Impact of the moisture content on the cyclic embedding behavior parallel and perpendicular to the grain of wood

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Abstract

One common assembly for wood construction is the rod type assembly, this connector is made up of a plate and fasteners (dowels, bolts, etc.). The behavior of this type of connector is driven by the material characteristics (wood, dowel, plate, etc.) and by the contact zone. The vibration behavior of a timber building is partly governed by the assemblies. The cyclic behavior of this type of assembly shows non-linearity and dependencies according to component characteristics; this behavior is thus transposed to the building. One of these dependencies is the moisture content, since wood is a hygroscopic material. To study the impact of this parameter on the cyclic behavior of wood, a process is defined to reduce the variability. The analyse is made for parallel and perpendicular to the grain loading for three different moisture contents (below the fiber saturation point). A loading control test is used with four load levels, going from the elastic domain to the plasticity. This type of testing permits to compare different samples conversely to a displacement control test. Thus, a hardening or softening behavior is observed. A significant difference in terms of general deformations and energy dissipation is found. The observation of the samples shows that the microstructure of the contact surface is changed according to the moisture content of the sample. This kind of phenomenon needs to be taken into account when modelling the dynamic behavior (or in long term analysis) of wood assemblies.

1 Introduction

The construction of mid- and high-rise timber buildings increased in recent years. The knowledge about the behavior of wood and the assemblies helps that development in the wood construction sector. Meanwhile, some issues still exist in characterizing the mechanical or even biological behavior of wood in a high humidity environment.

For years, the mechanical behavior of wood was associated to its density, since there is a correlation between resistance, heat value and other mechanical parameters with the density [7]. In fact, the density can be defined at a specific moisture content, in current standards it is defined as the density at 12% of moisture content [1].

The moisture content on wood produce variation of dimensions, according to the referential axis of wood (longitudinal, radial and tangential) coefficients of dimension variations are defined for different species of wood. Being the longitudinal variation the smaller one per unit of moisture content variation [7].

It is known that the moisture content modifies the mechanical behavior of wood when the moisture content varies below the point of saturation of wood fibers [17]. A relation between moisture content and Young modulus, for a given referential axis of wood, can be defined [17].

When applying a heat-bath treatment and with a non modified moisture content, the toughness is reduced [2]. For long term loading, creep is strongly impacted by the moisture content and the variation of the last [10], [6], [5], [15] [12]. The failure, apparition of cracks due to the hygromechanical loadings is also studied in the literature, showing the difficulty of this type of simulations and differences with experimental results, [13], [14].

So, the behavior of the assembly is also dependent on the moisture content. In the case of steel, the main issue with humidity is corrosion, for that reason most of the connectors are made with stainless steel or have a

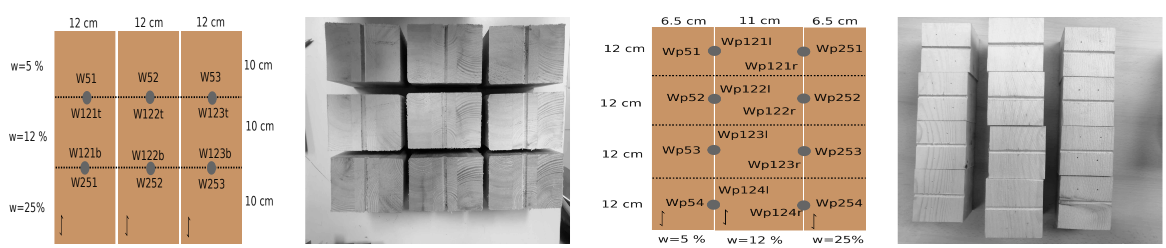
protection against corrosion, the mechanical behavior is not impacted by the humidity. Conversely, the wood foundation is strongly affected. The stiffness may stay unchanged, and an increase in moisture content (MC) compared to a MC of reference of 20% and 65% of RH increases the strength and conversely. The assembly history (different degrees of moisture content in the history) seems to do not affect the embedment strength. The stiffness considerably increases when drying the assembly. When adding artificial cracks below the dowel, the strength is reduced about 10-15%. A reduction of 15-20% of the stiffness is observed. All these observations were made on reinforced specimens of wood and with full hole samples for embedding [16].
Other studies with a half hole samples shows that dowel-bearing strength increases with decreasing MC. The relation founded seems to be independent on the wood species. In addition, the impact seems to be independent of the dowel diameter [11]. Testing on bamboo scrimber, green wood and other type of sections shows similar results [8], [9].
Thus, the moisture content impact the embedding strength so the complete behavior of an assembly. High variability of testing is observed. The most appropriate way to evaluate the impact of the moisture content is on an embedding test.
Cyclic behavior characterize the behavior of the assembly under a 'dynamic' loading by a quasi static equivalent. This type of tests is applied to a half hole sample, the procedure is explained in the next section.

2 Experimental program

All samples were made with a GLT24H wood with 8 mm steel dowel. In order to reduce the variability, the drilling was made at the same time for two corresponding half-holes (see figure 1).

2.1 Specimen details

Ass the wood has an important heterogeneity, the half holes were made 2 by 2. It helps to reduce the variability due to wood and due to the drilling quality. Standards give a minimum thickness of 2d (1.6 cm). The thickness of 8 cm is used since there is no bending of the dowel and the heterogeneity is reduced for higher thickness. The width is fixed as 12 cm (15d) compared to the minimum of 4d for parallel or perpendicular to the grain given in the standards [4]. After cutting, it can be seen that the surfaces are correspondent (almost the same form and quantity of annual rings). The middle samples have two half holes (figure 1 (b)(d); Since the behavior of the half hole is local, this configuration does not impact greatly the embedding behavior. The comparison after experience can be made only for corresponding surfaces (w51-w121t, w122b-w252,...).
For the parallel to the grain embedding, three samples are compared (at 5% and 12% MC); and 3 others



(a) (b) (c) (d)

Figure 1: (a) Parallel to the grain embedding samples dimensions and (b) surface after cutting. (c) Perpendicular to the grain embedding samples and (d) surface after cutting

from 12% to 25% moisture content. For the perpendicular to the grain embedding, 4 samples are compared (one of them present a knot). Few tests are necessary since the variability is strongly reduced thanks to the cutting and drilling procedure.
All samples thus obtained are stocked in the same humidity controlled space. As specified, a row of samples have the same conditionning. In order to obtain the moisture contents of 5% 12% and 25%, the corresponding samples have the same conditions of drying or wetting, the middle samples do not have any treatment.

Table 1: Samples caracteristics

||	w(%)	ρ (kg/m3) $\sim$ 12%
w51	4,7	542
w52	4,9	531
w53	5,2	487
w121t	13,8	529
w122t	13,8	561
w123t	14	499
w121b	13,8	520
w122b	13,8	546
w123b	14	533
w251	23,4	531
w252	23,9	515
w253	25	523

$\perp$	w(%)	ρ (kg/m3) $\sim$ 12%
wp51	4,5	450
wp52	4,3	447
wp53	4,2	495
wp54	4,4	459
wp121l	14,2	506
wp122l	14,5	528
wp123l	14,3	512
wp124l	14,1	526
wp121r	13,2	506
wp122r	14,6	528
wp123r	14	512
wp124r	14,4	526
wp251	24,4	504
wp252	26,4	471
wp253	23,8	483
wp254	23,3	525

In the drying and wetting process, previous tests were taken into account in order to obtain an approximate moisture content in all samples. The reference moisture content will be used for all notations hereafter, for example a sample having a reference of 5% moisture content, can present a moisture content of 4.5% or 5.2%. In addition this moisture content correspond to the mean value for an depth of $\sim$ 4mm (depth of pin moisture meter figure 2(c)). Another moisture content is measured at 1.5 cm of depth (see figure 2(d)) with special pins for the moisture meter (insulated pin until the metallic end), the moisture content is lower than the one taken as reference. The moisture content of 4mm depth is taken into account since the embedding behavior is more related to a local behavior and because all slips are much lower than 4 mm.

For the wetting procedure (figure 2(a)), a wet surface surrounds the sample in order to accelerate the transfer

(a) (b) (c) (d)

Figure 2: (a)Wetting procedure. (b) Drying procedure, (c) pin moisture meters and (d) 1.5cm moisture measurement

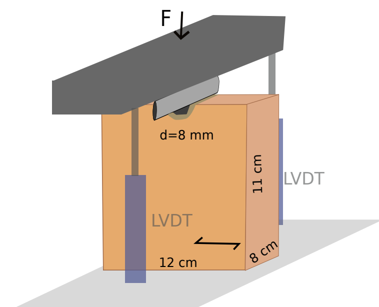
of humidity on the interest zone for the assembly ($\sim$ first cm of depth on wood). This element keeps wet for 24h on the sample and the moisture content is measured on the interest zone in order to verify the vicinity with the reference value (25%). For drying, an oven is used, the samples are spaced and put inside, the temperature increase until to 103 C° and keep it constant for 6 hours. After this procedure, the moisture content is verified before and immediate test. The density is measured directly at the reference moisture content ($\sim$ 12%). In fact, the local structure of wood define the embedding procedure, for example a knot can be present in a soft foundation so in a sample of law density.

The table 1 shows the principal characteristics of the samples, the moisture content is a median of the values measured perpendicularly to the sample (3 measurements). The maximum variation for samples of 5% and 12% moisture content is around $\pm$0.6%, for samples of 25% of moisture content the maximum variation is

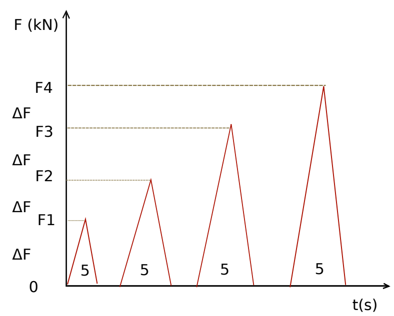
greater (±1.5%). The signification the name is as follows, Wp122r is the 12% moisture sample, is the sample number 2, it is on the right of the sample (left if 'l', top if 't' and bottom if 'b') and (p) if it is for the perpendicular to the grain test.
It is important to note that the moisture content differs on the depth, for parallel to the grain embedding samples the moisture content at 1.5 cm of depth decreases on around 5%. For perpendicular to the grain embedding, it is around 8%.

2.2 Loading protocol

Once the samples present a moisture content in the vicinity of the reference value, the cyclic test is applied. The conditions of all tests are the same (see figure 3). The same dowel of 8 mm is used for all samples, after testing almost no modification (diameter variation) is measured on the dowel.
A cyclic load of 4 amplitudes is employed, two in the "elastic" domain and two in the "plastic" domain of the embedding response. Five cycles are applied at each amplitude, conversely to the standards [3], this quantity of cycles permits a stabilized (variation of ±2%) energy dissipation. In addition, a force controlled test is employed in order to obtain comparable data. All amplitudes of loading have the same variation (ΔF). For the parallel to the grain embedding ΔF is 4 kN and for the perpendicular one is 2.5 kN.



(a)



(b)

Figure 3: (a) Test set-up. (b) Loading protocol

Two LVDT's are used, a pin connector ensures that the loading is homogeneously transferred on the dowel but the deformation will depend on the foundation, for these reasons, two LVDT's are necessary. The speed of loading is fixed lower than the limit given by the standards [3] (<0.2mm/s), the maximum rate used is 0.12 mm/s. A preload of 50 N is applied to all samples.

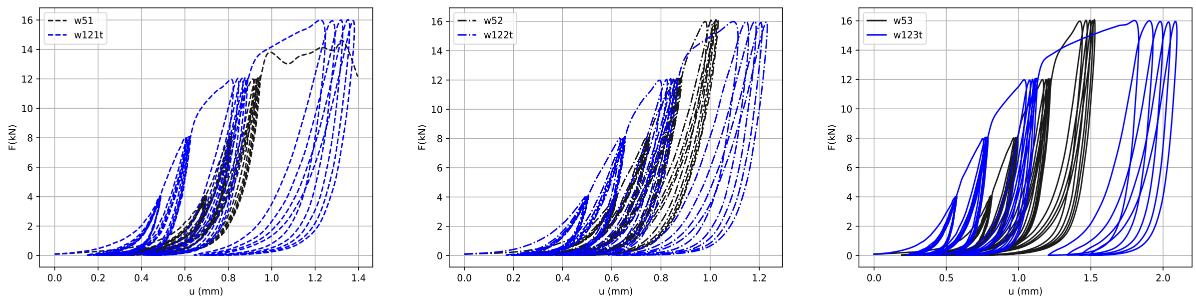
3 Results for parallel to the grain embedding

All tests start at the same force displacement value of the imposed preload. The displacement is the average of the result obtained from the two LVDTs. The force is recuperated directly from the loading machine. The energy dissipation is an important parameter when evaluating the non linearity and hysteresis of the assembly, in addition the stiffness of loading and unloading is measured at the complementary values of the percentages given by the standards (10% and 40%), this choice is made because in this interval the loading or unloading curve is close to a straight line.

3.1 Force displacement result

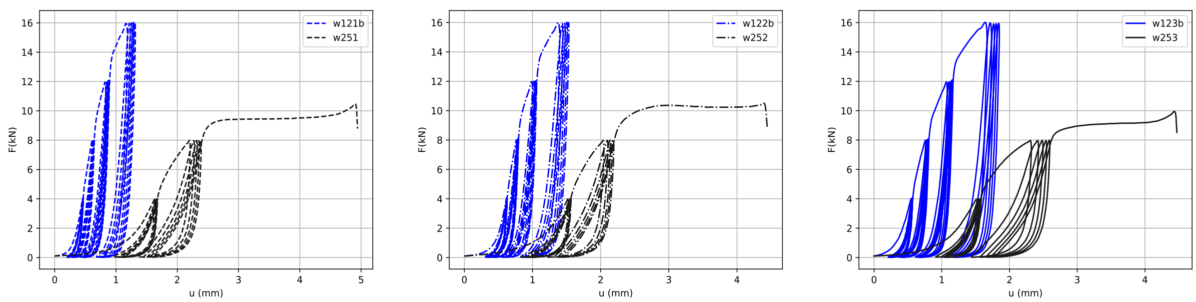
The force displacement curves show lower final slip is attempted for a sample of 5% MC compared to the one of 12%. The sample W51 fails before the final amplitude of loading. All samples have an initial soft slip (±

0.2mm) (see figure 4).
Higher final slip is obtained from a sample of 25% MC compared to the one of 12%. All samples of 25%



(a) (b) (c)

Figure 4: Force displacement response 5% - 12%



(a) (b) (c)

Figure 5: Force displacement response 12% - 25%

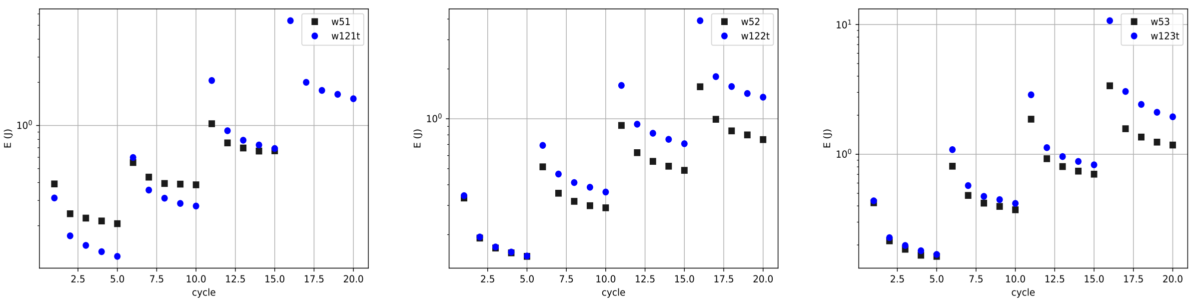
MC fails after the second amplitude only.All samples have an initial soft slip, this slip is more important for samples of 25% MC (see figure 5). A horizontal curve is obtained at the end of loading for samples of 25% MC, since a half hole is used only 4mm of slip is allows, after this value the curve increases because of the contact with the wood sample.

3.2 Energy dissipation

The energy dissipation is measured as the surface defined by a cycle of a loading and unloading. This surface is characteristic of the hysteresis, for a linear material non energy dissipation is allowed. The energy dissipation of the first cycle differs from the others since this cycle reaches the envelope curve and it starts from the last loading curve. In most of the cases, the energy dissipation is slightly higher for samples at 12% MC compared to the 5% MC. The final energy dissipation (after 5 cycles) increases when increasing the loading level. The energy dissipation decreases for a same level of loading.
For samples of 25% MC, the energy dissipation is higher compared to the 12% MC samples (more than 2 times), energy dissipation increases when increasing the loading level.

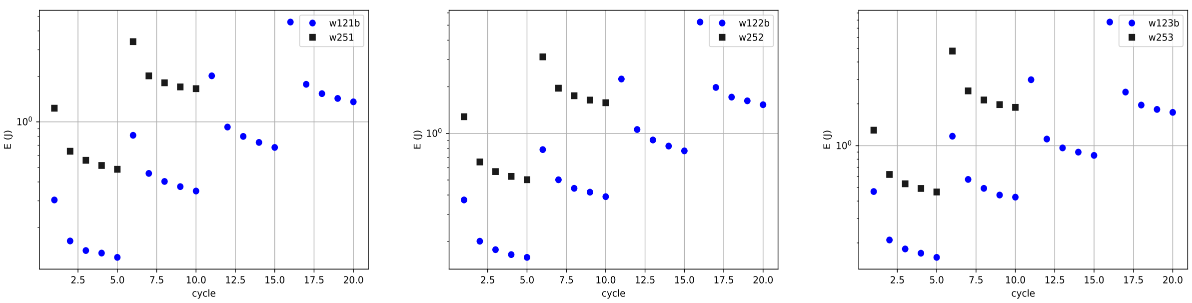
3.3 Stiffness at loading and unloading

The stiffness is measured as a secant stiffness between 60% and 90% of the loading level for each cycle. In fact, the tangent stiffness shows a hardening behavior when cycling for all loading levels, excepted the first cycle.



(a) (b) (c)

Figure 6: Energy dissipation per cycle for samples at 5% - 12% MC

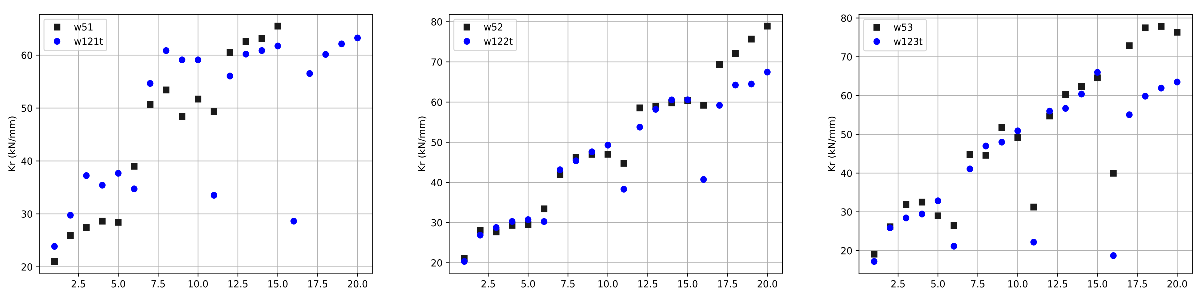


(a) (b) (c)

Figure 7: Energy dissipation per cycle for samples at 12% - 25% MC

The reloading stiffness (Kr) is thus defined, as show in the figure 4, 5, the first value does not correspond to a linear section, for these reasons only reloading stiffness are analysed (from the second cycle of each amplitude).

The reloading stiffness increases in almost all the cases, the reloading stiffness for samples of 5% compared



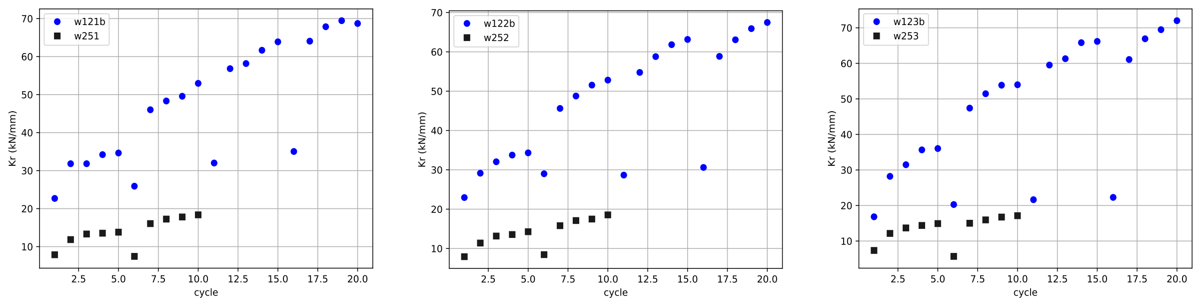
(a) (b) (c)

Figure 8: Loading stiffness per cycle for samples at 5% - 12% MC

to 12% is initially lower but increases to exceed the stiffness of 12% MC samples in the two last loading levels. It is why the final slip is lower for samples at 5% MC compared to the ones at 12% MC.

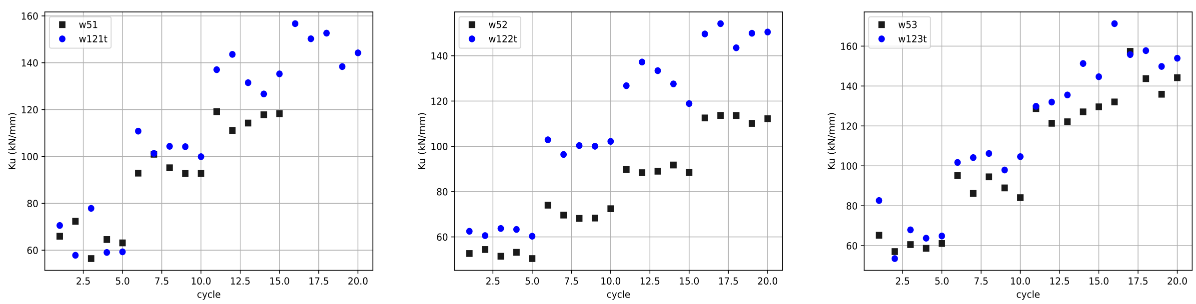
For samples at 12% the stiffness is more than two times the stiffness of samples at 25% MC. In all cases, the stiffness increases when increasing the loading level but tend to a stabilized value around in most cases after 4 cycles (see figures 8, 9).

It is difficult to establish if the unloading stiffness increases, in general it keeps almost constant. The unload-



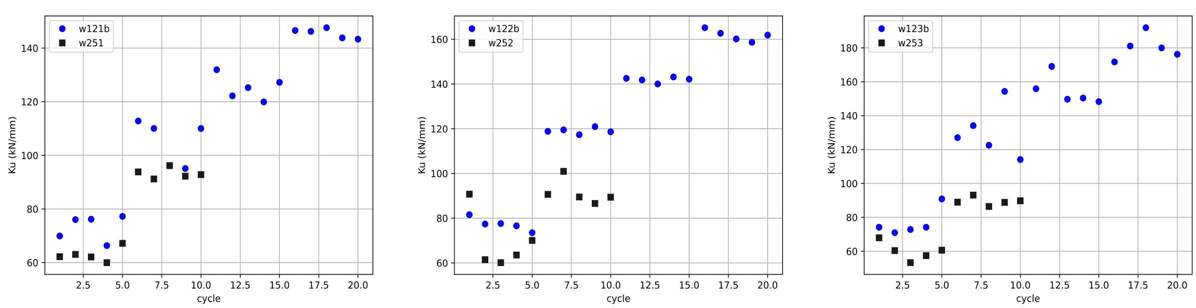
(a) (b) (c)

Figure 9: Loading stiffness per cycle for samples at 12% - 25% MC



(a) (b) (c)

Figure 10: Unloading stiffness per cycle for samples at 5% - 12% MC



(a) (b) (c)

Figure 11: Unloading stiffness per cycle for samples at 12% - 25% MC

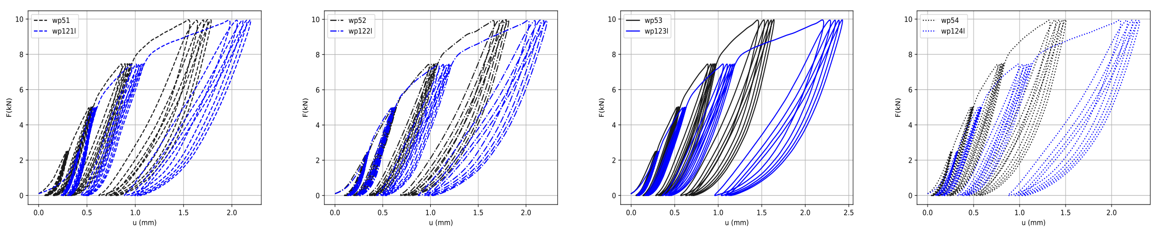
ing stiffness for samples of 5% compared to 12% is lower in general. This unloading stiffness is higher than the reloading stiffness (around two times), it permits energy dissipation. In general, this stiffness increases when increasing the loading level.
For samples of 12% compared to 25% the stiffness keeps almost constant for a given loading level. The unloading stiffness for samples of 25% compared to 12% is lower in general. This unloading stiffness is higher than the reloading stiffness (around two times) and increases when increasing the loading level (see figure 8, 9).

4 Results for perpendicular to the grain embedding

As defined previously. Force displacement curves, energy dissipation and reloading and unloading stiffness are analysed. For these configurations of test, four samples are analysed.

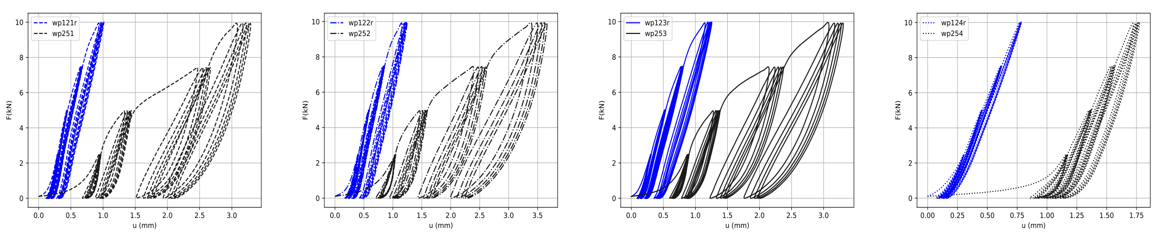
4.1 Force displacement result

In the same way, a smaller final slip is attempted for a sample of 5% MC compared to the one of 12%. The sample. The initial soft slip is smaller than the test parallel to the grain (see figure 12).
Higher final slip is obtained from a sample of 25% MC compared to the one of 12%. Any sample of 25% MC



(a) (b) (c) (d)

Figure 12: Force displacement response for samples at 5% - 12% MC



(a) (b) (c) (d)

Figure 13: Force displacement response for samples at 12% - 25% MC

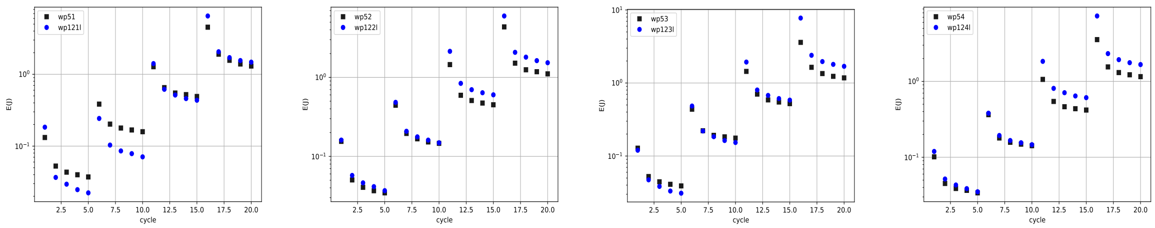
fails. The initial slip is more important for samples of 25% MC (see figure 13). For the sample with a knot, an important initial slip is observed (see figure 13(d)).

4.2 Energy dissipation

The energy dissipation of the first cycle is always the higher for all loading levels, and it decreases with the cycles for a same loading level. In most of the cases, the energy dissipation is slightly higher for samples at 12% MC compared to the 5% MC excepted for the first and second loading level. The final energy dissipation (after 5 cycles) increases when increasing the loading level.
For samples of 25% MC, the energy dissipation is higher compared to the 12% MC samples (more than 4 times), energy dissipation increases when increasing the loading level (see figure 14, 15).

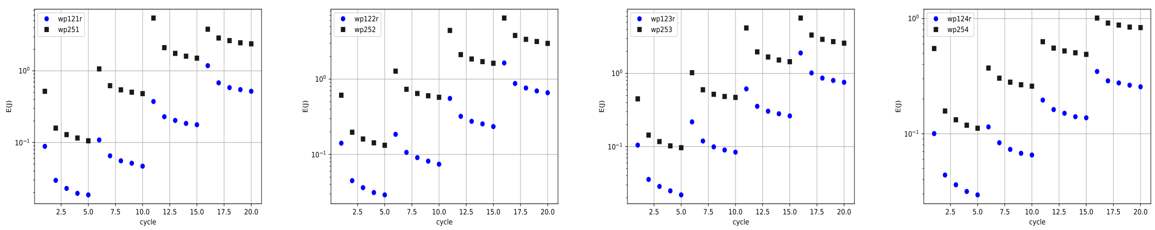
4.3 Stiffness at loading and unloading

The stiffness is measured as a secant stiffness between 60% and 90% of the loading level for each cycle as precised previously.



(a) (b) (c) (d)

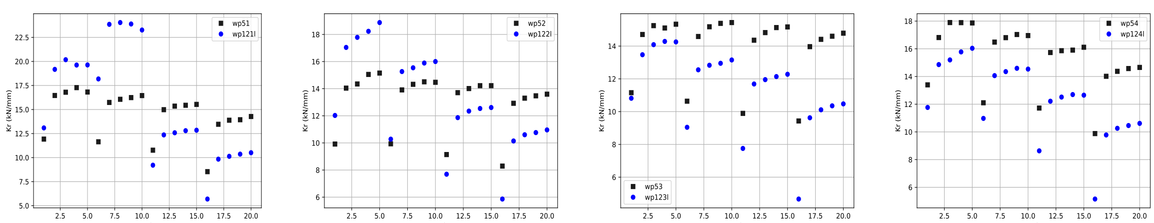
Figure 14: Energy dissipation per cycle for samples at 5% - 12% MC



(a) (b) (c) (d)

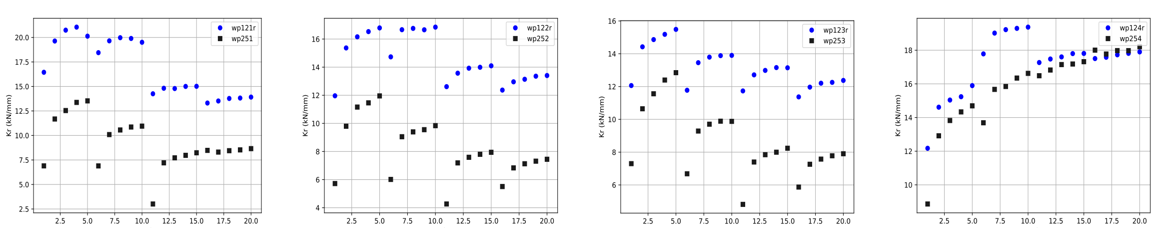
Figure 15: Energy dissipation per cycle for samples at 12% - 25% MC

The reloading stiffness increases for a given loading level but decreases in general increasing the loading



(a) (b) (c) (d)

Figure 16: Loading stiffness per cycle for samples at 5% - 12% MC

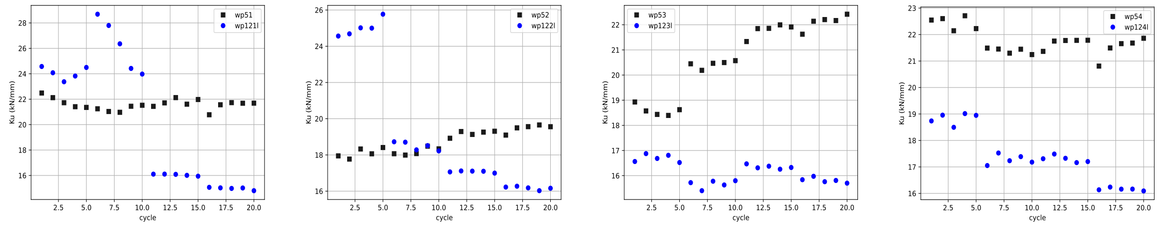


(a) (b) (c) (d)

Figure 17: Loading stiffness per cycle for samples at 12% - 25% MC

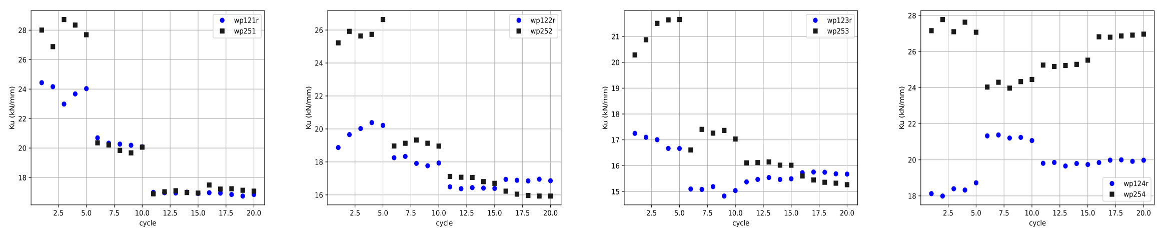
level. The stiffness for samples of 5% compared to 12% are more constant or decreases in a lower rate when increasing the loading level.

For samples at 12% the stiffness is almost two times the stiffness of samples at 25% MC, excepted for the sample with a knot (see figure 17). In this last, the stiffness increases when increasing the loading level conversely to the three others samples (see figure 17).
It is difficult to establish if the unloading stiffness increases, in general it keeps almost constant or increases



(a) (b) (c) (d)

Figure 18: Unloading stiffness per cycle for samples at 5% - 12% MC



(a) (b) (c) (d)

Figure 19: Unloading stiffness per cycle for samples at 12% - 25% MC

for the samples at 5% MC. The unloading stiffness for samples of 5% compared to 12% is higher for the two last loading levels. The reloading and unloading stiffness of samples at 12% MC is comparable.
For samples of 12% compared to 25% the stiffness keeps almost constant for a given loading level. The unloading stiffness for samples of 25% compared to 12% is higher in general. This unloading stiffness is higher than the reloading stiffness (around two times)(see figure 18, 19).

4.4 Observations on the drilling surface

The surface in contact with the dowel has an important role in the effort transmission, images were taken before and after the tests, for brevity only the images after tests are shown below. For the surface aspect when testing parallel to the grain, the surface at 5% MC present similar surface compared to the 12% MC samples, but the samples at 25% MC have a strongly scaled surface, the crack appears at the end of the test, it cannot be seen in the face but only in the drilling.
For perpendicular to the grain samples, almost no difference exists between the surfaces of drilling for samples at 5% and 12% MC. A scaled surface appear clearly for samples at 25% but it is less important than the scaled surface of samples in parallel to the grain embedding.
As expected, the initial surface quality is almost the same after the drilling. It means that the obtained scaled surface appears because of the high humidity at the interface when wetting the samples.

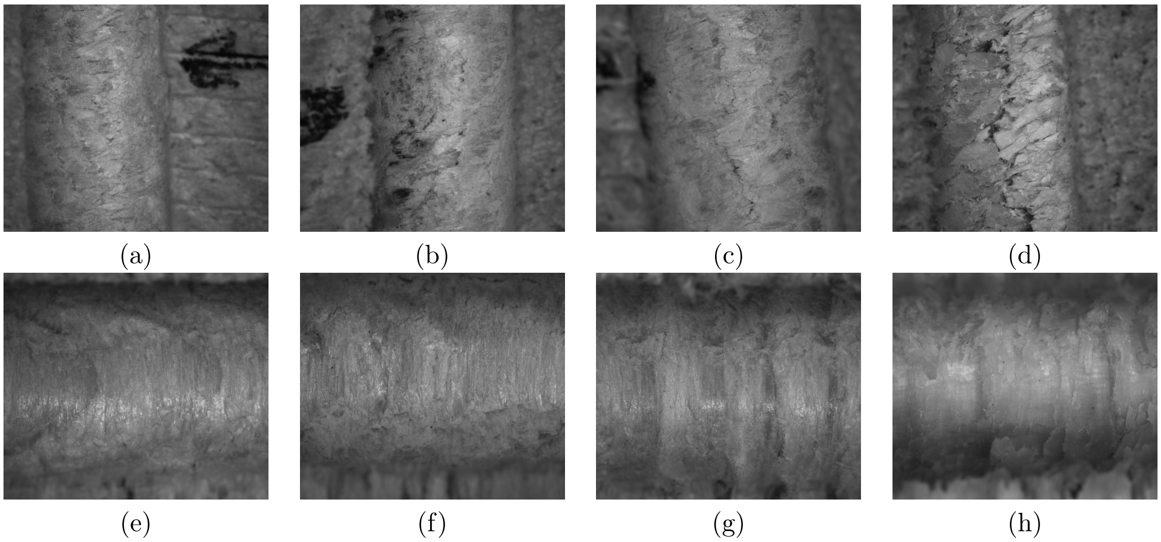


Figure 20: (a) Sample W53, (b) sample W123 after the test, taken with a scale of 0.75 and at almost the same position in the hole (c) Sample W123, (d) sample W253 after the test,(e) Sample Wp51, (f) sample Wp121l after the test, taken with a scale of 1 and at almost the same position in the hole, (g) Sample W121r, (h) sample W251 after the test, taken with a scale of 1

5 Conclusion and discussion

Since wood is a hygroscopic material, the moisture content is an important parameter to describe when characterising the mechanical properties of wood. It was seen that the moisture content is not a constant value for a sample but a value at a position in the wood and at a certain depth. In this study, the impact of the moisture content on the cyclic behavior of wood is analysed. A special procedure is established in order to reduce variability due to wood and due to the drilling process. An appropriate conditioning is applied to the samples in order to obtain the desired moisture content on the zone of interest for this study. Applying a cyclic test with force control, the behavior in terms of force displacement result, energy dissipation and reloading-unloading stiffness is analysed.

For the test parallel to the grain, the force displacement curve is stiffer for a 5% MC, but starts initially softer than samples at 12%. Samples at 25% are strongly affected by the MC. Conversely, these samples dissipated much more energy than others. Reloading and unloading stiffness increases when increasing the loading level. The unloading stiffness is at least two times the reloading stiffness in general. For the tests perpendicular to the grain, samples have a lower initial soft slip, for 5% MC samples a lower final slip is obtained, conversely for samples at 25% a high slip is observed. The energy dissipation increases when increasing the loading level, the samples at 25% MC dissipate much more energy than samples at 12% (more than four times) compared to around 2 times inr parallel to the grain embedment. Concerning the reloading-unloading stiffness, no clear relation can be found. In most of the cases, the stiffness does not increase when increasing the loading level.

Some pictures taken at the end of testing show the surface condition for the samples. At 25% MC, a strong modification of the surface condition is observed for parallel embedment, this is lower but exist for the perpendicular to the grain samples.

This study is limited to GL24H wood, and for a diameter of 8 mm, additionally different other types of conditioning can be employed and the measure of moisture content can be more accurate (for a given depth).

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