Comparison between wood hygromechanical description and deformation modification factors of Eurocode 5

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COMPARISON BETWEEN WOOD HYGROMECHANICAL DESCRIPTION AND DEFORMATION MODIFICATION FACTORS OF EUROCODE 5

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ABSTRACT: Engineers need confidence in standards to achieve timber structures. Structural design is performed to ensure safety issues and answer qualitative constructions regarding to an economic competitive objective. In order to improve and provide well matched normative rules and wood material behaviour we performed laboratory creep experiments to quantify and describe the kinetics of wood material facing hygro-mechanical history. Furthermore it allows a direct comparison with deformation modification factors of Eurocode 5 (EN1995) regarding an increase of structural longevity of timber structures.

KEYWORDS: timber, deflection, viscoelasticity, mechanosorption, wood-water interactions, rheology

1 INTRODUCTION

Wood is a marvellous material for many aspects. It allows us to build environmentally friendly civil engineering structures with a widespread renewable natural resource. Moreover it combines good mechanical performance to face structural actions through a high strength-to-weight ratio, a high adaptability from raw material transformations combined to a large variety of wood-based products, and a moderate price.

The structural longevity of timber structures have been proved by our civil heritage where a large part of it pass through centuries without severe structural pathology or intensive renovation procedures. But even if it is well-known that timber structure longevity is directly dependent on design choices and execution quality of the construction the long-term mechanical performance of constitutive materials is of decisive importance [1]. For instance to prevent excessive deflections of structural components within criterions in order to limit troubles of structural integrity and respect human perceptions of the structure, e.g. ceilings, floors, connections etc.

The long-term performance of wood impact all massive wood-based products were wood microstructure is preserve such as obviously timber beams but also glulam beams or cross-laminated panels. Expanding the use of wood and wood-based products in modern structures requires a good knowledge of material performance facing climatic conditions.

When subjected to external loading wood exhibit time-dependent behaviours, called in material science *viscoelasticity* at low mechanical loading [2-4].

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This behavior is induced by the multi-scale organization of wood components (cellulose, hemicelluloses, and lignin) and their polymeric constitution [5].

In addition wood-water interactions have a major impact on the viscoelastic response of wood. Wood subjected to high moisture content level presents a higher viscoelastic response . Wood members continuously exchange water with the surrounding air environment, such an interaction induces variations of moisture content (m.c.) influenced by temperature and providing internal diffusion within wood tissue.

The combination of time-dependent behaviour and wood-water interactions provokes unexpected mechanical response called *mechanosorption*. To understand the origins and describe the kinetics of this phenomenon is of major importance in timber design [6-8].

Within the EU countries common rules for structural design codes (Eurocodes EN1995) [9] have to be verified based on two major criteria. First the Ultimate Limit States (ULS) aims at ensuring the safety of people and structural integrity. Second, the Serviceability Limit States (SLS) aim at ensuring comfort and limited deformability of the timber elements. Therefore an efficient standard require a good match between the description of the mechanics and the criteria to be verified. The reliability of the serviceability criteria of Eurocode 5 have already be pointed out for its non consistency when facing given actions [10]

In this paper, we present isolated experiment on selected wood samples through combined mechanical and hygrothermal history to quantify and describe the kinetic of wood hygro-mechanical couplings [11-12] within extreme moisture content variations. The basis of measurement analysis are reminded to place the results in the field of mechanics of materials. The prediction toward a reference lifetime is discussed and compared to standard values.

2 MATERIAL AND METHODS

2.1 WOOD SPECIMENS

Clear wood specimens of Norway spruce have been used in this study in small dimensions (100 mm longitudinal, 10 mm in radial and 2 mm tangential) to minimize moisture diffusion within specimen thickness. Specimen air-dry density was 0.482 kg/m^3 (at 24°C, 58%RH). The mean microfibril angle were measured by wide-angle X-ray scattering before creep test as 18° and the fibre alignement was less than 1°.

2.2 CREEP EQUIPMENT

Four point bending devices with 40 mm inner span and 80 mm outer span have been designed. A serial arrangement of specimen into a single device have been made to increase repeatability within an identical environment regulated by climatic chamber device (temperature +/- 0.5°C, relative humidity +/- 2%) The experimental device is presented in figure 1.

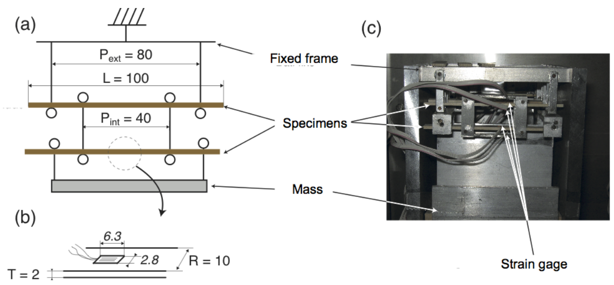

***Figure 1**: Illustration of serial arrangement of specimens (a), gage position and dimensions on each specimen (b) and experimental realization picture (c).*

Creep tests on 4 specimens have been performed. Strain gages were placed on the upper and lower side of each specimens to measure tensile strain level ε^+ and compressive strain level ε^-.
Two matched specimens were kept unloaded for moisture content estimations based on their hygroscopic deformations. The moisture content estimation have been verified by three additionnal gage-less specimens, weighted occasionnally and over-dried at experiment end. Consistency between occasional and calculated measurements are presented in figure 2.

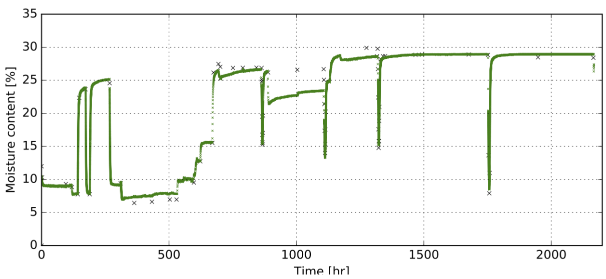

***Figure 2**: Consistency of moisture content estimation (—) and occasionnal measurements (x).*

2.3 MEASUREMENT ANALYSIS

The strain field is calculated with linear interpolation through specimen thickness according to Bernouilli's principle with the expression (1) below:

$$\varepsilon(y,t)=\underline{\varepsilon}(t)+\Delta\varepsilon(t).y \quad (1)$$

The mean strain $\underline{\varepsilon} = (\varepsilon^+ + \varepsilon^-)/2$ reveals stress-independent phenomenas such as hygroscopic expansions. The differential stress $\Delta\varepsilon = (\varepsilon^+ - \varepsilon^-)/2$ is proportional to specimen curvature.
The effect of transverse dimensions changes according to moisture content variations were considered in stress calculations by measuring the moisture expansion coefficient $\alpha_T=0.305\%/\%$ with the expression (2) below:

$$\sigma_i(t)=\frac{\sigma_i^0(t)}{1+\alpha_T(w(t)-w(t_0))} \quad (2)$$

The instantaneous compliance at loading have been calculated by the ratio of curvature strain by stress level using following relation (3):

$$J_i(t)=\frac{\Delta\varepsilon_i(t)-\Delta\varepsilon_i(t_0)}{\sigma_i(t)} \quad (3)$$

The compliance ratio between time evolution of the compliance and the instantaneous compliance is called *relative compliance* and have been calculated with the expression (4) below averaging the *n=4* specimens of the set:

$$\bar{J}(t)=\frac{1}{n}\sum_{1}^{n}\frac{J_i(t)}{J_i(t_0)} \quad (4)$$

2.4 HYGROMECHANICAL HISTORY

The experiment was performed at a constant temperature of 25°C. The total duration of the experiment was 92 days. A preliminary acclimation phase of around 30 days without loading was applied to clean out specimen residual stress history by cycling RH in the range of further experiment climate. After this phase, specimens were loaded in wet state (approx. 26% m.c.). After a period of creep of approx. 1 week at this high moisture level climate was punctuated by short (less than a 12 hrs) drying and moistening cycles.
The force was applied manually within 30 sec. with lead masses designed to produce between the inner span a maximum stress σ_0 of approx. 8MPa in air-dry conditions. The instant of loading have been carefully established to increase accuracy of logarithmic analysis of compliance evolution by quantifying half-loading strain level. An example of loading determination is presented in figure 3.

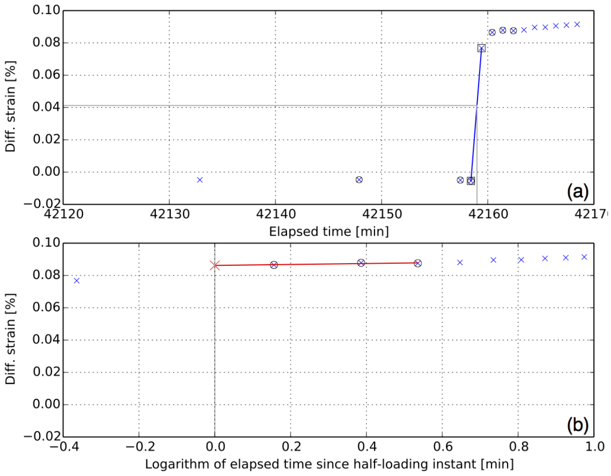

***Figure 3**: Example of determination of instant of loading of the specimen (a) and determination of differential strain level after loading (b).*

Bending tests up to failure performed within the 4-points bending device after the experiment allowed to evaluate of the stress level as 9% of the failing load weel bellow the observed elastic limit of 60%, although the non-linearity of mechanosorptive behaviour in bending was found to start at about 10-20% of the ultimate stress [13].

3 RESULTS

3.1 EXPERIMENTAL MEASUREMENTS

The experimental measurements of the relative humidity [%], the force applied [N] and curvature strain [%] are presented in figure 4.

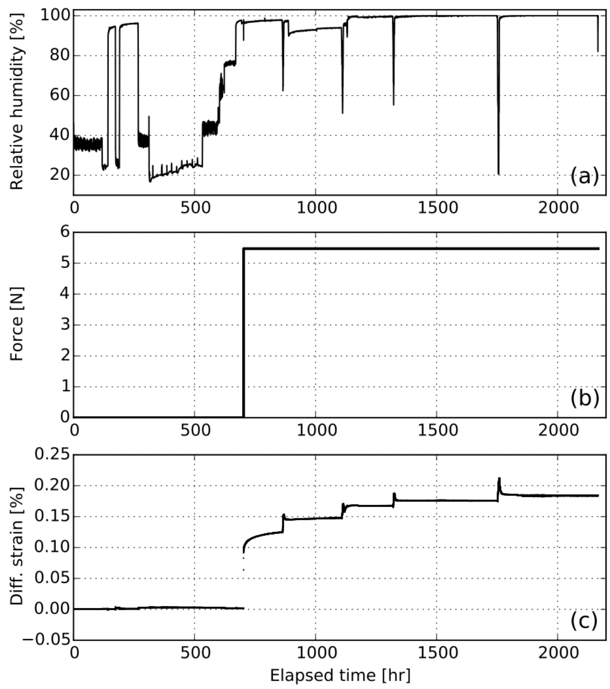

***Figure 4**: Overview of the experimental data: (a) relative humidity of the environment [%], (b) force level applied [N], (c) differential strain [%]vs elapsed time [hr].*

3.2 EXPERIMENTAL RESULTS

The experimental results are presented in figure 5 with tje evolution of the moisture content [%], the corrected stress [MPa] and the compliance level [GPa^{-1}] during the experiment.

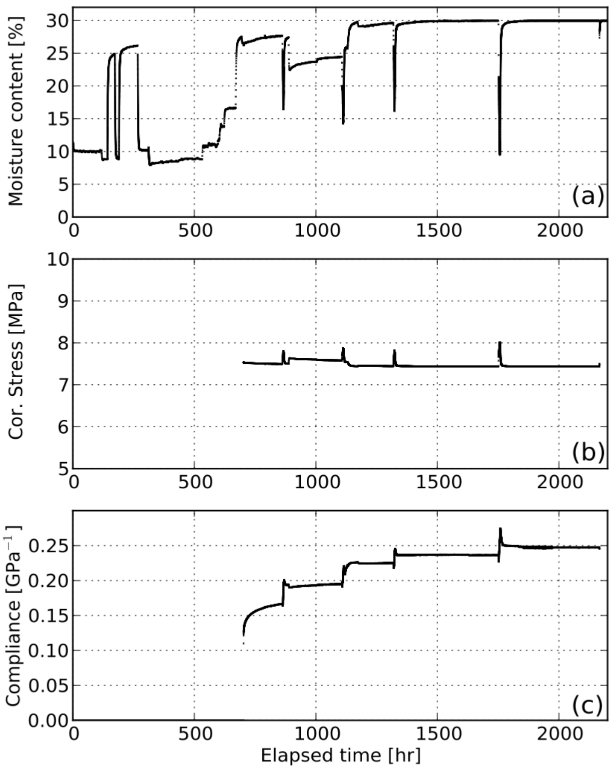

***Figure 5**: Overview of the analysed results: (a) moisture content [%], (b) corrected stress [MPa], (c) compliance level [GPa^{-1}] vs elapsed time [hr].*

4. DISCUSSION

4.1 LONG-TERM VISCOELASTICITY

Differents studies have tried out to describe wood viscoelasticticity kinetic and propose models for the long-term longitudinal creep of wood. Based on our measurements of the relative compliance during approx. 1 week of creep at constant moisture content (less than 1.5% increase), the evolution of the relative compliance up to 50 years can be described according to various models.

The experimental results and three models of extrapolation are presented on figure 6.

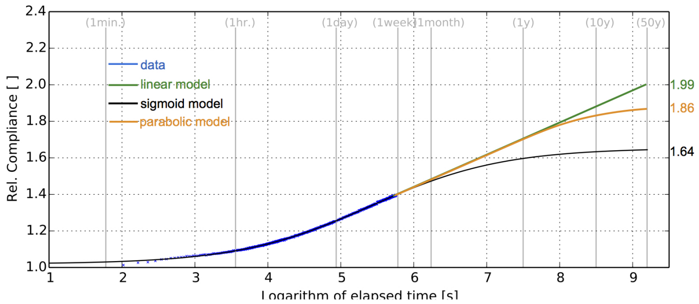

Figure 6*: Evolution of relative compliance during 1 week of creep at constant moisture content of 26% and predictive models toward 50 years.*

Firstly a linear extrapolation of the last day (from log t = 5.0 to log t = 5.75) leads to a relative compliance level of 1.99 at 50 years of loading. This approach is leading to infinite compliance level. This statement is not compatible with the observation of components of civil heritage structures defending the concept of creep limit of wood.

Secondly, wood contains semi-crystalline polymers with a kinetics of deformation typically following a sigmoid model. A symmetric sigmoid function has been fitted on all the data based on the following equation 5 :

$$\bar{J}(\log t)=\bar{J}_0+\frac{\bar{J}_\infty-\bar{J}_0}{1+\exp\left(\frac{\log t_\infty-\log t}{\tau}\right)} \qquad (5)$$

This model provides a compliance level at 50 years of 1.64. Such a symetric function description have the advantage to fit all data history but relies on the hypothesis that short term and long term effects are based on identical potential of kinetics.

Thirdly to improve the sigmoid description the creep kinetic have been approached by generalized Kelvin-Voigt models with a Gaussian distribution of internal compliances with logarithm of time. Such a parabolic model based on Alfrey's description of material rheology relies on the representation of the relative compliance evolution according to logarithm of elapsed time $\bar{J}(\log t)$ against its derivative with a circular form factor [15] following the equation :

$$\bar{J}'\simeq\bar{J};\bar{J}''\simeq(\pi/2).d\bar{J}/d\ln t \qquad (6)$$

The evolution of the relative compliance in this complex plane representation is presented in figure 7.

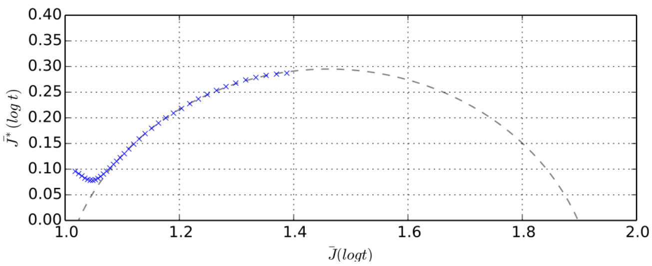

Figure 7*: Complex plane representation (Cole-Cole plot) of the evolution of the relative compliance.*

This approach is leading to a relative compliance level of 1.86 which is an intermediate value within the two previous models shown.

4.2 INFLUENCE OF MOISTURE CHANGES

Cycling from 26% moisture content to air-dry moisture content (~12%) induces mechanosorptive creep. The decrease of moisture content leads to an increase of deformation called *pseudo-creep*. Then re-humidifying up to initial moisture content presents (i) a change of viscoelastic kinetics observed by the decrease of slope and (ii) an increase of compliance level. This observations confirms Hanhijarvi's results [15]. The results are presented in figure 8 and summarized in table 1.

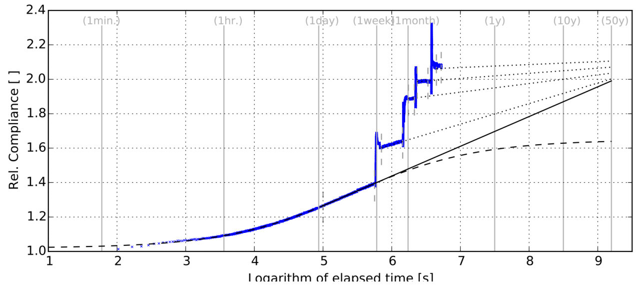

Figure 8*: Evolution of relative compliance of creep at high moisture content of 26% m.c. interspersed by 4 moisture cycles at air-dry m.c. and predictive models toward 50 years (- - - sigmoid model, —linear prediction)*

Table 1: *Description of duration of creep period used for each 50 years linear prediction and the relative compliance value predicted.*

	Duration (hr)	Rel. compliance at 50y
Initial	128	1.966
After 1st cycle	205	2.016
After 2nd cycle	109	2.059
After 3rd cycle	284	2.085
After 4th cycle	217	2.111

Firstly, this change of slope indicates that viscoelastic creep in variying moisture content level depends on mecanosorptive creep accumulation indicating a major interaction between both phenomena A single moisture content cycle is enough to reveal this interaction. The mechanosorptive creep is often described as an acceleration of the viscoelastic response.

Secondly, the increment of mechanosorptive creep seems to be exhausted from cycle to cycle leading to the existence of a mechanosorptive creep limit reached at high moisture content level.

Each creep period of constant moisture content level has been extrapolated linearly from a suitable time range to determine the slope of the relative compliance. The maximum relative compliance level reached during the experiment was 2.33

4.3 COMPARISON WITH TIMBER STANDARD EN1995

The Serviceability Limit States of the Eurocode 5 are based on deformation factor k_{def}. This single factor is used for the determination of various mechanical parameters such as final value of modulus of elasticity, shear modulus or slip modulus.
In the case of the beam deflection of solid timber elements the deformation modification factor k_{def} is directly given using the relative compliance description with the relation :

$$\bar{J} = 1 + k_{def} \qquad (7)$$

In the experiment detailed the test have been performed at high moisture content level corresponding to a service class 3 where the average moisture content is higher of 20% with a value of $k_{def} = 2.0$ therefore a relative compliance level of 3.0.
In our eperiment we observed a maximum value of relative compliance reached of 2.33 far below Eurocode k_{def} value. EN1995 even consider an increase of k_{def} value by 1.0 for elements closed to fibre saturation point subjected to drying out under load which lead to a larger gap between standard value and experimental measurements.

In the case of timber structures with solid timber with larger cross-section, the wood-water transferts are reduced. This observation is leading to a lower expression of mechanosorptive creep of the members and therefore a higher degree of safety between relative compliance of constructive members and design values. This size effect is an important information that should be accounted in the k_{def} calculation either with a specific description or the integration of the depth factor.

However our observations are made only in the case of timber deflection. Therefore it could also be propose different deformations factors according the mechanical parameter to affect in order to improve the adequation of the k_{def} factor.

5. CONCLUSIONS & PERSPECTIVES

Experiments on small wood specimens make possible to describe the kinetics of both wood viscoelastic and mechanosorptive creep of wood with long-term prediction models even it could be noted that some progess into modelling wood rheology would lead to ensure prediction of long-term behaviour. In that sense it could be important to perform experiment at long time scales with different moisture content conditions and/or temperature levels on well-matched specimen set.
Such experiments and the measurement description based on relative compliance allows a direct comparison with structural Eurocode standard. This could be extended to perform similar comparison to the other service class 1 and 2. Such a work could lead to the applicability of a dedicated deformability factor for deflection of timber elements.
However the experiment performed are based on clear wood and attentive selection of specimen. The presence of defects and knots areas in strucural beams could affects significantly our observations.
Moreover this work should be completed with various specimen dimensions to investigate size-effects in the interactions between viscoelasticity and mechanosorptions in relation to water diffusion within the cross-section and also be extended to a larger spectrum of wood species of hardwood and softwood used in structural applications to complete the characterisation.
Those actions on material rheology should be also completed with structural health monitoring techniques on well-characterized elements in order to provide *in-situ* data of strain evolution compared to well-identified actions of dedicated structures or in service timber structure projects.

This presentation will be the opportunity to present different study cases to improve the relationship between wood rheology and structural code standard deformation modification factors.

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