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CHARACTERIZATION OF ROLLING-SHEAR CREEP FOR CROSS LAMINATED TIMBER PANELS

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ABSTRACT: This article presents an experiment to characterize the rolling shear modulus $G_{r,mean}$ of CLT panels and its creep. A four-point bending test is achieved on sandwich beams with steel skins and wooden core. This allows to isolate the CLT cross-layer and to characterize the shear behaviour. The experiment is performed in a constant environment during 6 months. The short term $G^0_{r,mean}$ is estimated at 97.7 MPa with a coefficient of variation of 7.2%. Then, a power law is fitted to the results and the creep coefficient k^G_{def} is estimated as 2.3 at 50 years which corresponds to a long term rolling shear modulus $G^{\infty}_{r,mean}$ = 29.6 ± 2.6 MPa.

KEYWORDS: Rolling Shear, Cross Laminated Timber, long-term behaviour, creep

1. INTRODUCTION

Everywhere around the world, high wood buildings are rising. The construction of these new buildings is possible thanks to the mainstreaming of some engineering products such as cross-laminated timber panels (CLT). CLT panels gained in popularity for several reasons. First, they are a more sustainable solution than concrete designs. Second, the prefabrication process makes them easy to assemble on site. Third, these panels have a high dimensional stability under variation of moisture content compared to other timber products. Because of all these advantages, high buildings up to 80-meters, such as the Mjøsa tower in Norway, are being erected. CLT panels can be used both as walls and floors in those constructions.

Because of the cross-layers of CLT panels, rolling-shear deformations are involved in their mechanical response. The value of the rolling shear modulus $G^0_{r,mean}$ for short-term lies between 50 and 200 MPa [1]–[4] which is about 200 times lower than the longitudinal Young modulus. Large differences between the studies are due to the difficulty to obtain a pure shear stress and to represent the behaviour of cross layers. Additionally, the sawing pattern and aspect ratio of the board are of importance for CLT [1], [5], [6].

Whereas the short-term rolling shear modulus has been quite investigated during the last decade [1] there are very few attempts to characterize the long-term behaviour of rolling shear [7], [8]. In these works, bending tests of CLT panels are achieved and an overall creep factor is derived. It appears clearly that creep is larger with CLT than with GLT. A possible explanation may be a faster creep behaviour coming from rolling shear strains in cross layers.

This paper presents an experimental protocol to measure directly the rolling shear stiffness and creep of Norway spruce used in CLT panels following the methodology originally presented by Perret et al. [4].

The paper is organized as follows. First, the sandwich-beam theory and the rolling-shear measurement are briefly recalled and the experimental set-up is introduced. Then, the short-term characterization of the rolling-shear stiffness modulus by means of linear regressions is presented. Finally, the 6-month creep curves and the estimation of the Eurocode coefficient k_{def} [9] by means of a power law are discussed.

2. EXPERIMENTAL PROCEDURE

2.1 SANDWICH THEORY

The rolling shear modulus $G_{r,mean}$ is characterized by means of a four-point bending test on sandwich beams constituted of a wooden core glued between two steel skins (Figure 1). The full methodology is detailed in [4].

The sandwich beam model [10] requires a contrast between the stiffness and the thickness of the core and skins so that: $E_a e_a >> E_b e_b$, $e_b >> e_a$. The conditions are satisfied here with E_a = 210 GPa the skins modulus and

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e_a = 1.2 mm its thickness, E_b = 0.43 GPa the core modulus and e_b = 30 mm its thickness. Because of this contrast, the skins contribute mainly to the bending stiffness D and the core mainly to the shear force stiffness F as follows [11]:

$$D = \frac{b(h^3 - e_b^3)}{12} E_a \quad (1)$$

$$F = \frac{b(e_b + e_a)^2}{e_b} G_{r,mean} \quad (2)$$

with $h = e_b + 2e_a$ the total thickness and b the width of the beam section.

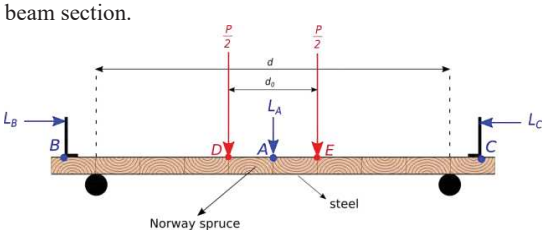


Figure 1: *Four-point bending configuration on a sandwich beam*

The beam is simply supported on a span d = 602 mm and two load $P/2$ are applied at a distance $d_0/2$ from the mid-span, with d_0 = 200 mm. The beam is under pure bending between these loads leading to a constant curvature. It is assumed that steel don't creep in time. Therefore, the bending stiffness D can be estimated from the absolute rotations measured at B and C; φ_B and φ_C as follows:

$$D = \frac{P(d^2 - d_0^2)}{16\Delta\varphi} \quad (3)$$

where $\Delta\varphi = (\varphi_B + \varphi_C)$.
Finally, the shear force stiffness F can be expressed as a function of the mid-span deflection f_A and the bending stiffness D:

$$\frac{1}{F} = \frac{4 f_A}{P(d - d_0)} - \frac{1}{8D}\left(d^2 - \frac{1}{3}(d - d_0)^2\right) \quad (4)$$

2.2 SPECIMEN FABRICATION

Norway Spruce (*Picea abies*) board were used to make the specimens. They were conditioned at a moisture content of $u = 10.6 \pm 0.3$ % and visually graded C24. Their density was measured to be ρ = 495 ± 32 kg.m^{-3}. The boards were oriented so that the pith is alternatively at the bottom or at the top which average their effect on the global behaviour (Figure 2).
The layer thickness of CLT in Europe are 20 mm, 30 mm and 40 mm according to [12]. It was chosen to use a 30 mm thick layer. Eighteen boards were glued together on their narrow edges with a wood glue (Titebond Ultimate 141/5). Glued narrow edges is not a common practice in the industry but sometime is used to reduce the width of the gaps. It will allow here to reduce the stress concentration in the specimens. This wooden plate was then planarized to a thickness of e_b = 30 mm. Then, 800 mm long specimens with a width b = 40 mm and a thickness e_b = 30 mm were cut in this plate. They were cut so the wood fibres are oriented in the transverse direction. Carbon steel XC75 sheets of Young modulus E_a = 210 GPa were used. They are 800 mm long, b = 40 mm wide and e_a= 1.2 mm thick. They were sanded and glued on the top and bottom faces of timber with a two components glue including a thixotropic epoxy based impregnating resin and adhesive (Sikadur® 300). The thickness of the glue layer is about 0.5 mm.

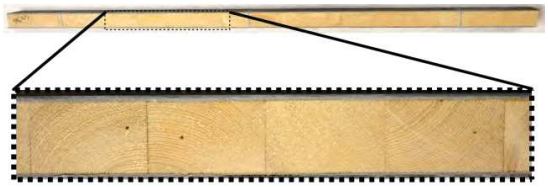


Figure 2: *Specimen*

Five specimens (A-E) were fabricated and tested during this experiment. One example of the specimens is shown Figure 2.

2.3 EXPERIMENTAL SET-UP

Figure 3 shows the schematic representation of the frame (0). The specimens (1) are supported on two cylinders (2) of radius R = 23 *mm* with a span d = 602 *mm*. They are loaded vertically and symmetrically by two loading fixtures (3) spaced of a length d_0 = 200 *mm*. The contact between the loading fixtures and the beam is made with a steel ball of diameter d_b = 1.2 *mm* (10). The rotation of the motor (6) drags a metal thread (9) that ascend and descend the loads (5) and the lever arms (4).
Several sensors are positioned to measure the different variables:

- Three Orbit® linear variable differential transformers (DP20S) are placed on each span of the frame (8). Two of them measure the horizontal displacement of the steel flat angles. They are represented Figure 3 as arrows L_B and L_C. The last linear variable differential transformer (LVDT) measures the vertical deflection of the beam at mid-span (f_A: arrow L_A). They have an accuracy of 0.001mm.
- Two AEP transducers ® S-type load cell (TS) (7) are placed in the loading fixture (3). They measure the load on points D and E. They have an error of 0.018%.

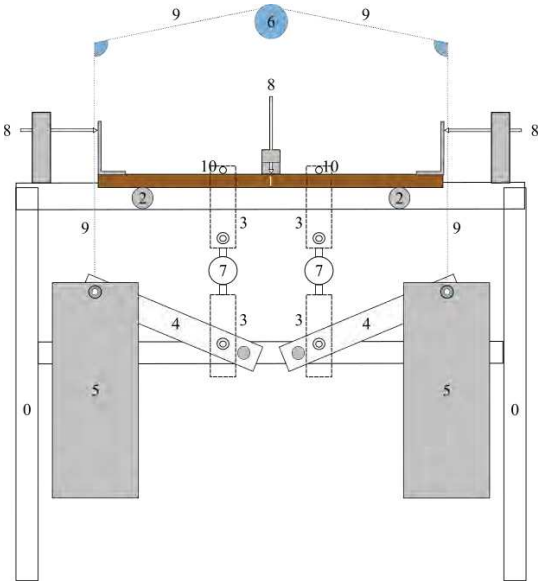


Figure 3: *Framework*

A steel beam lightly loaded (573 N) is placed on the experimental frame as a reference to verify measurements with environmental control. It is equipped with the same captors than all the specimens. The data from those captors confirmed that they don't drift in time and that their values was not impacted by the small changes of humidity and temperature in the room.

The rotations are measured with a lever arm which gives a better accuracy. Their height is h_B=140 ± 0.3 mm and h_C=141 ± 1.1 mm respectively for the lever arm at point B and C. Local punching on the steel skins will be neglected compared to the natural variability of wood characteristics [4]. The recording of the rotations also verify that the skins don't creep in time and that the observed creep is indeed only due to rolling-shear.

2.4 TEST METHOD

The viscoelastic limit has been well studied in the longitudinal direction [13]–[18] and observed to be between 40% to 50%. It is a priori not the same for the cross-layer shear stiffness. Therefore, the specimens were tested under different load conditions. They are summarized in Table 1. The load is indicated as a percentage of the characteristic shear strength $f_{r,mean}$ = 1.88 MPa [1]. These stress levels are approximate since the shear strength varies from one board from another.

Under the viscoelastic limit, Hunt [19] proposed to separate creep into three different components: pure viscoelastic (time dependent creep), mechano-sorptive creep and pseudo-creep followed by a recovery phenomenon. These components are independent but coupling effects may appear. The present experiment will be achieved such that the pure viscoelastic behaviour is isolated. Therefore, the tests were performed in a climate-controlled room with constant temperature of 18.8 °C ± 1.1 °C and a relative humidity in the air of 58 % ± 8 % as seen Figure 4. The specimens were conditioned in this room for one week.

Table 1: *Load level for each specimen.*

Name	Measured load (kN)	Stress level (%)
A	1.14	27
B	1.63	39
C	1.68	40
D	1.39	33
E	2.19	52

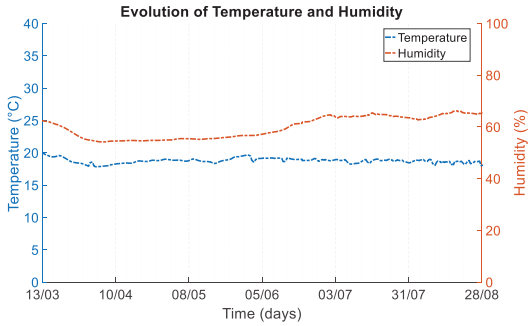


Figure 4: *Temperature and Humidity in the testing room*

Since the moisture of the room was subject to some small changes the specimens were wrapped with duct tape (TESA) to prevent humidity exchanges. Two control beams (beam F and G) were fabricated with the protocol described in Section 2.2 and conditioned in the same conditions than the five specimens. The beam F was wrapped in the same adhesive tape while the beam G was let as is. Both were weighed several times during the experiment. The changes in moisture content were below 0.1 % for beam F and equal to 3.2 % for the beam G. This confirms that wrapping prevents changes of moisture content during the experiment. Possible stress induced by moisture content changes was therefore neglected.

The test started the 13th of March 2020 and is still running at the date of the publication of this paper. Thus 170 days of experiment will be presented here.

2.5 DATA PROCESSING

Data is recorded with a period of 0.1 s through a LabVIEW program. It is averaged over 1 s batches during the loading and over 100 s after. Averaging allows to be more accurate than the precision of the sensors. Moreover, the number of averaged data increases during the

experiment since the creep rate is expected to decrease in time. This allows to have a better precision of the creep displacements.

3. RESULTS

3.1 SHORT TERM

Results are plotted for beam B but are similar for all the specimens.

In Figure 5 the force P is plotted as function of the symmetric part of the rotations for the first two minutes of the experiment. A linear regression on the linear part of this curve gives an estimate of the Young modulus of the steel skins using Equation (3) and (1). Moreover, the asymmetries of the load applications are removed. The results found are presented in Table 4. The error between the estimated value and the reference of 210 GPa is 3% which is very low and confirms that measurements are consistent.

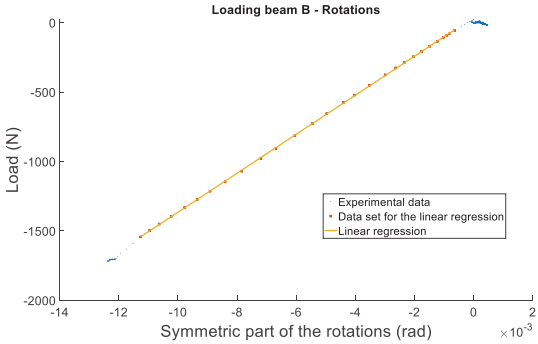


Figure 5: *Applied force as a function of the rotation at support* $\Delta\varphi$

The same method was used to determine the short term rolling-shear modulus. Figure 6 shows the load P plotted as a function of the deflection f_A. Again the linear part of the curve is isolated and with Equation (2) and (4) the modulus $G^0_{r,mean}$ is calculated. Table 2 summarizes the identified moduli with their coefficient of variation.

Table 2: *Instantaneous values*

Name	$G^0_{r,mean}$ (MPa)	E_a (GPa)
A	89.3	205
B	105	212
C	91.3	204
D	103	206
E	100	204
Mean	97.7	206
CoV[1] (%)	7.2	1.74

[1] Coefficient of Variation

The cross-layer shear modulus $G^0_{r,mean} = 97.7$ MPa with a coefficient of variation of 7.2% is consistent with the literature results given in Table 3. A rather high value is consistent with the sawing pattern presented in Figure 2. The coefficient of variation found is very low compared to the literature and comparable to the one already found by Perret [4]. Indeed, the four-points bending test averages the rolling-shear stiffness on several boards.

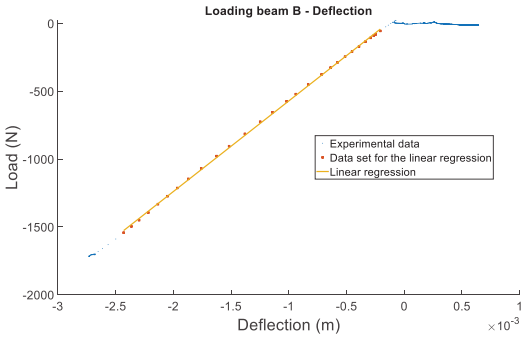


Figure 6: *Applied force as a function of the mid-span deflection* f_A

Table 3: *Short term rolling shear modulus from other experiments*

Reference	MC[1] (%)	$G^0_{r,mean}$ (MPa)	CoV[2] (%)
Krabbe [6]	12	36	25
Hörig [20]	10	37	18
Neuhaus [21]	12	42	20
Aicher [5]	12	50	20
Keunecke [22]	12	53	
Franzoni [23]		110	27
Perret [4]	10-13	124	6.7
Aicher [24]	12	370	8

[1] Moisture Content

[2] Coefficient of Variation

3.2 LONG TERM

The measured relative creep of the specimens during this experiment are plotted in Figure 7 for the rolling-shear modulus $G^{\infty}_{r,mean}$. It can be observed that those curves are linear in a log-log scale at long time, therefore the creep can be modelled with a power law:

$$\frac{J(t)}{J_0} - 1 = mt^n \tag{5}$$

where n, m and J_0 are experimental parameters and t the time in seconds. They are independent from the load as long as it is in the linear viscoelastic domain.

Indeed, wood creep has been modelled with empirical and mechanical models. Mechanical models come from the

thermodynamics [25]. They are systems composed of Kelvin and Maxwell elements. Those models are useful to differentiate the several creep components: elastic, viscous and viscoelastic. They are mostly used to model creep occurring with climate changes [26]–[28]. Empirical models are power or logarithmic functions and they fit and predict well those phenomena. Youngs [29] was the first to model wood creep from a 3-days experiment as a power law similar to the equation (5). Clouser [30] and Gressel [31] used this same equation to fit their 10-year creep tests. It has been widely used since then to fit and predict creep wood behaviour [16], [18], [32]–[35].

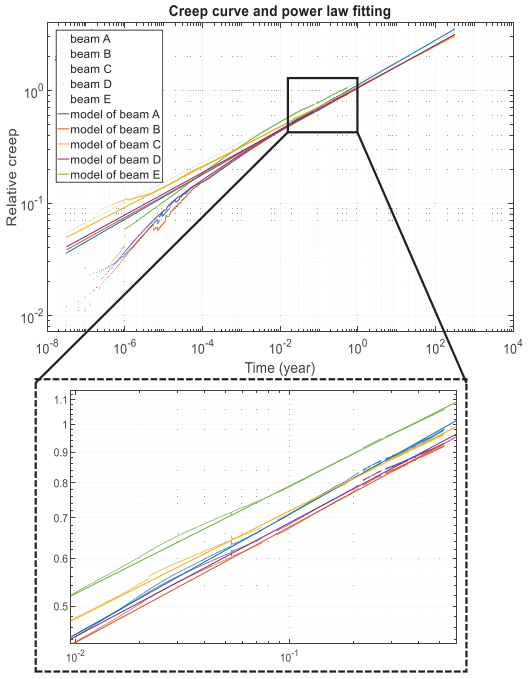


Figure 7: *Rolling-shear relative creep curves and power law fittings.*

In international standards the design of buildings has to be estimated at 50-years. Therefore, a prediction model is required to extrapolate a value of the deflection of wood at such time period. In the Eurocode, this is taken into account by means of the coefficient k_{def} which corresponds to the relative creep at 50-years. Considering exclusively rolling shear deformations, we define k_{def}^{G} as:

$$G_{r,mean}^{\infty} = \frac{G^{0}_{\ r,mean}}{1+k_{def}^{G}} \qquad (6)$$

with $G_{r,mean}^{0}$ the short-term rolling shear modulus and $G_{r,mean}^{\infty}$ the secant rolling-shear modulus in 50 years.

A linear regression was done on the logarithmic values. The k_{def}^{G} values found are summarized in Table 7 with a mean value of 2.3 and a coefficient of variation equal to 7.5% which correspond approximately to the coefficient of variation of the instantaneous modulus. The stress level does not seems to have a significant influence on k_{def}^{G} which comforts the assumption of linear visco-elasticity.

Table 7: *Values of* k_{def}^{G}

	k_{def}^{G}
A	2.46
B	2.24
C	2.18
D	2.23
E	2.40
Mean	2.30
CoV[1] (%)	7.5

[1] Coefficient of Variation

The fitting of creep curves in Figure 7 was achieved with t_0 = 1 s, corresponding to the moment when the whole load was applied to the specimen. In the literature t_0 is taken as 1 s [13], [14], [16], or as 1 min [36]. Figure 8 shows that the choice of t_0 does not impact the value of k_{def}^{G} unless t_0 is larger than several hours.

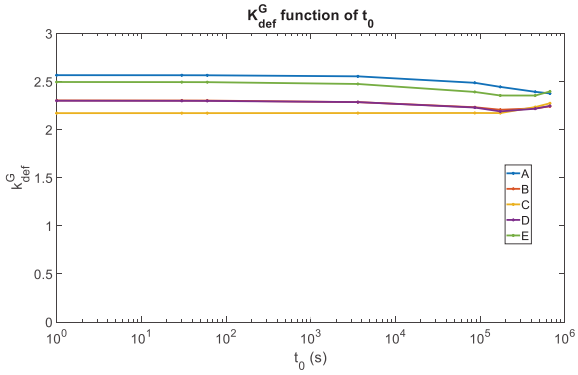


Figure 8: k_{def}^{G} *estimate as function of* t_0.

The values found for the coefficient of Equation (5) are shown in Table 8.

Table 8: *Fitting coefficients values*

Name	J_0	n	m
A	89.3	0.199	0.0360
B	105	0.191	0.0384
C	91.3	0.178	0.0495
D	103	0.188	0.0409
E	100	0.178	0.547

They fall into the spectrum of coefficients found in the literature and summarized in [37].

4. CONCLUSIONS

The value found in the current version of the Eurocode of the creep coefficient k_{def} is 0.6. This value is the same for all orthotropic elastic moduli [9]. The value of the rolling shear coefficient k_{def}^{G} identified in the present experiment is 2.3.

This rather large value is not inconsistent and was expected considering previous attempts to estimate k_{def} for CLT panels [7], [8]. Indeed, the deflection of a CLT panel is the superposition of the bending and the shear deflection. The shear contribution in the global creep depends on the slenderness of the panel and varies from 30% of the total deflection for thick panels to few percent for slender panels. Hence, a distinction between the different deformation types might be necessary to have a better estimation of the long term deflection in CLT panels. Indeed, the present results clearly indicates that rolling shear creeps faster than longitudinal traction.

More experimental campaigns need to be performed to obtain statistically significant results. If the present value is confirmed it could have consequences for the design of CLT and other timber products. For instance, this may lead to more accurate design guidelines either for serviceability limit state (SLS) or long-term buckling strength of CLT walls, which completes recent recommendations for more accurate modelling [23], [38], [39].

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