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Original article

Tree mechanics and wood mechanics: relating hygrothermal recovery of green wood to the maturation process

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Summary — Growth stress can be approached from the point of view of the mechanical standing of trees as well as that of the loading history applied to the material before tree felling. Stress originates in wood maturation causing both rigidification and expansion to the cell-wall material. Locked-in strains are partially released by cutting specimens from the tree, and, more completely, by boiling them in a green state, so as to exceed to softening point of lignin. It has been supposed that the rheological conditions during such hygrothermal recovery might be similar to those existing during maturation, when lignification of the secondary cell wall occurred. A rheological model of wood in the process of formation is proposed to support this hypothesis and derive information on the average maturation rigidity.

wood rheology / viscoelasticity / growth stress / hygrothermal recovery / cell wall

Résumé — Mécanique de l'arbre et mécanique du bois. Relation entre la recouvrance hygrothermique du bois vert et le processus de maturation. *Les contraintes de croissance peuvent être abordées du double point de vue de la tenue mécanique des arbres et de l'histoire du chargement appliqué sur le matériau jusqu'à l'abattage de l'arbre. Elles trouvent leur origine dans la maturation du bois qui provoque à la fois la rigidification et l'expansion de la matière constitutive des parois. Les déformations bloquées sont partiellement relâchées lorsque des échantillons sont extraits de l'arbre ; elles le sont plus complètement si ceux-ci sont chauffés à l'état vert au-dessus de la température de transition de la lignine. On a émis l'hypothèse d'une similarité des conditions rhéologiques de cette recouvrance hygrothermique avec celles qui prévalent lors de la maturation, caractérisée par la lignification de la paroi secondaire des cellules. Une analogie rhéologique représentant le comportement du bois au cours de sa formation a été proposée dans le but d'appuyer cette hypothèse et d'en déduire des informations sur la rigidité moyenne de maturation.*

rhéologie du bois / viscoélasticité / contrainte de croissance / recouvrance hygrothermique / paroi cellulaire

INTRODUCTION

In the review by Kübler (1987) on growth stresses, a whole chapter dealt with the thermal strain of green wood, characterised by a tangential swelling and a radial shrinkage. Since Koehler (1933) and MacLean (1952) these have been identified as the main cause of heart checking during log heating (fig 1) (Gril *et al,* 1993b). This abnormal thermal strain results from the viscoelastic recovery of growth stress (Kübler, 1959c) and for that reason it is called 'hygrothermal recovery' (HTR) after Yokota and Tarkow (1962). These authors clarified the contribution of conventional thermal expansion, cell-wall drying due to the decrease of fiber saturation point, and viscoelasticity, to the total thermal strain. Kübler (1973a, 1973b) went one step further in the fundamental understanding of HTR when he observed that the viscoelastic contribution is not the mere amplification of instantaneous release strains observed during tree felling and subsequent processing operations. The greater part of 'true' HTR must be related to the maturation process, *ie* the last stage of secondary cell formation characterised by polymerisation of lignin monomers and completion of cellulose crystallisation in the cell wall. The remaining part results from the action of subsequently formed wood layer. In the past years, research on growth stress has received growing interest from French teams (Guéneau, 1973; Saurat and Guéneau, 1976; Chardin and Bege, 1982). It has recently evolved into a more comprehensive approach where the regulation of tree form is studied in relationship to tree architecture, wood structure and tree mechanics (Thibaut, 1989, 1990, 1991, 1992; Loup *et al,* 1991; Fournier *et al,* 1992). The main objective of this paper is to show that HTR studies might contribute to this general framework of research because they involve simultaneous investigations on the material properties (wood rheology), the mechanics of the living structure (tree mechanics), and the transformation of a living structure into material (wood processing).

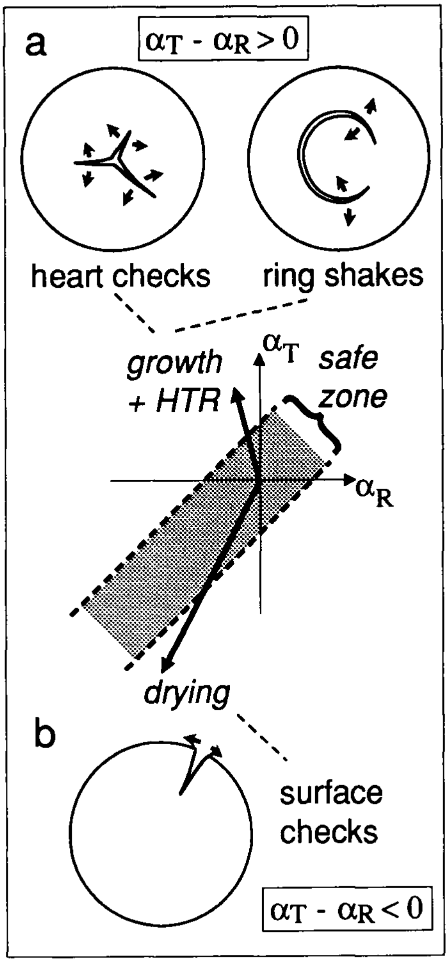

Fig 1. Checking risk of log ends according to the type of transverse expansion anisotropy. α_T: tangential expansion; α_R: radial expansion; a) HTR type with $\alpha_R < 0 < \alpha_T$ yielding heart checks or ring shakes; b) drying type with $\alpha_T < \alpha_R < 0$ induding rupture surfaces starting from the periphery.

Tree mechanics and wood mechanics

Two points of view are made implicit in the research on architecture, structure and mechanics of trees. Trees appear as complex structures managing to stand up through the wood constituting their stem. On the other hand, wood is considered as a material that has been produced by trees and thus has gained properties depending on the biological conditions of its elaboration. Figure 2 shows that a different use of the temporal dimension underlies these 2 points of view. The discs correspond to the cross-section of a portion of stem axis; this is a level of observation that is most adequate to link the 2 fields of research. Only smooth variations of wood properties are observed at this level, such as juvenile/adult wood or sapwood/heartwood transitions. Local variations like intra-ring heterogeneity, corresponding to seasonal cycles, are not accounted for. For the tree stem, time started when the pith was initially placed in the space explored by the bud. As the stem grows older, it increases in diameter. For wood, time started when it was made; the nearer to the pith, the older the wood. Two opposite directions of time result, as shown by the arrows: stem age increases towards the periphery; wood age increases towards the centre. The juvenile/adult wood transition (fig 2, top left) is related to the age of the stem, while the sapwood/heartwood transition (fig 2, top right) is related to the age of the wood. We do not mean to suggest that a direct causal relationship exists between stem age and the transition form juvenile to adult wood, or between wood age and heartwood formation, although it might be partially the case, we simply have in mind here the location of events in time.

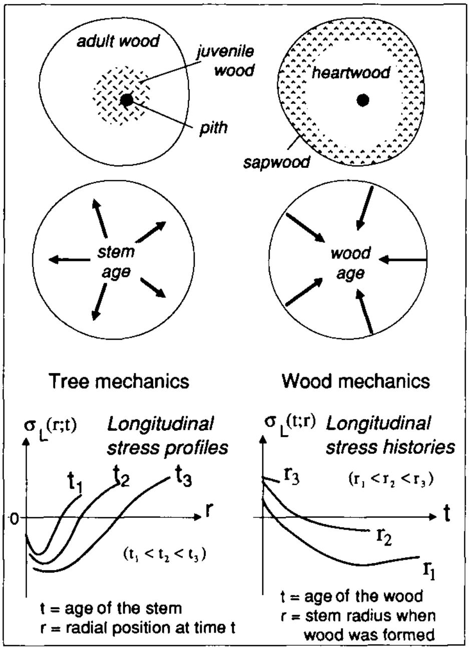

Fig 2. Radial variations of mechanical properties from the point of view of tree mechanics or wood mechanics.

This results in a 2-fold approach to growth stress in trees, illustrated at the bottom of figure 2 by different representations of the history of the longitudinal growth stress. From the tree mechanics standpoint (fig 2, bottom left), we deal with successive stages of stem development, where the existence of a self-equilibrated stress field participates in the overall mechanical standing of the tree. From the wood mechanics standpoint (fig 2, bottom right), we are concerned with the loading history to which the material has been subjected since the moment of its creation until the tree was felled and wood started to exist as a 'technical' material. What happened to wood while it was a part of the tree, 'in tree' wood, could be called the 'prehistory' of the wood, as opposed to the history of 'outside-tree' wood. The 'history' of the material includes cutting, drying and various treatments. Such data are more or less accessible provided that records of what happened to the wood since the tree was felled have been kept. Its 'prehistory', however, is not directly accessible. In order to estimate prehistoric factors, we have to question trees, like historians who must rely on mythic or folklore records and a few archaeological remains, to figure out what humanity was and did in ancient times (Gril, 1991a).

Stress profiles and corresponding stress histories, such as those shown in figure 2, can be calculated theoretically, based on assumptions about stem growth and geometry, constitutive equations of wood, and the mechanical effect of maturation. For instance, Kübler (1959a, 1959b) considered the case of a long cylindrical stem portion with circular cross-section, made of an elastic, homogeneous and transversally isotropic material, subjected at the periphery to an initial growth stress having nonzero components in the longitudinal and tangential directions only. Later more complex situations were considered (Archer, 1986). Although more realistic stress profiles can be obtained, in particular near the centre, by accounting for the different properties of juvenile wood (Fournier, 1989), all these calculations assumed elastic behaviour. Sasaki and Okuyama (1983) have shown the limits of the elastic approach by actually measuring radial variations of both the stress field and the elastic constants. They found a systematic gap between prediction and reality whatever additional assumptions they made. At the same time, they measured hygrothermal recovery of wood specimens taken from corresponding portions of the same trunk, and observed that the gap could be related to the amount of viscoelastic locked-in strain liberated by the heating test.

Such results suggest that a viscoelastic approach of growth-stress generation might improve the prediction of stress profiles (fig 3) and, consequently, yield a more realistic analysis of the stress histories applied to the material, depending on its radial position at the time of tree felling (fig 4).

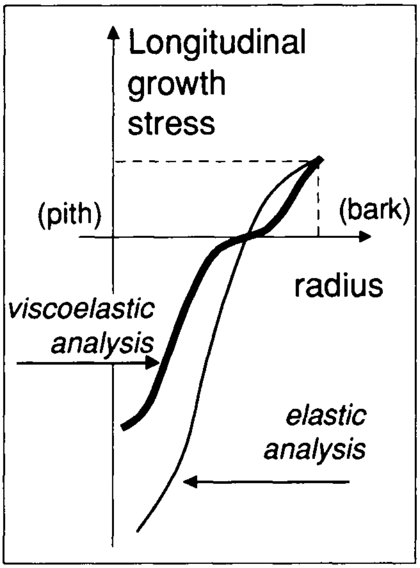

Fig 3. Improvement of stress profiles prediction through viscoelastic analysis.

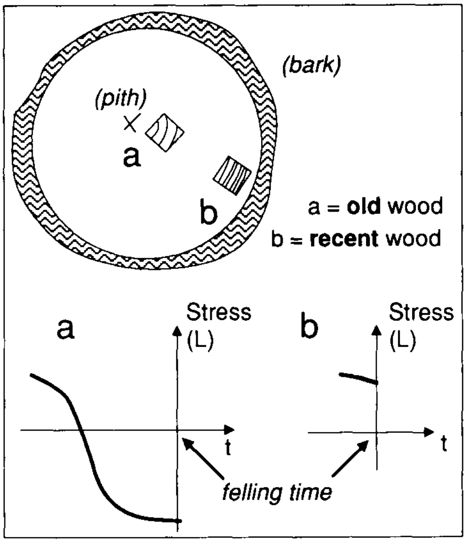

Fig 4. Locked-in strains as a hidden source of material variability.

THE MECHANICAL CONSEQUENCES OF MATURATION

Growth stress originates in the maturation process. Wood maturation includes all the biochemical processes happening after the deposition of secondary layers, such as lignin polymerisation, completion of cellulose crystallisation, or cross-linking in the amorphous regions of the cell-wall material. For most of the cells (parenchyma cells must be excepted), this process corresponds to the end of the biological activity, but it is also the most active period mechanically, because the expansion tendency characterising cell maturation occurs after a certain amount of rigidity has been acquired by the cell wall. The main definitions used to described the successive stages of wood formation and transformation are illustrated schematically in terms of stress and strain in figure 5. The amount of deformation that a given portion of newly formed wood (fig 5a) tends to reach will be defined as the maturation strain (fig 5b). As most of this deformation is prevented by the neighbouring layers, especially in the tangential and longitudinal directions, the new portion of wood is put under stress, named here the initial growth stress (fig 5c). The method used to evaluate the initial growth stress consists of isolating a portion of wood located near periphery and measuring the instantaneous recovery (fig 5d). If the piece of wood is left for some time, there will be a delayed recovery, that might be considerably accelerated by heating while still wet, which provokes hygrothermal recovery (fig 5e).

The separation between an instantaneous and a delayed component of recovery might seem arbitrary. Indeed, some stress relaxation may occur between the various steps of experimental measurements. For the sake of simplicity, we assume that the amount of delayed recovery at ambient temperature remains negligible compared with that obtained through hygrothermal treatment. Moreover, we have purposely drawn identical wood portions in figures 5b and 5e, to suggest a rheological similarity between maturation and hygrothermal recovery, which will be discussed later.

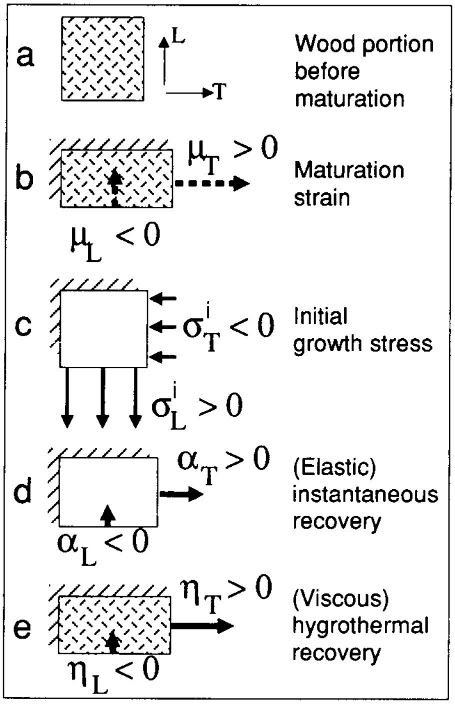

Fig 5. Maturation strain, initial growth stress and recovery.

Although cell-wall formation, especially maturation, is very short (a few weeks) compared with the subsequent duration of wood existence as a supporting part of the stem, it is of the utmost importance both for the tree stem and for the wood, because of its mechanically active mature (Wilson and Archer, 1979; Fournier *et al*, 1992).

Angular variations of initial growth stress provide the stems with the only mechanism of secondary reorientation compatible with their thickness and rigidity. The amount of maturation strain and the resulting initial growth stress depend on morphological factors (such as the mean inclination of cellulose crystallites in the secondary walls, or the lignin content), which can be adjusted during the formation of the secondary wall under the action of growth regulators. The formation of reaction wood is an extreme illustration of the potential for such morphological variations.

Wood layers located near the stem periphery are pre-strained by longitudinal tension and tangential compression as the expense of less vital internal layers, subjected by compensation to longitudinal compression and transverse tension. This situation favours stem flexibility and tends to prevent breaking or surface damage under bending loads, as illustrated in figure 6. This shows the effect of stem bending on the variation of peripheral strains relative to an assumed failure criterion in strain space; bending strains may reach more considerable levels, when superimposed on peripheral prestrains, without provoking either longitudinal or transverse rupture.

Biochemical reactions occurring during maturation tend to increase the molecular mobility of the cell-wall material dramatically, so that the viscoplastic effect of stresses is considerably higher than in mature wood. We deal here with a 'chemo-rheological' situation, similar in some way to the so-called 'mechano-sorptive' effect observed during loading under moisture changes (Grossman, 1976; Gril, 1991a), only more pronounced.

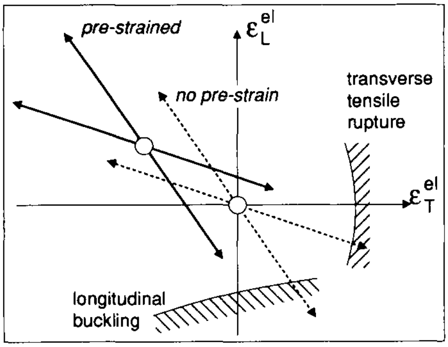

Fig 6. The positive effect of growth stresses on stem flexibility. ε_L^{el}, ε_T^{el}: elastic strain produced by stem bending near stem periphery in the longitudinal and tangential directions, respectively; dotted lines: without pre-strain, the material would fail either by transverse tensile rupture or longitudinal buckling; thick lines: pre-strains improve stem flexibility.

A MODEL OF MATURATION AND RECOVERY

Maturation determines the essential features of the material. It would thus be a great achievement to gain knowledge on the transient mechanical properties of wood during the process of formation. There is no direct way of obtaining such information, basically because wood responds actively to stresses during its formation, and in such situations conventional approaches of solid rheology lose their validity. To obtain some information, we have proposed an indirect approach which has been detailed elsewhere (Gril, 1991b), the principles of which are summarised here.

What matters in the maturation process, from the mechanical point of view, is the existence of a gradual rigidification followed by a gradual expansion tendency (maturation strain). As shown in figure 7a, both processes may be partially simultaneous, but there has to be a time gap so that the material starts to expand after having gained some rigidity. For the purpose of modelling, in figure 7b we propose replacing in the simplest possible way, the gradual changes by step changes with an equivalent qualitative effect. During the period called 'maturation' (between t_1 and t_3), the material has a rigidity intermediate between 'zero' representing the very low rigidity at the end of primary wall formation, and 'mature' corresponding to the final state of biologically dead and mechanically passive wood.

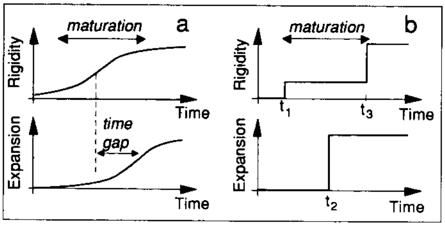

Fig 7. Schematic representation of the maturation process. a) Time between rigidification and deformation kinetics; b) the concept of equivalent maturation rigidity.

At some time t_2 during maturation, the maturation strain appears.

The rheological analogy illustrated in figure 8 accounts for the 2-fold nature of the maturation process. It is made of a series of 3 rheological elements: (i) an elastic mechanism represented by a spring of rigidity K (equal to that of mature wood), strained by σ/K under the external stress σ. (ii) A viscoelastic mechanism represented by a spring of rigidity K' and a dashpot having a characteristic time τ which is very small during the maturation process ($\tau << t_3 - t_1$), but much larger afterwards. In other words, during maturation the dashpot is 'open' and the element acts like an elastic spring K' strained by $\beta = \sigma/K'$; in the mature state, the dashpot 'locks' the mechanism and allows only slow viscoelastic variation of β. (iii) A maturation strain changing suddenly from 0 to μ at time t_2.

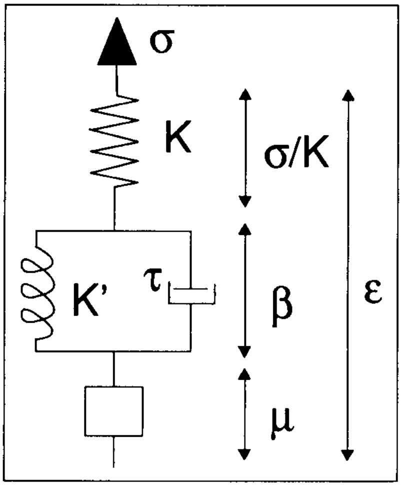

Fig 8. Rheological analogy. K: elastic rigidity; K': delayed rigidity; τ: characteristic time; μ: maturation strain.

A newly deposited wood portion might be represented at time $t < t_2$ (before maturation strain) by such a rheological analogy, with unstrained springs and zero stress. At time t_2, due to the expansion μ and the partial obstacle from neighbouring parts, which restricts the deformation, the wood subjected to the initial growth stress σ^{i}. It responds as if it had no dashpot, so that the total strain is equal to:

$$\varepsilon = \varepsilon^{i} = (1/K + 1/K')\sigma^{i} + \mu \qquad [1]$$

where ε^{i} is the initial growth strain actually allowed by the surrounding structure. At time t_3 nothing changes in the respective extension of the elements: the stress remains $\sigma = \sigma^{i}$, and the viscous component of strain $\beta = \beta^{i} = \sigma^{i}/K'$. Later (at times $t > t_3$), under the influence of stem growth, σ and β will be slowly modified according to some rate law, such as, for instance, a first-order rate law:

$$d\beta / dt = (\sigma / K' - \beta) / \tau \qquad [2]$$

If the wood portion represented by our model has been recently formed, it is still subjected to a stress approximately equal to the initial growth stress σ^{i}. Now let us imagine that it is suddenly isolated from the surrounding material. The stress σ to which it is subjected falls from σ^{i} to zero, resulting in a stress increment $\Delta\sigma = -\sigma^{i}$ and a strain increment:

$$\Delta\varepsilon = \alpha = \Delta\sigma / K \approx -\sigma^{i}/K \qquad [3]$$

where α corresponds to the instantaneous peripheral released strain measured experimentally on standing trees (Archer, 1986; Chanson *et al*, 1992).

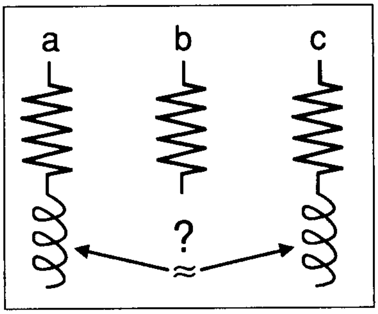

Fig 9. The hypothesis of rheological similarity between maturation and hygrothermal recovery. a) low rigidity during maturation; b) normal rigidity of mature wood; and c) softening induced by hygrothermal treatment.

RELATING HTR TO THE MATURATION PROCESS

After the recently formed wood portion has been extracted, the material remains strained, relative to the original dimensions prior to maturation by $\varepsilon^i + \alpha = \mu + \sigma^i / K'$. The maturation strain μ cannot be released in any way, because it was caused by irreversible modifications of the cell-wall material. The second component (σ^i/K'), however, is of a viscous nature, so that in theory it can be recovered provided the conditions for viscoelastic recovery are fulfilled. These are either time or temperature (Grzeczynsky, 1962; Kübler, 1987). On the other hand, the main difference between wood in the process of maturation and mature material is the lignification of the cell wall. As lignin has been shown to play a major role in the stimulation of hygrothermal recovery (Kübler, 1987; Gril *et al*, 1993a), to assume a rheological similarity between the 2 situations holds some physical basis. Although it remains to be proven and quantified, based on such physical considerations, we propose here the following working hypothesis (fig 9):

> *A hygrothermal treatment induces viscoelastic conditions similar to those that existed during maturation.*

Consequently, if a piece of wood previously separated from the tree (after measurement of α) is sufficiently heated in water, it undergoes a hydrothermal recovery:

$$\Delta\varepsilon = \eta \approx -\beta^{i} = -\sigma^{i}/K' \qquad [4]$$

One should be aware of the fact that although the strain recoveries (α and η) and the elastic rigidity of mature wood *(K)* are measurable quantities, the term K' does not bear such a clear mechanical meaning and cannot be observed directly. It corresponds to an 'average' mechanical response of wood in the process of maturation, not at any given instant. From the combination of equations [3] and [4], we deduce that α and η are related to each other by a simple equation:

$$K'\eta \approx K\alpha \qquad [5]$$

suggesting that a combination of data on α, η and K could provide indirect information on the components of K'. Although figure 8 makes use of linear elements such as a spring, a dashpot, *etc*, to represent the mechanical behaviour of the material, all the preceding quantities must be considered as multiaxial tensors. Strain variables like ε, α and η or stresses like σ and σ^i are described at least by 6 components, corresponding to the 3 extensions and the 3 shears in perpendicular directions R (radial), T (tangential) and L (longitudinal). Rigidities like K or K' must relate 6 components of stress to 6 components of strain. In Gril (1991b), we have derived multiaxial equations and obtained estimates of *K'* components according to some additional hypothesis made on its mathematical form.

CONCLUSION

Hygrothermal recovery data provide us with information complementing that provided by instantaneous recovery measurements. In the case of the peripheral material examined here, the analysis has been made simpler because the locked-in strain has not yet been modified by loading changes provoked by subsequent stem growth. The observed recovery can thus be directly related to the rheological conditions of maturation. In the general case of a piece of wood located towards the pith, the recovery should include an increasing proportion of conventional viscoelastic recovery (Kübler, 1973b; Gril *et al,* 1993a; Gril and Fournier, 1993). The basic hypothesis of the proposed rheological approach of the maturation process is a rheological similarity existing between maturation and hygrothermal conditions. Although reality is certainly not that simple, the question must be raised, at least to emphasize the importance of gathering complete sets of data on the constitutive equation, instantaneous release strain and hygrothermal recovery.

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