The salt spray chamber operated continuously during the exposure periods, ensuring consistent and uniform distribution of the salt fog over the specimens. The panels were positioned in the chamber to avoid direct contact with the chamber walls and to ensure that all surfaces were evenly exposed to the salt spray.

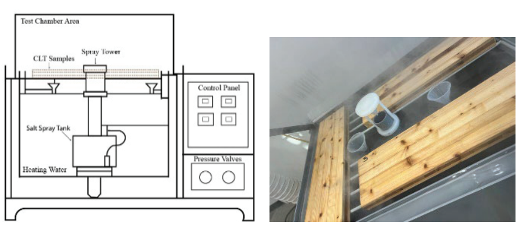

Figure 3. Demonstration of the Salt Spray Chamber Testing

3 – DATA & RESULTS

3.1 Mass Loss Analysis

The analysis of the mass change in cross-laminated timber (CLT) panels subjected to salt spray exposure reveals significant differences between coated and uncoated specimens. The percentage mass change (% Mass Δ) was measured for five coated and five uncoated panels before and after exposure to the salt spray chamber. It should also be noted that the average time spent for the panels to reach their (approximately) initial MC% was noted to be 50% faster for the coated panels compared to the uncoated ones when the coated dried in the same environmental condition in the average of 20 days and the uncoated ones took average of 42 days to dried to MC of 9-11%. The data presented in **Table 1** indicate that the uncoated panels experienced a higher percentage of mass change compared to the coated panels, suggesting that the protective coating effectively mitigates the effects of salt spray. The uncoated panels exhibited a range of mass changes, with an average mass change for the uncoated panels being approximately 1.61%. This variation can be attributed to the direct exposure of the wood to the saline environment, which likely led to increased moisture absorption and subsequent mass gain. The higher mass change in uncoated panels is indicative of the wood's vulnerability to salt-induced deterioration, which can compromise structural integrity over time. In contrast, the coated panels demonstrated significantly lower mass changes, with an average mass change of approximately 0.24%. The reduced mass change in coated panels highlights the effectiveness of the waterproofing polyurethane wood sealer in providing a barrier against moisture and salt ingress. This protective layer likely prevented the wood from absorbing significant amounts of moisture, thereby maintaining its structural integrity and reducing the risk of salt-induced degradation. The data suggests that the application of a protective coating is a crucial factor in enhancing the durability of CLT panels in coastal environments. The coating's ability to minimize moisture absorption and salt penetration is essential for maintaining the mechanical properties and longevity of the timber. These findings align with previous studies that have emphasized the importance of protective treatments in mitigating the effects of harsh environmental conditions on wooden structures.

Table 1. CLT Specimen's Mass Loss Percentage

Panel #	% Mass Δ	Panel #	% Mass Δ
Uncoated-1	0.20%	**Coated-1**	0.17%
Uncoated-2	1.41%	**Coated-2**	0.41%
Uncoated-3	1.60%	**Coated-3**	0.31%
Uncoated-4	1.95%	**Coated-4**	0.19%
Uncoated-5	2.90%	**Coated-5**	0.13%

Furthermore, the variability in mass change among the uncoated panels underscores the need for consistent and effective protective measures. The significant differences in mass change between coated and uncoated panels highlight the potential for coatings to significantly extend the service life of CLT panels in coastal applications. This study provides valuable insights into the practical benefits of using protective coatings and underscores the necessity for further research into optimizing these treatments for different environmental conditions. The protective coating effectively reduces moisture absorption and salt ingress, enhancing the panels' durability and structural integrity. These findings support the use of protective coatings as a standard practice for CLT panels in coastal environments to ensure their long-term performance and reliability.

3.2 Bending Strength and Stiffness Comparison

The data analysis centers on the results of center point bending tests performed on CLT panels that were subjected to salt spray exposure. Initially, non-destructive tests were conducted on the panels to determine their initial stiffness, measured as the modulus of elasticity (MOE). After exposure in the salt spray chamber, the panels underwent destructive testing to failure, which allowed for the measurement of ultimate load and strength, as well as the proportional limit for stiffness assessment. The ultimate load and strength values obtained from the destructive tests presented in **Figure 4**, highlighted the panels' capacity to withstand forces until failure, with coated panels generally exhibiting higher values compared to uncoated panels. This suggests that the coating provided some level of protection against the corrosive effects of the salt spray.

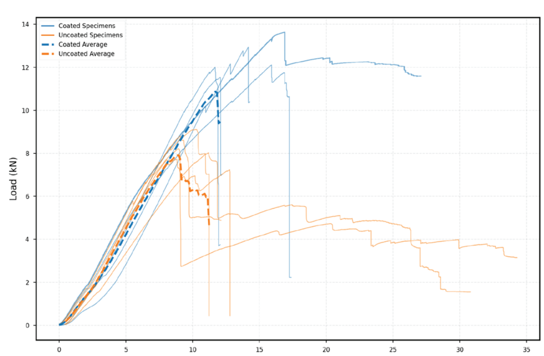

Figure 4. Load-Deflection Curves of Tested CLT Panels under Center-point Bending

Additionally, the proportional limit, marking the end of elastic behavior and the onset of plastic deformation, was higher in coated panels, indicating better retention of their elastic properties. The presented data from coated and uncoated panels in **Table 2** demonstrates that the coating significantly mitigated the adverse effects of the salt spray, as coated panels retained more of their initial stiffness and exhibited higher strength and proportional limits. Overall, the data underscores the importance of protective coatings in preserving the mechanical properties of CLT panels in corrosive environments, providing valuable insights into the durability and performance of materials subjected to harsh conditions.

Table 2. CLT Specimen's Structural Properties

CLT Panel	**Bending Stiffness (MPa)**			**Bending Strength (MPa)**		
	Ave	St. Dev	CV %	Ave	St. Dev	CV %
Uncoated	4,765	362.5	7.6	31.7	2.7	8.7
Coated	5,095	395.7	7.7	47.6	3.1	6.6

As shown in the following table, the results also revealed a significant reduction in stiffness for both coated and uncoated panels, indicating material degradation due to the corrosive environment.

Table 3. CLT Specimen's Stiffness and Mass Loss Comparison

CLT Panel	Average Mass Δ % from the initial	Average Stiffness Δ % from the initial
Uncoated	-1.61%	-9.2%
Coated	-0.24%	-3.3%

4 – DISCUSSION OF THE RESULTS

The analysis revealed that uncoated panels experienced an average mass change of approximately 1.61%, indicating significant moisture absorption and subsequent mass gain due to direct exposure to the saline environment. In contrast, the coated panels demonstrated a significantly lower average mass change of 0.24%, highlighting the effectiveness of the waterproofing polyurethane wood sealer in providing a barrier against moisture and salt ingress. This protective layer likely prevented the wood from absorbing significant amounts of moisture, thereby maintaining its structural integrity and reducing the risk of salt-induced degradation. The actual difference in mass change between uncoated and coated panels was 1.37%, representing an 85.09% reduction in mass change for coated panels.

Furthermore, the bending stiffness of uncoated panels decreased by 9.2% after exposure to the salt spray environment, indicating material degradation due to the

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corrosive conditions. In comparison, the coated panels experienced a 3.3% reduction in bending stiffness, suggesting that the coating provided some level of protection against the corrosive effects of the salt spray. The actual difference in stiffness reduction between uncoated and coated panels was 5.9%, representing a 64.13% reduction in stiffness loss for coated panels. These findings underscore the critical importance of protective coatings in enhancing the durability and performance of CLT panels in coastal environments, where exposure to saline conditions poses a considerable risk to the longevity of wooden structures.

While building codes are currently limiting the exposure of MT elements in the exterior applications, this work could be helpful for coastal climate regional codes to consider the time and level of exposure of CLT to the outdoor environment either during the construction or with a permanent exposure.

5 – CONCLUSION

This study highlights the significant impact of coastal deterioration, specifically salt spray exposure, on the structural integrity of CLT panels. The experimental results revealed that uncoated panels experienced substantial mass loss and a marked reduction in bending stiffness and strength after exposure to a simulated salt spray environment. In contrast, the application of an industry-standard waterproofing polyurethane wood sealer significantly mitigated these adverse effects, as evidenced by the lower mass change and higher retention of mechanical properties in coated panels. These findings underscore the critical importance of protective coatings in enhancing the durability and performance of CLT panels in coastal environments, where exposure to saline conditions poses a considerable risk to the longevity of wooden structures.

The data presented in this study provide valuable insights into the mechanisms of salt-induced deterioration and the effectiveness of protective treatments in preserving the structural integrity of mass timber products. The observed differences in mass change and mechanical properties between coated and uncoated panels highlight the necessity for incorporating protective measures in the design and construction of CLT structures intended for use in coastal regions. Furthermore, the results suggest that current building codes and standards should consider the specific challenges posed by coastal climates and incorporate guidelines for the use of protective coatings to ensure the long-term performance and reliability of mass timber structures. Future research should focus on optimizing coating formulations and application methods to further enhance the protective capabilities of these treatments and explore the long-term effects of continuous salt spray exposure on the structural integrity of CLT panels. By addressing these challenges, the construction industry can better ensure the durability and sustainability of mass timber structures in coastal environments, ultimately contributing to the broader adoption of environmentally friendly building materials.

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