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Assessment of glulam structures: moisture monitoring and investigation on the effect of climatic conditions on durability

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Abstract

Glulam is currently an interesting solution to build economical, environmentally friendly and mechanically strong timber bridges. Nevertheless, the durability of these bridges is influenced by the climatic wetting/drying (W/D) cycles to which they are exposed. This experimental study is aimed at setting up a technique for continuous moisture content (MC) monitoring of glulam beams over time (structural health monitoring), and to study the impact of W/D cycles on their mechanical properties. For this purpose, patch-type sensors were embedded between the lamellae, thus allowing local MC to be monitored. A system based on continuous resistive measurements was developed in the laboratory. Durability tests were carried out to expose the glulam specimens to accelerated W/D cycles in order to highlight the impact of variable climatic conditions, generally encountered in timber bridges, on the mechanical properties of glulam beams in bending. The results showed that the patch sensors and the developed measurement system will be able to be useful and functional for the continuous MC monitoring in glulam beams used in timber bridges. In addition, the exposure of glulam beams to these moisture variations has a significant influence on the bending strength whereas it does not seem to have one on the modulus of elasticity. These results also enabled to propose an experimental model for predicting the bending strength as a function of W/D cycles.

1 Introduction

In bridges construction, timber structures are economical, easy to build and use renewable materials providing solutions to current sustainable development issues. In order to increase the structural capacity of this material, glulam is increasingly used as a load-bearing element in these structures [1]. However, for a few years, durability problems have been observed in these structures, limiting their development [2-4]. Degradations related to excessive (often local) moisture in the material, and more particularly to climatic wetting/drying (W/D) cycles have been observed and can lead to severe structural damage. Moreover, little is known about the effects of these W/D cycles on the mechanical strength of these structures. It is therefore essential to associate to these timber bridges a continuous monitoring system of the local MC in order to quickly identify the zones likely to present risks of pathologies. So, this work aims firstly to propose a technique for continuous monitoring of local moisture content (MC) via the use of resistive sensors embedded into glulam beams. To do this, resistive patch-type sensors were integrated between the lamellae. The data were collected using a continuous measurement and recording system developed in our laboratory. The MC values were obtained using an equation relating MC and electrical resistance [5].

Then the effect of W/D cycles on the structural durability of glulam beams was studied. According to the literature, the study of durability under natural conditions is usually conducted by exposing the material to an outdoor environment, which requires a relatively long test duration [6]. As a result, it is often necessary to carry out durability tests with accelerated ageing cycles. These are usually based on exposing the material to controlled relative humidity and temperature conditions [7]. Indeed, moisture is an ageing factor that strongly impacts hydrophilic materials like wood. These hydric ageing induce a progressive mechanical degradation most often linked to heterogeneous shrinkage/swelling mechanisms in the wood [8]. Although some works have focused on accelerated ageing tests, no study refers to the actual ageing cycles encountered in timber bridges that could be used to study the durability of these glulam beams. Following this observation, the conditions of an accelerated W/D cycle were defined in order to come as close as

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possible to the reality encountered in the field, i.e. to obtain MC values equivalent to those present in timber bridges exposed outdoors, i.e. between 10% and 30% MC according to the literature [3,9,10]. Then, glulam specimens were exposed to accelerated cycles defined in the laboratory in order to highlight the impact of varying moisture and temperature conditions on the bending mechanical properties of glulam beams. The final objective is to establish models for predicting the residual life of these structures in order to optimise preventive maintenance operations.

2 Materials et methods

2.1 Specimens used, ageing conditions and moisture monitoring protocol

66 glulam beams made of Douglas fir were used. Douglas fir (*Pseudotsuga menziesii*) was chosen because it is very commonly used in the construction of timber bridges [2]. Each glulam beam was made of three lamellae and was 480 mm in length (L) with a cross-section 30 mm (R) x 30 mm (T), dimensions defined according to the standard EN 408 [11]. These beams were exposed to accelerated W/D cycles and the evolution of the mechanical properties in bending was evaluated. An accelerated W/D cycle is defined in three phases in order to obtain variable moisture between 10% and 30% MC (Figure 1). The first phase (AB) consisted of humidifying the specimens in a climatic chamber at 98% RH and 35°C until the mass was stabilised, thus achieving 20.8% MC. In the second phase, the specimens were immersed in water at room temperature (20°C) for 24 hours to simulate the presence of free water found in the wooden elements of the bridges [12]. This step allowed 30% MC to be obtained. The final drying phase consisted of returning the specimens to a climatic chamber at 50% RH and 35°C until the mass had stabilised, thus allowing the wood to return to 10% MC.

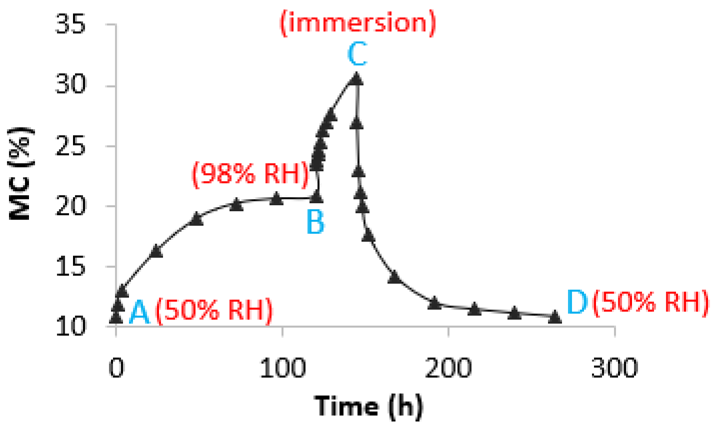

Figure 1: Wetting/drying cycle used for ageing glulam specimens

On the whole, seventeen accelerated W/D cycles were performed. Moisture content were monitored on six control specimens instrumented with three resistive patch-type sensors (MC1, MC2 and MC3) embedded between the lamellae (Figure 2). The instrumentation and measurement protocol are given in [5].

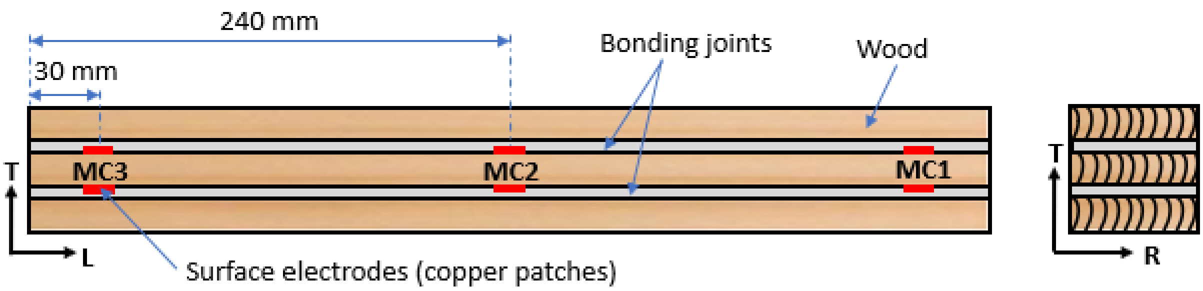

Figure 2: Representation of a glulam specimen instrumented with resistive patch-type sensors between the lamellae for moisture content monitoring

2.2 Mechanical characterization in bending

In order to identify the effect of moisture variations on the mechanical strength of glulam beams, four-point bending tests (Figure 3) were conducted during the different W/D cycles, in 11 sequences presented in Table 1. Before each bending test, the specimens were conditioned in a climatic chamber at 65% RH and 20°C until their masses were stabilised according to standard EN ISO 12571 [13]. The specimens had an average density of 558 ± 26 kg/m3 at 12 ± 1% MC. The bending tests were then conducted with an imposed displacement speed of 5.4 mm/min. The deflection was measured using a Solartron AX5S LVDT displacement sensor. The bending strength and modulus of elasticity were determined after each sequence, according to standard EN 408 [11].

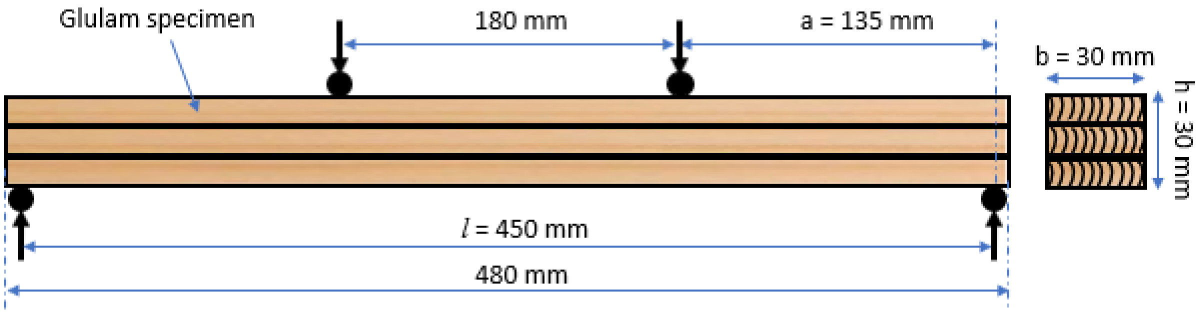

Figure 3: Four-point bending tests performed according to standard EN 408 [5]

Table 1: Sequencing of bending tests during W/D cycles

Number of cycles	**0**	**1**	**2**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**
Sequence number	1	2	3	4	5	6	7	8	9	10	11
Number of specimens	10	5	5	5	5	5	5	5	5	5	5

3 Results and discussion

3.1 Moisture evolution in glulam specimens during ageing

The Figure 4 shows the MC evolution of one specimen (all specimens having similar trends), monitored as a function of time for 17 W/D cycles. It can be seen that the wood MC measured in the climatic chamber are quite similar (phase AB) for all cycles. However, some variability between cycles in the immersion phase (BC) is noticed. According to the additional tests carried out, this variability can be explained by the change in conditioning when the specimens are moved from the climatic chamber to the immersion tank (and vice versa), which induces a sudden change in electrical resistance due not only to the electrolytic substances present in the water but also to the temperature change.

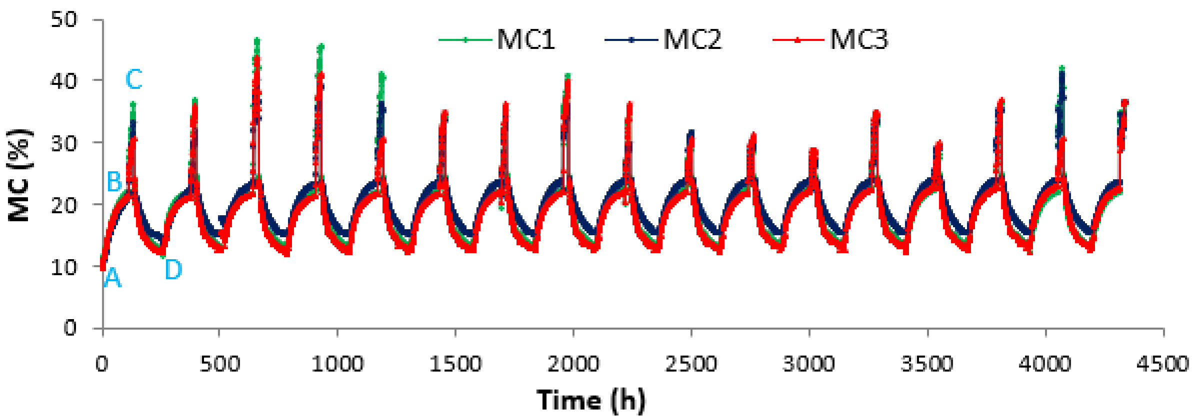

Figure 4: Evolution of the MC monitored by the three sensors MC1, MC2 and MC3 in glulam specimen

The MC curves (Figure 4) also enabled to show a difference in moisture between the edges (MC1 and MC3) and the centre (MC2) of the specimen during the W/D cycles. This allows to appreciate the ability of the embedded sensors to perform local MC monitoring, thus allowing to estimate the moisture gradients between the edges and the centre of the glulam beam.

Figure 5 shows the moisture gradients at points B, C and D of each W/D cycle for the three conditions (98% RH, immersion and 50% RH) between the edge and the centre of the specimen (average moisture (MC1 and MC3) - MC2). At the first sight, the moisture gradients are globally positive during the wetting phase (98% RH in the climatic chamber and in immersion), whereas they are negative in the drying phase (at 50% RH). This can be explained logically by the fact that during the wetting phase, the MC remains higher at the edge of the specimen (MC1 and MC3) than at its centre (MC2). Then the situation is reversed when the specimen is dried. It was also noted that the moisture gradients are very variable from one specimen to another with sometimes significant standard deviations, which can be explained by the heterogeneity between the specimens. Furthermore, these moisture gradients can generate internal stresses in the wood and create cracks in glulam wood structures [1,3,14]. The impact of these damage mechanisms created by cyclic moisture ageing is analysed in the next section.

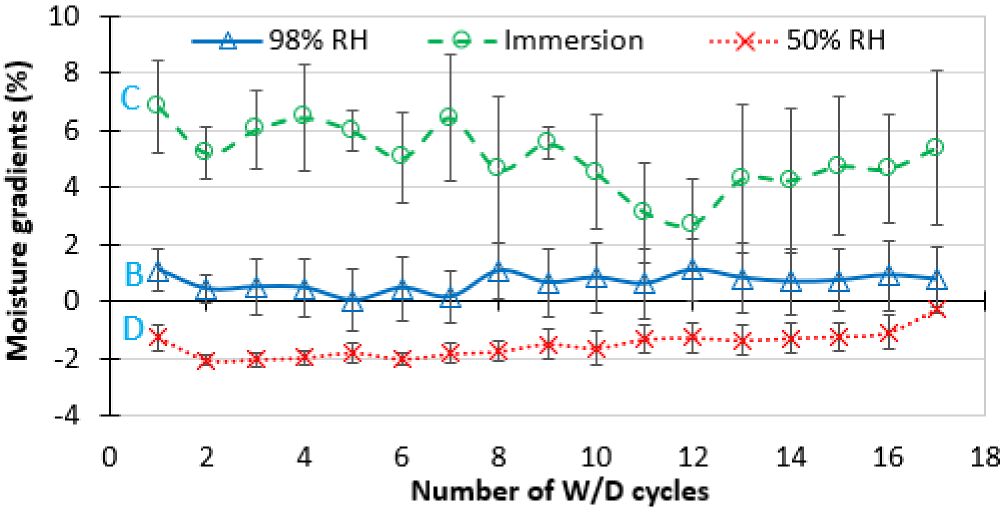

Figure 5: Moisture gradients measured between the edge and the centre of the specimen at points B, C and D of the W/D cycle

3.2 Influence of wetting/drying cycles on the mechanical strength of glulam

3.2.1 Mechanical behaviour in bending

Figures 6a and 6b show the load-displacement curves of specimens respectively before ageing and specimens exposed to 17 W/D cycles. In general, whatever the cycle, the curves show a linear part at the beginning of the load, where the load seems to be less than 50% of the maximum load. Then the curve becomes slightly non-linear until the load reaches its maximum value followed by specimen failure. This corresponds classically to the static bending behaviour of wood [15,16]. However, unlike the aged specimens after 17 cycles, it can be observed that the majority of the unaged specimens (at 0 cycles) shows a more pronounced load recovery even after a significant load drop in the non-linear zone. Furthermore, after 17 cycles, the material seems to lose its ability to deform in the non-linear zone, i.e. it loses its "ductility" after cyclic moisture ageing. A decrease of failure load of 2990 N (i.e. 43.5%) after ageing can also be observed as can be seen in Figure 6b by comparing the average values failure load at 0 and 17 cycles.

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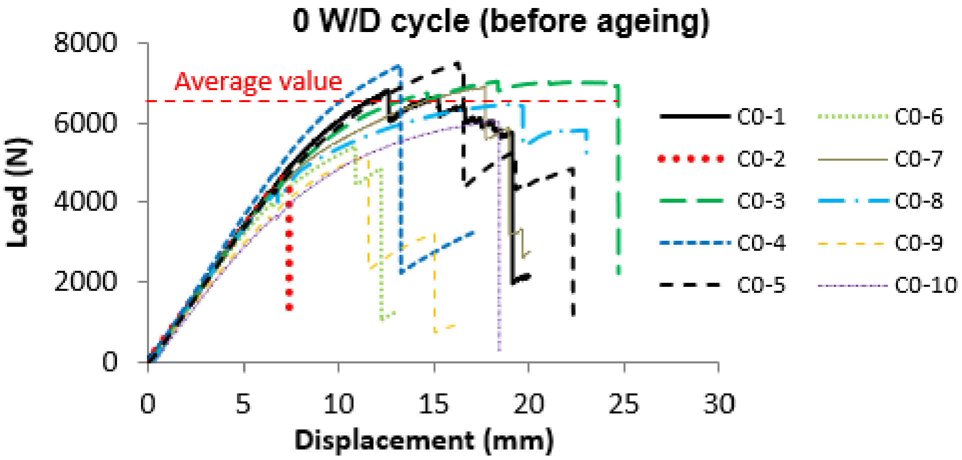
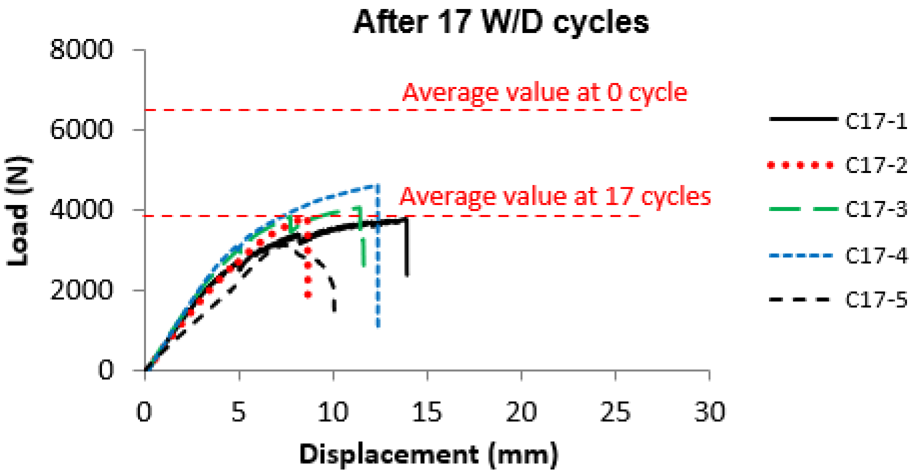


(a)



(b)

Figure 6: Load-displacement curves of the specimens tested in bending: (a) before ageing (0 W/D cycle); (b) after ageing (after 17 W/D cycles)

3.2.2 Influence of wetting/drying cycles on bending strength and modulus of elasticity

Figures 7a and 7b show the evolution of the bending strength and the modulus of elasticity respectively as a function of the number of W/D cycles. To determine whether there is a significant difference between the calculated average values as a function of the cycles, an analysis of variance at 95% confidence was performed using XLSTAT software. The results of this analysis for the 17 cycles are presented in Figure 7 by the letters "a, b, c, d". It can be seen that the bending strength of the unaged specimens (0 cycle) and those of the aged specimens (after 17 cycles) are significantly different. It can also be seen that the decreases in strength are much more pronounced after the first cycle and after the seventh cycle. This weakening of the bending strength can be explained by microstructural changes of the wood material under cyclic moisture stress [17,18]. Indeed, during the W/D cycles, some microcracks were observed in the material that caused irreversible damage and thus the weakening of the bending strength. Besides, from Figure 7b, it can be observed that no significant influence of the W/D cycles was found on the modulus of elasticity.

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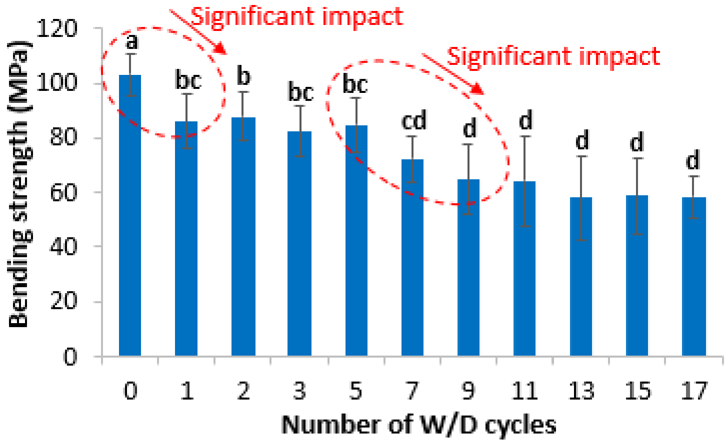
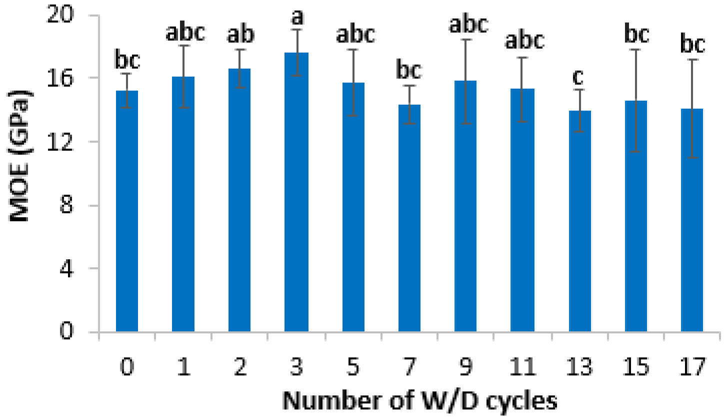


(a)



(b)

Figure 7: Evolution of the mechanical properties in bending of the specimens during the W/D cycles: (a) case of the bending strength; (b) case of the modulus of elasticity (MOE)

By considering the percentage decrease in strength caused by each W/D cycle, the loss of bending strength as a function of cycles can be calculated using equation (1).

$$\Delta\sigma_{max}(\%) = \frac{\sigma_N - \sigma_0}{\sigma_0} \text{x } 100 \qquad (1)$$

where $\Delta\sigma_{max}(\%)$ is the loss of bending strength,
σ_N(MPa) is the bending strength after N cycles,
σ_0(MPa) is the bending strength of the specimens before ageing.

Figure 8 shows the loss of bending strength as a function of the number of cycles. Overall, the 17 W/D cycles cause an average 43.5% loss of the bending strength of the unaged specimens (i.e. an average decrease of 44.8 MPa). The trend analysis enabled the predictive experimental model presented in Figure 8 to be proposed. This model allows to estimate the bending strength (**σ**max) as a function of the number of cycles (N) with a coefficient of determination (R^2) of 93%.

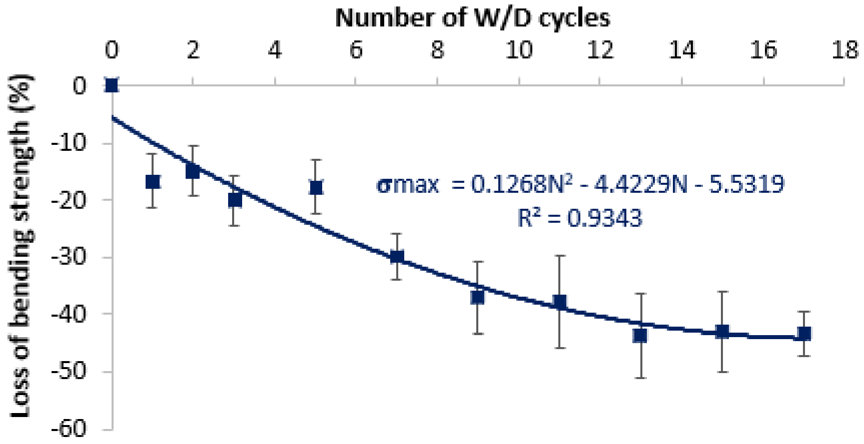


Figure 8: Experimental model of bending strength loss as a function of W/D cycles (N: number of cycles)

4 Conclusion

Within the framework of structural health monitoring of timber bridges, the objective of this study was to set up a system for continuous monitoring of local moisture content (MC) in glulam beams, and to highlight the impact of wetting/drying (W/D) cycles on the durability of glulam timber elements. The experimental results show that the developed measurement system allows to monitor in real time and continuously the MC of glulam beams. The resistive patch-type sensors embedded in glulam beams allow to trace the local MC in a lamella, to discretize different moisture areas in a beam, and thus to have an estimation of the moisture gradients between the edges and the centre of a glulam beam.

Regarding the impact of W/D cycles, the results showed that the exposure of glulam to moisture variations had a significant influence on the bending strength with an average decrease of 43.5% after 17 W/D cycles. The evolution analysis of the values allowed to propose a predictive model for the evolution of the bending strength as a function of the W/D cycles. Furthermore, no significant effect of W/D cycles was observed on the modulus of elasticity of the specimens.

Other works are currently underway in the laboratory to evaluate the durability of these structures under real conditions, i.e. outdoors. In addition to highlight the impact of natural whether conditions on the mechanical strength of timber beams used in bridges, this will enable to validate the reliability of the accelerated W/D cycle developed in the laboratory. Afterward, a model for predicting the residual life of glulam structures will be established in order to optimise maintenance operations on timber bridges.

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