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OVERVIEW OF ORTHOTROPIC VISCOELASTIC MECHANOSORPTIVE MODELS FOR WOOD

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ABSTRACT: Wood is one of the most widely applied engineering materials due to its favourable physical and mechanical characteristics. As an inhomogeneous biomaterial, wood exhibits complicated mechanical properties including anisotropy, elasto-plasticity, viscoelasticity, and hygroscopic characters. To analyse the time- and moisture-dependent behaviour of timber structures, both mechanical loading and moisture evolution has to be taken into account. This study analyzes the capability and limitations of different rheological models. A 3D-orthotropic viscoelastic, mechano-sorptive model for wood is presented here, which covers the timber behavior under varying moisture condition during loading and unloading phases.

1 INTRODUCTION

Wood is an anisotropic elasto-plastic viscoelastic hygroscopic material. During the service life of a timber structure, the material is subjected to an interaction of mechanical loads and environmental influences such as humidity variations. Since the 1960s, experimental works [1] proved a strong influence of moisture variation on viscoelasticity, which is known as mechano-sorption or mechano-sorptive creep. This phenomenon is of physical-chemical origin (chemical reaction kinetics) and partially correlates with the behaviour of molecular bonds; however, the real mechanism has not yet been well understood [2].

Multiple theories (such as hydrogen-bonding [3], deformation kinetics [4], lenticular trellis model [5], and slip-plane [6]) were proposed to explain the micro-mechanism of the time- and moisture-behaviour in wood. Subsequently, analytical models based on these theories were developed [7–12]. These models offer good quantitative illustrations of the theories, yet most of them turned out to be very laborious and facing the difficulty to be expanded to 3D, due to the complexity of mathematical equations [7] and the great number of parameters [13]. First attempts for developing an empirical model of the time- and moisture-dependent behavior date back to the 70s [14, 15]. Different model constructions [16–22] Computational analysis of quality are capable of describing the viscoelastic and mechano-sorptive behavior under specific loading and environmental conditions. An analysis of the performance of different models is given in this study and the differences and gaps between models are identified. In addition, possible limitations of current models are discussed. Finally, a modified rheological model is proposed, covering a wider range of the mechano-sorption features of wood, and this model is compared with existing ones.

2 PHYSICAL EXPLANATORY THEORIES AND MODELS

It is observed that the mechano-sorptive creep of wood is in general greater than the pure viscoelastic creep [23], so that the repeated moisture cycling can lead to structural damage even at a moderate load level. However, this is primarily true for small scale specimens, as in large scale specimens the effect is much less pronounced because of the moisture diffusion. From a physical viewpoint, the underlying mechanisms of mechano-sorptive creep remain somewhat unclear. Several theories at either molecular or structural level have been developed during the last century and an overview is presented in [7]. In the following, the basic concepts for the model development are discussed at both molecular as well as inter-fiber levels.

Hydrogen-bonding: Gibson [3] suggested that wood can be considered as a hydrogen-bonded structure, such that the temporary breaking of hydrogen bond between cellulose chains will give rise to a temporary weakening of wood and hence is responsible for creep. However, the theory of hydrogen bonding does not explain the reason for which drying wood creeps more during a moisture change than moist wood. New evidence of additional breaking of hydrogen-bonds under mechano-sorption condition is provided by Stevanic [24] utilising FTIR spectroscopy. Navi et al. [8] developed a molecular model and simulated the

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effect of continuous breaking and reforming of hydrogen bonds during moisture variation.

Deformation Kinetics: This is basically the origin of hydrogen-bonding theory. In this theory, the plastic flow is considered as a special form of chemical reaction (such as hydrogen-bonding). The applied mechanical stress changes the potential energy of the molecules, hence the chance of reaching the activated state for surpassing the energy barrier [4]. Van der Put [25] gave a multi-energy barrier approach and an explanation of mechano-sorptive effect, such that the changing of moisture content causes an extremely rapid reaction of water with the hydrogen bonds and results in low activation energy and volume. The modelling of time-dependent behaviour including non-linear viscoelasticity, duration of load and damage was discussed [26–28]. Based on the generalized Maxwell model consisting of linear spring and non-linear dashpot [26], Hanhijarvi [7] developed a new model that couples the creep deformation process and moisture swelling/shrinkage process, where the mechano-sorptive effect is an outcome of the non-linearity of the two processes.

Lenticular trellis model: According to [5], in between the wood microfibrils, there is a viscous gel, whose yielding is responsible for the normal creep. Due to different hygro-expansion coefficients of the gel and microfibrils, they can be detached from each other during moisture change, resulting in higher loading on the microfibrils, hence an increased deformation. Bardage et al. [29] used samples prepared by rapid-freezing-deep-etching techniques for transmission electron microscopy observations, showing the undulating cellulose aggregate structure, and confirming the assumption of the lenticular framework of the cell wall. Schänzlin [10] modeled a simplified system consisting of microfibrils and interlayered gel. Yet, instead of considering the gap between gel and microfibrils, the time-moisture-dependent creep is interpreted as the reaction of microfibrils on moisture-induced eigen-stresses due to the hydro-expansion of the gel.

Slip Plane: Under compression, local buckling of the microfibrils may occur, forming slip planes [6]. Since the moisture content influences the stiffness of wood, the resistance against the local buckling decreases with increasing moisture content, resulting in a larger amount of slip planes and hence exhibiting accelerated creep in the macroscale. However, a shortcoming of this theory is that it is only applicable to compression cases, but fails to explain the mechano-sorption observed also under tension loading.

Transient Stress: Armstrong and Christensen [1] suggested that transient stresses are introduced in the material during changes in moisture content, adding to the stresses caused by the external load, thereby giving an increased creep. According to [30], the differential shrinkage between different cell wall layers resulted in transient stress, causing slippage of cell wall layers, and hence the mechano-sorptive deformation. A model [11] composed of two Burgers models together with an additional hydro-expansion component is developed and verified [31]. Another micro-mechanical model based on the assumption of inhomogeneous hydro-expansion and non-linear creep is developed in [12] for paper and a good agreement with the experimental creep curves is obtained.

As a summary, the first three theories explain the mechano-sorptive creep at the molecular level while the latter three are at the inter-fiber level. To find out which level is responsible for mechano-sorption, a single fiber was isolated and tested under mechanical loading and simultaneous moisture cycles: contradictory to some earlier findings [32], recent studies claimed that mechano-sorption is also present in individual wood fiber [33–35]. The contradictory outcomes may have resulted from humidity changing rate [34] or methods for fiber isolation [35]. With these new pieces of evidence, it is clear that the theories based solely at the inter-fiber level, such as the latter three, are not sufficient to explain the mechanism of mechano-sorptive behaviour.

3 EMPIRICAL MODELS

Models of *Section 2* have already been verified based on their background theories [7, 8, 12, 31]. However, generally these models represent some limitations such as [7, 36]

- limitations in the detailed input parameters with physical meanings for these models,
- missing of experimental validation,
- difficulties of implementing such theories for three-dimensional and orthotropic cases.

Therefore, empirical models consisting typically of mechanical elements like springs and dashpots exhibit higher flexibility and practical value. In this section, some representative models, as shown in Figure 1, are analysed in detail with a focus on how they capture empirical features of mechano-sorptive behaviour.

3.1 1D EMPIRICAL MODELS

Attempts for constructing empirical rheological models including mechano-sorptive behaviour can be dated back to the 1970s [14, 15]. Since the moisture-dependent mechano-sorption exhibits analogous features as the time-dependent normal creep, a “spring and dashpot” was first proposed (Figure 1a), in which the accumulated absolute moisture change $|\Delta u|$ is used as a substitute for time, as shown in Equation 1:

$$\Delta\varepsilon^{ms} = a\sigma|\Delta u| \qquad (1)$$

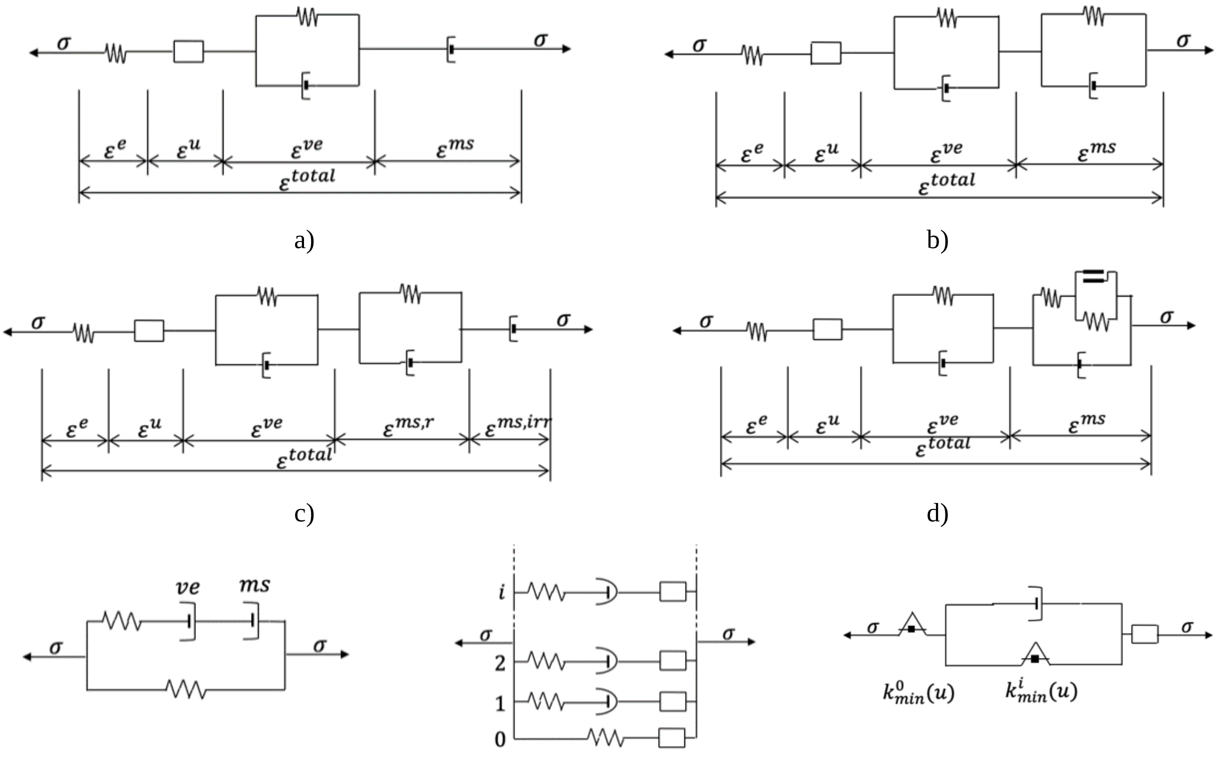
where ε^{ms}, a, and σ represent mechano-sorptive strain, compliance of mechano-sorptive creep, and stress, respectively.

On this basis, the simple "dashpot" can be expanded and modified in order to cover more features and to be able to represent the mechanical behavior of wood more accurately. Grossman [37] and Mårtensson [23] gave a summary of the observed phenomena of mechano-sorption in wood. Some observations, such as the compliance value of mechano-sorptive creep and the extent of recovery, varied considerably between different species [14], loading and environmental conditions, as well as the measuring methods. Therefore, the empirical models may only partially describe the features of mechano-sorption. A list of some essential features, which are to be considered for modelling the rheological behaviour, is presented here and the corresponding model constructions are reviewed. These features are justified mainly for 1D longitudinal cases at moderate stress levels and are important for accurate prediction of wood behavior under loading and continuous humidity variations.

Feature 1: In the stressed samples located in environments with humidity variations, both desorption and adsorption lead to a change of creep rate in comparison to a constant humidity environment. Desorption leads to accelerated creep in both tension and compression cases, while adsorption showed to increase the creep compliance in some experiments [14] and decrease in others [38]. This difference may be related to the difference in wood species [14].

Feature 2: By separating the fluctuating and accumulative part of deformation under cycling humidity, Hunt and Shelton [38] concluded that hydro-expansion is influenced by mechanical stress or strain.

Feature 3: At a low stress level, when moisture cycling takes place between two fixed limit values, the 'final' deflection goes towards a limit value, named as a "creep limit" by Hunt [39]. However, at higher stress levels, the mechanical response of wood is different. As an example, it is deduced that under higher compression the strain would keep increasing and lead to failure [23].



a) b) c) d) e) f) g)

Figure 1: *Schematic representation of different rheological models where the mechano-sorption is modelled by: a) dashpot; b) Kelvin-type elements; c) combined Kelvin-type elements and dashpot; d) combined Kelvin-type and plastic elements; e) co-excitation; f) Maxwell-type elements; g) combined Kelvin-type elements and hydro-lock spring*

Feature 4: It is certain that most and possibly all of the mechano-sorptive strains are recoverable when the specimens are subjected to continuing moisture variations after mechanical unloading. However, it is not so clear that under what specific conditions and to what extent would this strain be recovered. Armstrong and Christen [1] observed that the recovery is larger during adsorption than during desorption. Leicester [15] proved that there exists however an irrecoverable part for drying after unloading. Ranta-Maunus [14] and Hanhijärvi and Hunt [40] observed a greater recovery when the moisture content exceeds the one at the unloading instant.

Feature 5: When the moisture content exceeds the historical limit, the mechano-sorptive strain caused by the moisture change is more pronounced than in between the limits. Experimental results suggested that the first moisture change generates a larger strain change than the subsequent moisture changes [16]. In addition, some models adopted the historical limit during the complete loading history [23, 17], while some suggested to use the limit for each loading phase [2, 14].

Feature 6: Mechano-sorptive effects are observed in tension, compression, shear, and bending mode, yet the magnitudes vary. According to the experiments of [16], in the longitudinal direction, it is shown that mechano-sorptive effects in compression are bigger than in tension, especially under constant creep. The mechano-sorptive effects which give only a minor contribution to uniaxial loading can cause significant deflection in bending mode. However, as in the direction perpendicular to the grain, the difference between compression and tension exhibited to be minor [41, 42].

Typically, the total strain ε^{total} is the sum of different strain components (as shown in Figure 1a - 1d):

$$\varepsilon^{total} = \varepsilon^{e} + \varepsilon^{u} + \varepsilon^{ve} + \varepsilon^{ms} \qquad (2)$$

where ε^{e}, ε^{u}, ε^{ve}, and ε^{ms} representing the elastic, hydro-expansion, viscoelastic and mechano-sorptive strain, respectively.

Differences between desorption and adsorption in Feature 1 can be covered by using different a values, as presented in Equation 3 [14]:

$$a = \begin{cases} a^{+}, & if\ \ \Delta u > 0 \\ a^{-}, & if\ \ \Delta u < 0 \end{cases} \qquad (3)$$

In order to take into account Feature 2, the following strain-dependent hydro-expansion function is widely used:

$$\Delta\varepsilon^{u} = (\alpha - b\varepsilon^{mech})\Delta u \qquad (4)$$

where $\varepsilon^{u}, \varepsilon^{mech}, \alpha, b$ represent the hydro-expansion, mechanical strain, hydro-expansion coefficient, and influence coefficient of mechanical strain on hydro-expansion. Hence, the hydro-expansion coefficient $(\alpha - b\varepsilon^{mech})$ is larger with compressive strain and smaller with tension strain. Such application can explain partially the difference of apparent recovery during subsequent sorptions [18].

Mårtensson [23], covered the Features 3 and 5 in a model by using a strain-dependent mechano-sorptive parameter as:

$$a = \begin{cases} a_0 & if\ u < u_{min}\ or\ u > u_{max} \\ a_0 \exp\left(-\dfrac{\varepsilon_{mst}}{\varepsilon_{ms\bowtie} - \varepsilon_{mst}}\right) & if\ u_{min} \leq u \leq u_{\max} \end{cases} \qquad (5)$$

where ε_{mst} and $\varepsilon_{ms\bowtie}$ are the total and limit of mechano-sorption, $u_{min}\ and\ u_{max}$ are the moisture limits that were attained previously. However, an inherent feature of dashpot is that the strain remains irrecoverable. Hence, unless using an additional term that is specialized for the unloading condition as in [43], Feature 6, the recovery, cannot be described.

At the same time, another more concise method to take into account Feature 3 and 6, which uses a Kelvin element instead of the simple dashpot (Figure 1b), is proposed in Salin [19]. Compared to Equation 1, an additional constant m is introduced:

$$\Delta\varepsilon^{ms} = (m + a\sigma)\ |\Delta u| \qquad (6)$$

Later, in [18] it is pointed out that the Kelvin model which is calibrated by short-term experiments does not adequately describe the mechano-sorptive behavior when extrapolated for a long-term experiment, especially the irrecoverable parts as described in Feature 4. As a solution, Toratti [18] developed a more advanced model consisting of an additive dashpot for irrecoverable strain term for compression case besides the Kelvin components, as shown in Figure 1c. Alternatively, Mackenzie-Helnwein and Hanhijärvi [20] introduced a plastic element into the Kelvin element and calibrated it into the 2D orthotropic model, as shown in Figure 1d.

In addition to the above Kelvin type models, Hanhijärvi [7] also discussed the possibility of using co-excitation models (Figure 1e) and Maxwell type models (Figure 1f). The co-excitation model is developed based on the observations that indicate the interaction of the creep rates between viscoelastic creep and mechano-sorptive creep. Maxwell-type models that are based on the deformation kinetic theory are also developed by van der Put [26] and Hanhijärvi [7].

Based on the observation that wood has a memory effect during mechano-sorption, a hydro-lock model was proposed [44, 9] consisting of a "hydro-lock spring" (Figure 1g), which is able to lock the strain during drying phases under load conditions and whose stiffness is dependent solely on moisture content instead of moisture variation. Thus, “hydro-lock spring” well captures ++ effect [14], i.e. the excessive strain increase when moisture content surpasses the highest historical value under load. Further researches developed the “hydro-lock spring” into Kelvin type elements and proved a good ability of such models to cover lots of mechano-sorptive features including Feature 2 – 5 [8, 45].

Most of the mechanical analogous models are only valid over the time span for which the parameters are calculated. Due to the different assumptions and model constructions, it is not proven whether they are reliable when extrapolated to assess the serviceability and ultimate limit state of timber structures. Hence, in [10] four models from previous literature [18, 7, 23, 46] have been evaluated for a duration of a load of 50 years. As a result, [10] claims that Toratti’s model [18] with some modification fits best with the deformation data, which was measured on several buildings in South-West Germany.

3.2 3D MODEL

In the last decades, attempts were made to develop and apply the rheological models for 3D orthotropic wood material behaviour. Ormarsson [36] developed two 3D models where the mechano-sorptive behavior is represented by a dashpot (based on Ranta-Manus [14]) or a Kelvin element (based on Salin [19]), respectively. Vidal-Sallé and Chassagne [13] developed a generalized 3D Maxwell model, where two non-linear elements were adopted. It is suggested that the viscoelastic-viscoplastic constitutive law can be possibly introduced in order to further take the irrecoverable strain into account. Based on Toratti [18], Fortino et al. [17] proposed a 3D rheological model where the mechano-sorption is divided into recoverable and irrecoverable parts, represented by a three-Kelvin-element part and a dashpot part, respectively. Moreover, Qiu [21] introduced the orthotropic failure into the rheological model of wood by using 9 damage factors [47]. Hassani et al. [22] extended Fortino’s model to take into account the plastic behavior as well. There, all material input parameters have been defined as a function of the moisture level.

4 A NEW MODIFIED 3D MODEL

Fortino et al. [17] proposed a 3D rheological model based on the one-dimensional model developed in [42]. The model shows a good agreement with the long-term experimental results, yet it could not correctly capture the recovery that can be observed in the short-term experiments [41]. Hence, a new modified 3D model (referred to as Model 2) based on the model in [17] (referred to as Model 1) is developed here. In the experiment, clear heartwood samples of Scots pine were subjected to tension load in the tangential direction and relative humidity variations. The Abaqus model can be seen in Figure 2 in a reduced form.

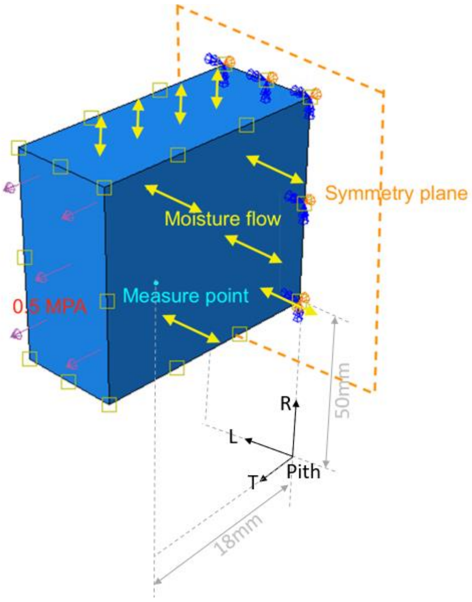


Figure 2: Abaqus model for the tests in Toratti and Svensson [41, 42]

A schematic representation of Model 1 can be seen in Figure 1c. The model consists of elements representing elastic, hydro-expansion, viscoelastic, and mechano-sorptive behaviors. The elastic, hydro-expansion, and viscoelastic strains are calculated as:

$$\Delta\varepsilon^{e} = \Delta C^{e^{-1}}:\sigma + C^{e^{-1}}:\Delta\sigma \tag{7}$$

$$\Delta\varepsilon^{u} = \alpha\Delta u \tag{8}$$

$$\Delta\varepsilon_i^{ve} + \frac{1}{\tau_i}\varepsilon_i^{ve} = \frac{1}{\tau_i}C_i^{ve^{-1}}:\sigma \tag{9}$$

where $C^{e^{-1}}$ and $C_i^{ve^{-1}}$ are the elastic and viscoelastic compliance tensor, respectively, τ_i is the retardation time of i^th^ Kelvin element.

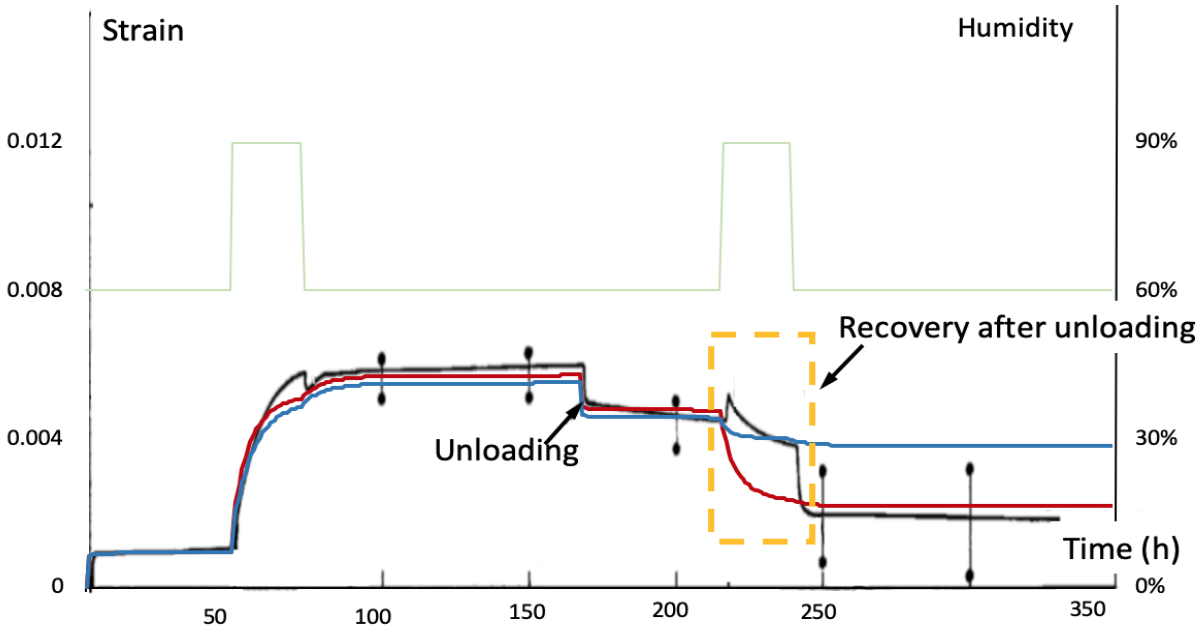
The mechano-sorption is composed of a fully recoverable part, represented by three Kelvin elements, and an irrecoverable part, representing by a dashpot:

$$\begin{cases} \Delta\varepsilon_j^{ms,r} = \dfrac{C_j^{ms,r^{-1}} : \sigma - \varepsilon_i^{ms,r}}{\tau_j} |\Delta u| \\ \Delta\varepsilon^{ms,irr} = C^{ms,irr^{-1}} : \sigma |\Delta U| \end{cases} \tag{10}$$

where $C_j^{ms,r^{-1}}$ and τ_j are the compliance of retardation time of jth Kelvin element (j=1,2,3), $C^{ms,irr^{-1}}$ is the compliance of the irrecoverable dashpot. |Δu| and |ΔU| represent the absolute value of moisture content change and the absolute moisture change when the moisture content transcends the previously attained level at the current mechanical load condition, respectively.

Hence, the recoverable part describes the general mechano-sorption that is observed during both adsorption and desorption, while the irrecoverable part captures the more pronounced strain when moisture content is exceeding the historical load levels.

Figure 3 shows the numerical results of the original model (Model 1) and the modified model (Model 2) in comparison with the short- and long-term experimental results. It can be seen that Model 2 captures the recovery during moisture change after unloading in the short-term experiment and retains a good agreement with the long-term experiment.



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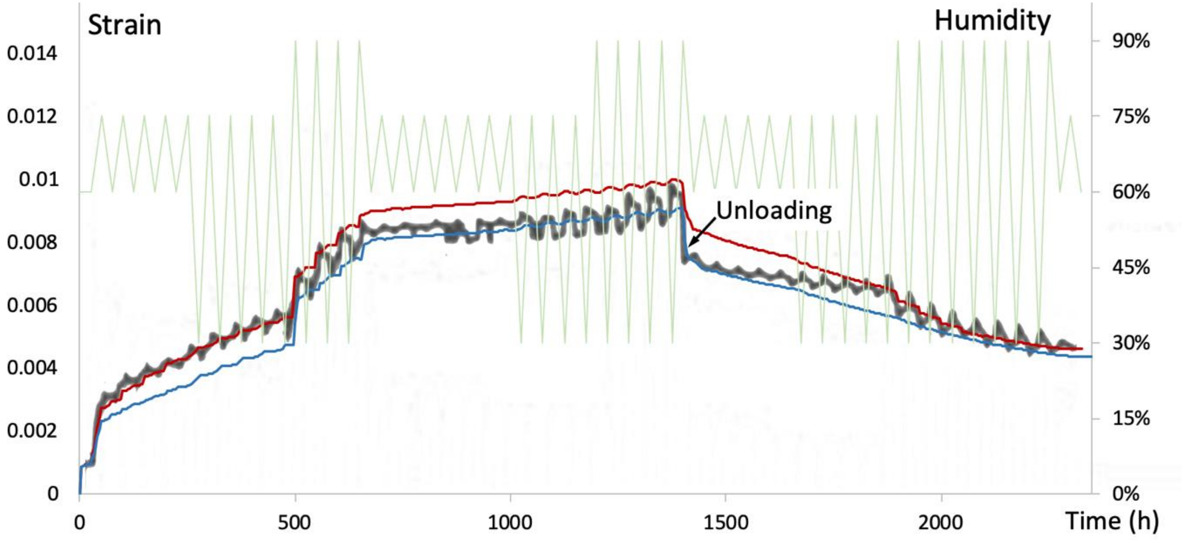
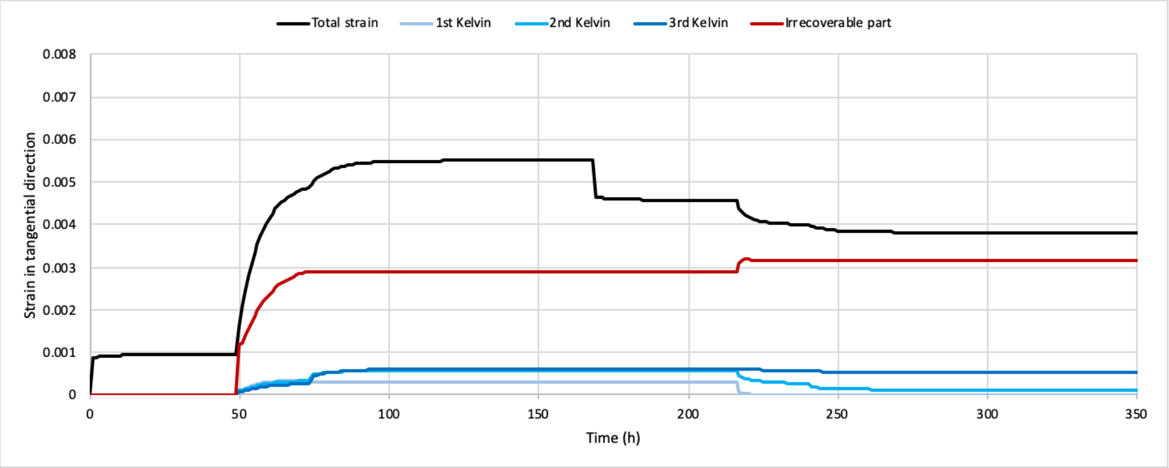


b)

Figure 3: *Comparison of models for a) short- b) long-term tension analysis: —— experimental result [41, 42] —— numerical results of Model 1, —— numerical results of Model 2, —— relative humidity*



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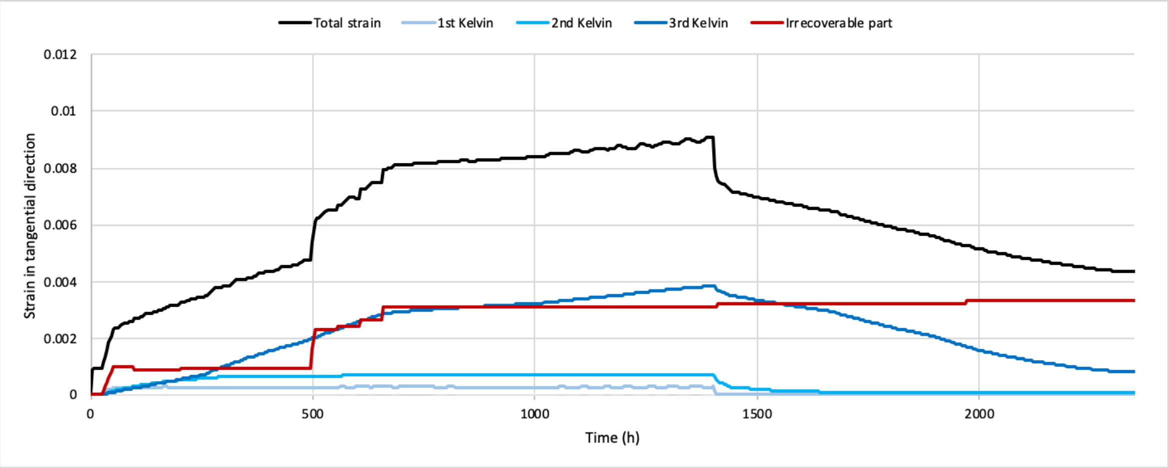
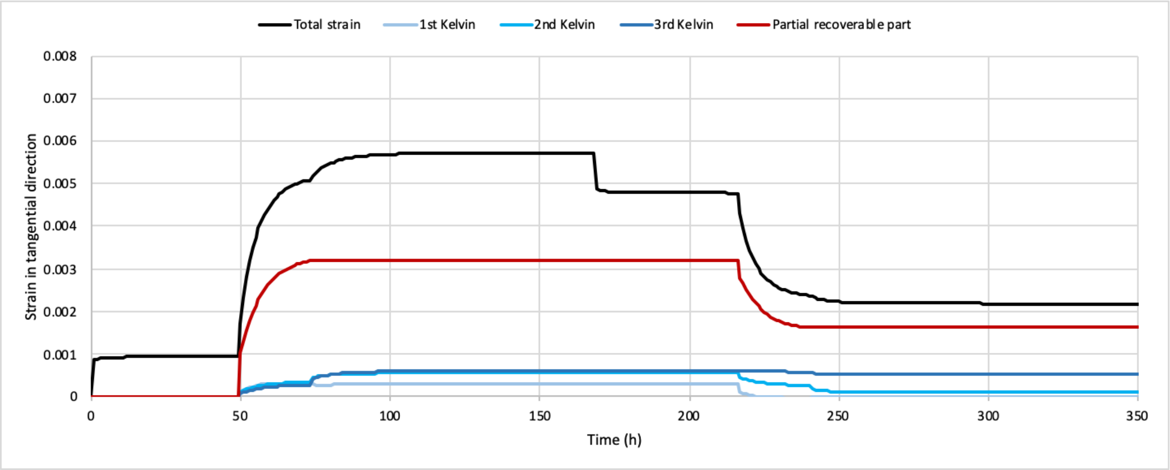


b)

Figure 4: *Decomposition of mechano-sorptive strain into each element for Model 1: a) long-term test; b) short-term test*

To better visualize the contribution of different parts of the mechano-sorption, Figure 4 shows the decomposed strain of the three recoverable Kelvin elements and the irrecoverable dashpot. In the short-term test, during the first adsorption, the strain of the irrecoverable dashpot is almost double the sum of the three Kelvin elements. However, in the desorption phase under loading, no increase is exhibited in the dashpot, since the U does not update. After unloading, the 1st and 2nd Kelvin elements exhibit recovery. Due to the large retardation time of the 3rd Kelvin element ($\tau_3 = 1$), its recovery is minor. On the contrary, in the long-term test, the contribution of the 3rd Kelvin element is significant in both creep and recovery phases. However, the strains of the 1st and 2nd Kelvin element remain small, as both of them reaches their creep limits after a few cycles, i.e. the dashpot is “empty” and the stress-strain ratio equals to the stiffness of the spring in the Kelvin element.

Based on the results of Model 1, the main goal of model modification is to capture the recovery. According to most experimental results [14, 23], the major recovery is observed when the moisture content exceeds the highest moisture value ever reached during the phase after unloading. Hence, in Model 2, a recovery feature is introduced into the part associated with the parameter U and the recovery part is kept the same as Model 1. The input parameters in the models are estimated and derived based on the graphs from the literature [41, 42] and the reference values of Fortino et al. [17]. For better illustration, all the parameters, except for the new partial recoverable part of mechano-sorption, are kept the same.



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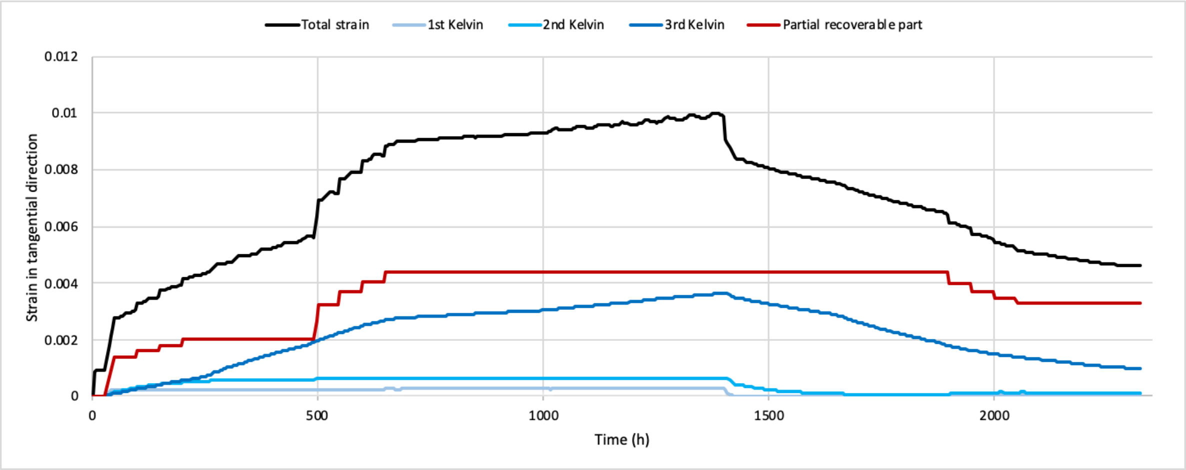

b)

Figure 5: *Decomposition of mechano-sorptive strain into each element for Model 2: a) long-term test; b) short-term tes*

As a result, Figure 5 shows the contribution of different mechano-sorption parts of Model 2. In comparison to the results shown in Figure 4, the main difference comes from the partial recoverable part of Model 2 and the irrecoverable part of Model 1. In the simulation for the short-term test, since the specimen experienced a moisture content increase that exceeds the initial value at the unloading point, a large recovery is exhibited in the newly modified part (seen the red line in Figure 5a), which is the main source of the total recovery. In the simulation for the long-term test, as the specimen is unloaded at a high moisture content point, the U value hardly updates during the unloading phase, hence the total behaviour is kept similar to Model 1, also retaining good agreement with the experimental data. As a conclusion, based on the current simulation results, Model 2 successfully introduces the recovery feature while retaining almost fully the capability of the initial Model 1. However, to check the applicability of this model to a greater variety of loading and environmental conditions, further calibration and experimental validation are needed.

5 CONCLUSIONS

In the current study, a comparison between different rheological models for wood is conducted. It is found that each model is specialized and validated for a certain combination of moisture variations and loading conditions. However, up to the authors' knowledge, the mentioned models are limited in capturing all the features observed in viscoelastic and mechano-sorptive creep, especially for the 3D cases, recognizing that many of the mechano-sorptive phenomena are not clearly understood yet. Based on the work of Fortino et al. [17], a modified model is proposed in this study. The simulation results of the modified model fit well with the original model in long-term cases and it is capable of capturing the extra recovery when the specimens were subjected to continuing moisture variations after mechanical unloading, which is observed by [41] in the short-term analysis. However, for completion and validation of the presented model with more reliable parameters and for development to cover more features, further experimental and calibration work is ongoing.

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