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Predictive model associated to wood infrastructures damaging

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Abstract

Glulam moisture sensitivity is characterized by biological degradations at high humidity rates or cracks, delamination and internal stresses caused by humidity variations leading to a loss of mechanical properties. An integrated system, developed during two theses, allows us to record Moisture Content (MC) with patch type sensors using resistive measurement method and stresses in glue joints using strain gauges, both embedded within the thickness of the glue joints.

Long Term experiments are currently conducted in real climatic conditions with loaded and unloaded beams exposed in an outdoor application. The objective is to correlate the effects of real-life wetting/drying (W/D) cycles combined with duration of load effects on the mechanical properties. The running experiment started in august 2020 with 198 30x30x480mm model glulam beams. The bending strength of our samples is evaluated to compare our data with accelerated aging tests conducted in climatic chamber. MC measurement during accelerated W/D cycles showed encouraging results to predict the actual condition of glulam.

Keywords: SHM, Glulam, Moisture content.

1 Introduction

As an answer to actual environmental challenges, wood and specifically wood composites such as glued laminated timber (glulam) became a good alternative to “traditional” building materials such as concrete or steel. Glulam can be used to build large load-bearing elements, up to 50m long, while being a renewable and carbon dioxide storing material. However, durability issues related to its environment sensibility, especially to moisture, could be a limiting factor to the development of these structures. Moisture is a factor contributing in the apparition of different damages in glulam structures. Excessive moisture can cause mould formation or expose the wood to xylophagous insects, this phenomenon is often local where the design or defects allows too much water exposure or stagnant water. Also, climatic variations lead to moisture content (MC) variations in the material. Those wetting/drying (W/D) cycles can cause cracks and delamination, altering the structure integrity on long time period. The loss of mechanical



properties of wood elements under load considering time and climatic exposure in structure is defined in the Eurocode 5 with the coefficient k_{mod} based on the Madison curve [1]. However, any study considering the specificity of glulam couldn't be found in the Eurocode references [2] and in the literature. The W/D cycles effect on glulam mechanical performance was shown under accelerated W/D cycles with a 40% loss of bending strength over 17 cycles [3]. Following these results, this study proposes a long-term experiment to show the effect of real climatic conditions on mechanical properties of glulam. Also, to allow glulam to be more widely used in infrastructures such as bridges we propose an embedded structural health monitoring system, measuring durability parameters in real time. It will allow a live structural health monitoring by identifying zones where moisture may lead to pathologies and a survey of the mechanical condition of the structure. To do this the MC monitoring system developed in our laboratory is used to associate the measured W/D cycles on glulam samples with their loss of mechanical properties.

2 Materials and methods

2.1 Specimens and data collecting system

A five-years outdoor aging campaign was launched in August 2020. 198 glulam beams were made using three Douglas fir lamellae glued with PUR. These materials were chosen because they are widely used in glulam industry. The beams are 480mm long with a cross section of 30mm x 30mm. These dimensions are defined according to the standard EN408 [4] for our bending tests. The use of small samples allows us to have a high sensibility of our specimen to moisture changes so we could have important aging effects appearing within few years. We have three aging scenarios, 66 beams are exposed outside with a 600 N load (4 points bending), 66 beams are exposed outside without loading, 66 beams are aging inside in a thermo-hygro regulated room without load as a reference. The load applied to the beam is approximately 10% of the maximum load. It corresponds to 70 % of the maximum load (ELU) according to the Eurocodes. This low rate of loading should guarantee that our beams don't break under fatigue before the static bending tests as it could be observed for other small samples under W/D cycles [5]. Our outside aging conditions correspond to a class 3 exposition as defined by the Eurocode 5. These conditions of outside exposure without protection toward rain can be found in real life for glulam infrastructures such as bridges. No loaded samples in controlled environment were built because of space issues. Live humidity and temperature are monitored on site and the weather station of Tarbes-Ossun-Lourdes [6] helps us to keep track of raining events. The specimens are equipped with a monitoring system recording moisture content within the beams (**Figure 1**). The moisture measurement solution was developed in our laboratory. It consists in resistive sensors made of copper patches embedded within the glue joints. At a large scale, this solution allows the integration of multiple sensors during the making of the beams without altering its mechanical properties [7]. Gauges glued on lamellas on both side of the glue joints assesses the differential displacement in the radial direction of wood between the lamellas. This displacement may lead to the delamination of the joints.

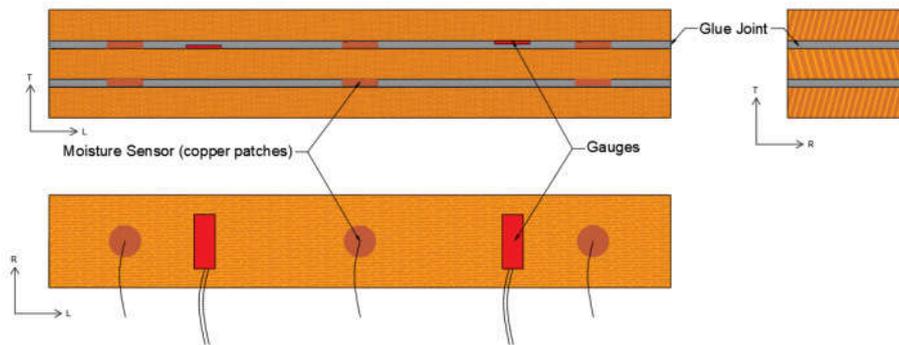


Figure 1: Glulam specimen with embedded moisture and displacement sensors representation

We use thermocouple also embedded within glue joints as a temperature compensation for our measures. Our monitoring system allows us to record data each 10 minutes on a dedicated server. Measurement cards are linked to a transmission card which transfer data via radio signals to a receptor connected to a dedicated computer collecting data. Every 6 month, 6 beams of each aging situation are collected to asses aging effects on mechanical properties of glulam.

2.2 Measured aging effects

To evaluate the loss of mechanical properties of glulam in outside exposure, we record evolution of static bending strength and elastic modulus following the norm EN408 (**Figure 2**).



Figure 2: Four points bending experiment configuration

We apply a constant displacement of 0.09 mm/s. We measure the force applied and the displacement of the sample under loading. The deflection is measured with a LVDT with a 2cm course. We use the LVDT displacement measurement to evaluate the young modulus of the samples. The bending experiments are video recorded to analyse the cracks evolution during the tests, Infrared Camera and Acoustic emission sensors are used to detect and localize cracking events during the banding tests. Stereo-correlation is used to measure the shear modulus. Before destructive bending tests the evolution of delamination rate is measured, and we visually analyse the apparition of cracks, decay, or fungal growth.

3 Moisture evolution in glulam in outside conditions

The data recorded during the first months of outside exposure showed three different scales of moisture variation. As our specimens are quite small, we could record daily variations due to moisture evolution between night day. The moisture changes observed have an amplitude of around 1.5 to 3 %MC (Figure 3).

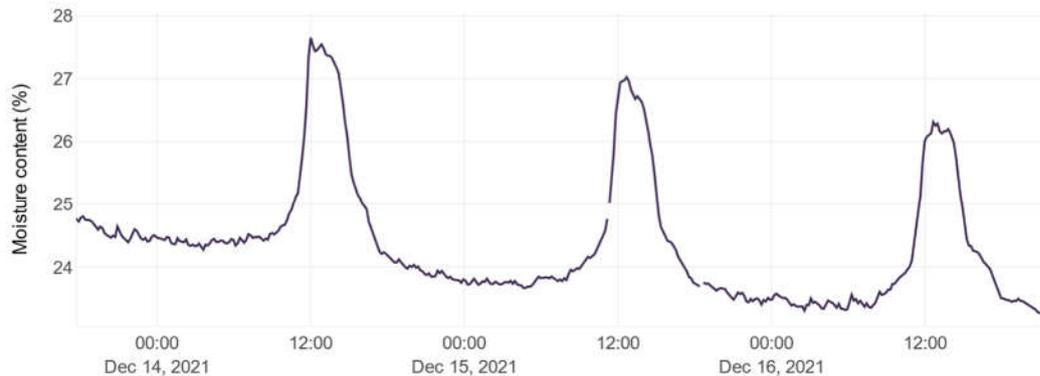


Figure 3: Moisture variation over 3 days

The upper scale of moisture change is due to daily weather changes, we could see moisture changes on short time ranges of few hours or days due to rainy or dry and warm weather. We could see an increase of over 10% MC within few days as shown in (Erreur ! Source du renvoi introuvable.) following rainy days.

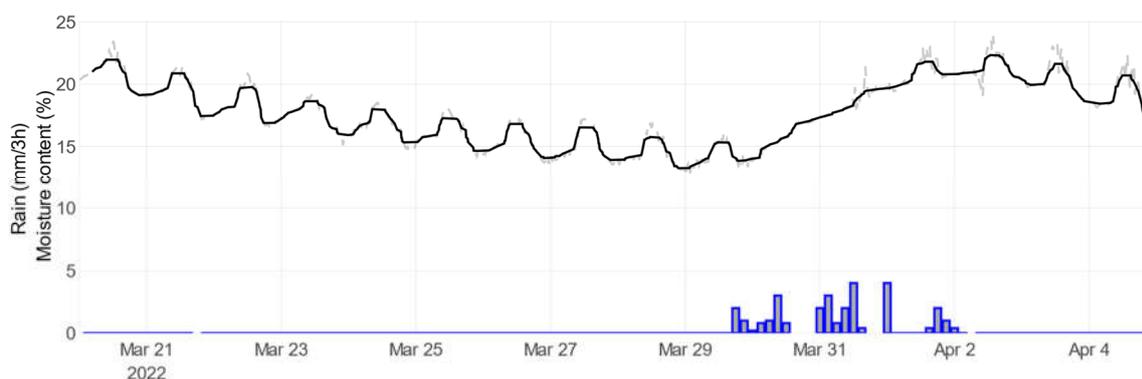


Figure 4: Moisture content increase during a raining event

Then on a longer time scale we can follow the yearly cycle of moisture evolution with an average MC between 12 and 25 %. This 10-month cycle (Erreur ! Source du renvoi introuvable.) clearly shows the increase of MC during the winter and the drying of the sample during spring. The effect of raining events is also recognizable as rapid increase in MC short after these events is visible. This moisture content variation is consistent with moisture content measured on timber bridges such as the Obermatt bridge [8].

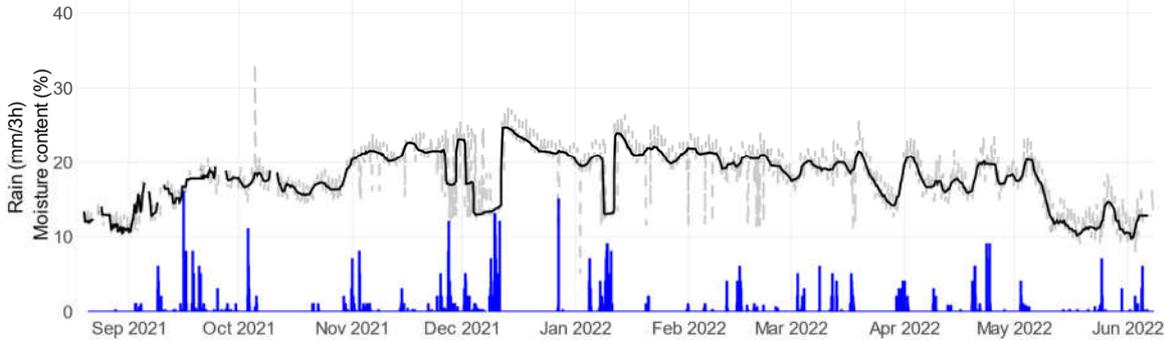


Figure 5: Moisture evolution over 9 months

During heavy rain period in December and January, water accumulation disrupted the measurement system, therefore incoherent MC are displayed with sudden low values. The measurements on our gauges on lamellae across a glue joint showed first sign of differential displacement (**Figure 6**). Those displacement may result in a failure of the glue joint.



Figure 6: Gauges elongation on top and middle lamella of a sample

The displacement we observe during outside exposure have a lower amplitude than in climatic chamber however the repetition of the cycles over long time may end up to similar results with delamination appearing in the glue joints. The displacement measuring during accelerated W/D cycles was problematic it led to the failure of gauges after couple cycles. It appears that in real life conditions the moisture content and displacement measured are less severe than in accelerated cycles. Our data clearly showed the cycle of wetting drying a sample undergoes during autumn, winter, spring cycle and its influence on deformations with consistent data regarding the meteorological conditions.

The influence of the outside conditions on mechanical performance is analysed in the following section.

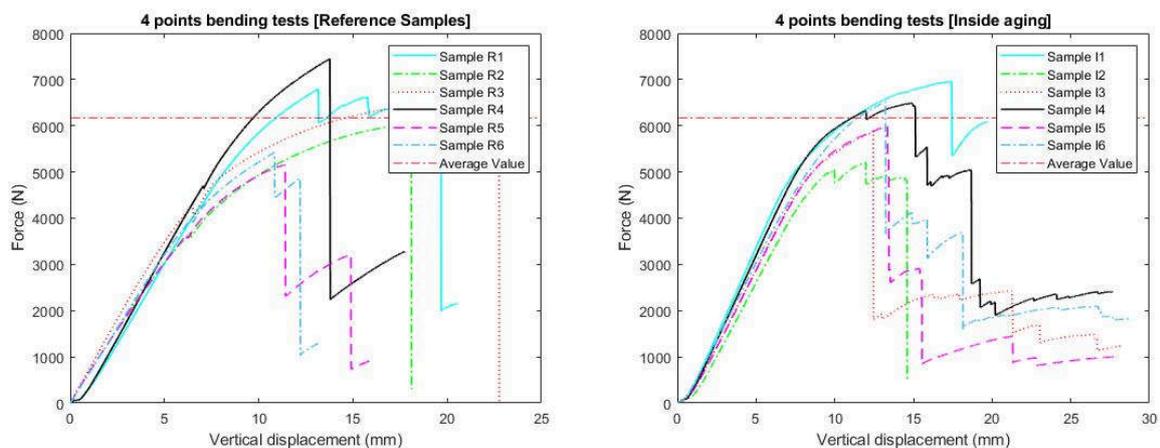
4 Influence of 6 month of aging on glulam

After 6 months, although we had few visual damages, the 4 points static bending test showed a loss of mechanical resistance for our outside exposed samples (Table 1). The reference samples are tested after manufacturing.

Table 1: Mechanical Properties under 4 points bending

N°	Reference samples		6 months inside aging (unloaded)		6 months outside exposure (unloaded)		6 months outside exposure (loaded)	
	Breaking stress (MPa)	Young Modulus	Breaking stress (MPa)	Young Modulus	Breaking stress (MPa)	Young Modulus	Breaking stress (MPa)	Young Modulus
1	104,31	10,52	101,91	10,34	88,51	10,16	81,79	8,28
2	78,16	8,85	88,74	9,26	84,61	9,63	79,17	8,43
3	88,15	9,31	94,63	10,744	80,57	10,56	81,96	8,79
4	97,32	10,27	111,72	11,144	96,93	11,09	84,28	9,6
5	89,95	9,45	77,31	9,16	94.69	9,66	89,87	10,05
6	97,81	9,22	81,34	9,84				
μ	92.61	10.08	92.62	9.60	89.062	10.22	83.41	9.03
σ	12.90	0.80	9.19	0.65	6.82	0.62	4.04	0.77

Four points bending experiments showed that for outside loaded samples, the breaking stress was significantly lower after 6 months. The breaking stress was 92.6 MPa in average for reference sample vs 83 MPa in average after 6 months. We also noticed a small loss of young modulus (9.6 vs 9.0). The properties for unloaded samples, outside aged and in constant conditions showed no significant loss. In average the mechanical resistance for outside loaded samples reduced by around 10% whereas no significant loss was observed for unloaded samples. (Figure 7). The loss of properties observed after one W/D cycle of accelerated aging for unloaded sample was about 10%.



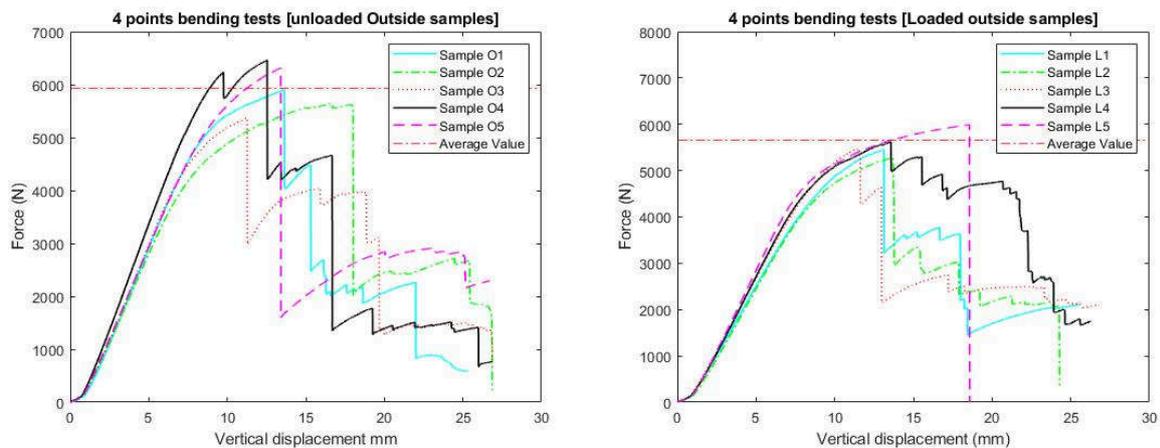


Figure 7: Mechanical behaviour under 4 points bending for reference samples and 6-month aged samples under different scenarios

The damage after 6 months of outside exposure seems to be associated to mechanical and moisture loading combination known as mechano-sorptive effect [9] more than to W/D cycles only. On outside exposed samples, glue joints started to show some visible delamination (**Figure 8**).

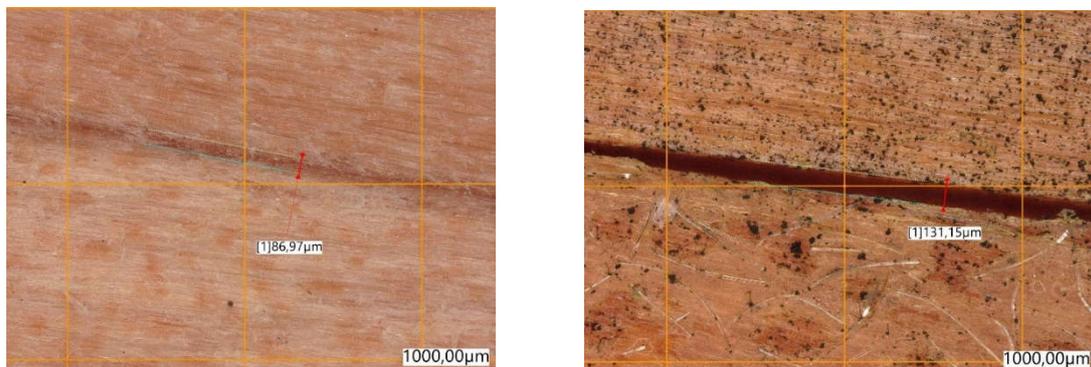


Figure 8: Reference sample glue joint (left) delamination of a glue joint after 6 months of outside exposure (right)

We measured the length of delaminated glue joint on each beam to compare the rate of delaminated joints related to time of outdoor exposure. The delamination rate was quantified as the length of opened glue joint divided by the total glue joint length on a sample. The average value of delamination is 8.2%, no significant variation was observed between loaded and unloaded samples. Delamination rates between 1.8 to 24.5% were measured. Glue joints between the top lamella and the middle lamella seemed to be more affected by W/D cycles than glue joints between middle lamella and bottom lamella, 9.7% vs 6.7% delamination rates. This observation seems to be consistent with the configuration of our samples as the top lamella is more exposed to sun and rain than the two lamellae under. Thus, the displacement between the middle and bottom lamellae are more homogeneous.

The other important aspect we observe during our bending tests is the evolution of the rupture mechanism. Non-aged samples tend to break sequentially under load with different small longitudinal cracks opening and gradually reducing the sample strength. Aging leads to samples breaking brutally with a transversal crack followed by a massive longitudinal crack leading to

a complete loss of mechanical strength of the sample. The evolution of rupture behaviour was also observed after accelerated aging. Complete delamination of glue joints leading to the failure under four points bending were observed only on aged samples (**Figure 9**).

This first campaign exposed the influence of load on loss of mechanical resistance under



Figure 9: Glue joint delamination under load

bending. Outside condition seems to have a low influence for short time periods on mechanical properties and a negligible effect compared to severe accelerated W/D cycles.

5 Conclusion

The first 6 months of experimentation confirmed the performance of our system as an integrated MC measuring tool. The MC variation observed were consistent with MC in real life glulam infrastructures.

The loss of mechanical properties for unloaded samples in real life conditions after 6 months is negligible regarding the loss of properties observed after accelerated cycles so these cycles might be relevant for long term behaviour simulation. The loss of properties measured appears to be linked to mechano-sorptive effects, as only loaded samples significantly lost bending resistance. The cracks and delamination caused by W/D cycles in outside exposure might not have affected mechanical performance of glulam. At the time of the firsts bending test the sample were quite visually undamaged, but with the first dry weeks of spring cracks and more delamination appeared. So, we expect to have even more loss of properties during the following experiments.

We plan to use our data to create a predictive model able to determine structural performance of glulam based on live moisture measurements. This system will allow a live mapping of humidity in glulam structures, it could help glulam structures managers in preventing moisture induced pathologies and evaluating their remaining lifespan.

Acknowledgements

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