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Guillaume Pot, Catherine Coutand, Jean-Benoit Le Cam, Evelyne Toussaint. Etude expérimentale à l'échelle intra-cerne de propriétés mécaniques du bois vert de peuplier au cours de sa maturation par des essais de tractions cycliques. CFM 2011 - 20ème Congrès Français de Mécanique, Aug 2011, Besançon, France. hal-03422798

HAL Id: hal-03422798

<https://hal.science/hal-03422798>

Submitted on 9 Nov 2021

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Etude expérimentale à l'échelle intra-cerne de propriétés mécaniques du bois vert de peuplier au cours de sa maturation par des essais de traction cycliques

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Résumé :

Lors de cette étude, des essais de traction longitudinaux cycliques ont été réalisés sur du bois de tension vert (i.e. saturé en eau) issu de peupliers cv. I4551. Les résultats mettent en évidence la présence de déformations rémanentes ainsi que la dépendance de la rigidité du matériau aux déformations qui lui sont imposées. Ainsi, le bois de tension se rigidifie sous déformation alors que le bois opposé présente l'effet inverse. Une large campagne expérimentale a permis de comparer les propriétés mécaniques d'échantillons situés à diverses positions à l'intérieur du cerne à différentes étapes de la réaction gravitropique. Elle révèle des phénomènes de maturation complexes pour lesquels les propriétés mécaniques évoluent au-delà de la zone d'épaississement des parois cellulaires. De plus, des mesures de densité montrent qu'il n'y pas de corrélation entre la rigidité du bois et son infradensité. Tous ces résultats montrent que les propriétés mécaniques des cellules du bois de tension évoluent selon un processus de maturation très complexe.

Abstract :

In this study, longitudinal cyclic tensile tests were performed on green wood samples of *Populus* cv I4551. Complex mechanical behaviour, such as a permanent set in terms of displacement and strain-dependent stiffness, was found. A linear relationship between stiffness and strain enabled each sample to be characterized. A large-scale experimental campaign led to the observation of the evolution of temporal and spatial intra-ring mechanical properties during wood maturation and tree gravitropic response. The results showed that tension wood exhibits strain hardening behaviour whereas normal wood exhibits strain softening behaviour. Variations in the strain hardening behaviour of tension wood occurred once cell wall deposition was achieved. Moreover, no correlation was found between infradensity and mechanical properties. These results show that cells undergo temporal variations in their properties, due to a complex maturation process.

Mots clefs : maturation, essais de traction cycliques, bois vert, peuplier, bois de tension, propriétés mécaniques, infradensité, strain hardening, strain softening

1 Introduction

Tree axes grow in length in their apical parts (primary growth), whereas pre-existing parts grow in diameter thanks to secondary cambium, by which wood cells are produced at the periphery of the trunk. Wood fibres are created and matured by a complex developmental process which consists of five major steps: (1) cell division from the vascular cambium, (2) elongation and radial enlargement, (3) secondary cell wall deposition and lignification, (4) programmed cell death, and (5) heartwood formation [1,2]. Trees control their posture by maintaining and modifying the orientation of their trunk and branches in space. To do this, they are able to generate internal forces to right-up (negative gravitropism). Asymmetrical production of reaction wood ensures these gravitropic movements in plant parts that have achieved their elongation [3]. In most deciduous species reaction wood is called Tension Wood (TW) because it is under tension within the living tree [4]. Wood is thus prestressed. These prestresses are generated during the maturation phase. Considering a tilted axis (e.g. trunk) of a deciduous species, TW is first produced on the upper side (true gravitropic phase) and then on the opposite side (autotropism phase) in order to be, finally, straight and

vertical [5]. TW prestresses are more important than in opposite wood (OW).

Biomechanical models designed to simulate gravitropic movements and to predict reaction wood zones exist [6-8]. Most of these models consider the maturation process as instantaneous, i.e. cell maturation occurs instantaneously once the cell has left the cambium. Therefore, maturation strains are immediately locked in and mechanical properties change instantaneously. Coutand et al. in [5] noted that in the case of temporal integration with a time step of one week, such biomechanical models no longer fit the experimental data. They formulated two hypotheses to explain this discrepancy: (1) spatial and/or temporal changes in the TW pre-stress levels during the gravitropic response are significant and become more important than geometrical effects, and (2) time lag between radial growth and the differentiation of a cell into TW fibres cannot be neglected at short time scales. To investigate these hypotheses, information about the temporal and spatial evolution of TW mechanical properties during secondary growth are required. Some works studied mechanical properties of wood samples at intra-ring scale [9-10] but to our knowledge there is no study that deals with either intra-ring spatial or temporal changes during maturation.

Considering the lack of data concerning changes in the mechanical properties of wood during maturation, the aim of the present study is to characterize, spatially and temporally, variations in the intra-ring mechanical properties of TW during the radial growth of the tree and its gravitropic response. For this purpose we have attempted to define a mechanical quantity which characterizes green TW and its maturation. Experimental work was performed on set of trees which mechanical state differed: tilted trees which were free to right up (where the mechanical state of the trees varies all along the gravitropic response) and tilted trees which were staked in a fixed position (whose mechanical state remains constant). Although this work focuses on TW, the OW of these trees was also studied using the same experimental protocol.

2 Material and methods

The work has been carried out on eighteen one-year-old hybrid poplars (*Populus deltoides* X *Populus nigra*, clone 'I4551'). The trees were tilted by tilting the pot about 35° from the vertical the 3rd of June 2010 at the start of the 2nd year growth following the procedure described in [5]. There were two series of experiments: nine trees were free to right up while the nine others were staked in a tilted position in order to maintain the trees in the same mechanical state during their growth until they were felled. Comparing staked-tilted trees to free trees allowed us to observe gravitropic movement effects on the evolution of the wood's mechanical properties. Trees were felled weekly at different times along the growing season (i.e. at different stages of gravitropic process) in order to characterize the temporal evolution of the mechanical properties.

The tested samples were thin lamellas of dimensions 0.2 x 6 x 70 mm (in respectively radial, tangential and longitudinal direction). They were gradually cut, using a sliding microtome, from the cambium to the innermost growth ring. As a consequence, the whole sequence of these lamellas represented the intra-ring radial evolution of wood. Before tensile test, each lamella's was measured in order to calculate the volume of the tested region of the wet sample. After tensile test, they were dried at 105 °C for 24 hours and then weighted. Dry weight over wet volume gave infradensity of each lamella.

Lamellas were tested in their longitudinal direction by means of a tensile test performed under controlled displacement conditions with a constant tensile rate of 1 mm/min. The tensile test was sequenced in 6 increasing load cycles. For each cycle, the maximum load was increased every 6 N from 6 N to 36 N. Digital image correlation using CORRELI^{LMT} software [11] was used to measure full field displacements without contacts. Longitudinal deformation was then computed by planar interpolation.

3 Results

3.1 Infradensity spatial variation

Figure 1a shows a typical infradensity curve obtained for TW samples with respect to the radial distance from the first lamella. We examined a TW cross-section under controlled moisture conditions (figures 1b and 1c) with an ESEM (Environmental Scanning Electron Microscope). Qualitatively, the infradensity increase (1-2 region in figure 1a) in the first millimetre after the cambium seemed to follow the increase in cell wall thickness (observable in figure 1b). Hence, at point 2 cell wall thickening was assumed to be complete. In the 2-3 region presented in figure 1a, the infradensity curve slightly decreased along the radius until reaching a minimum (point 3). Qualitative local ESEM observations did not enable a clear explanation of this slight

decrease. However, anatomical observations explained the origin of the minimum by the presence of a large number of vessels, i.e. large empty areas with low infradensity (figure 1c). This is consistent with the fact that deciduous species have numerous vessels at the beginning of the growing season (although there is no clear earlywood/latewood transition for poplar). Finally, the last region of the infradensity curve between points 3 and 4 showed an increase in infradensity in proportion to the distance from the first lamella. This last region corresponded to the beginning of the growth ring of the previous year. The two sets of experiments (tilted trees which were free to right up and tilted trees which remained staked) gave similar results in terms of infradensity.

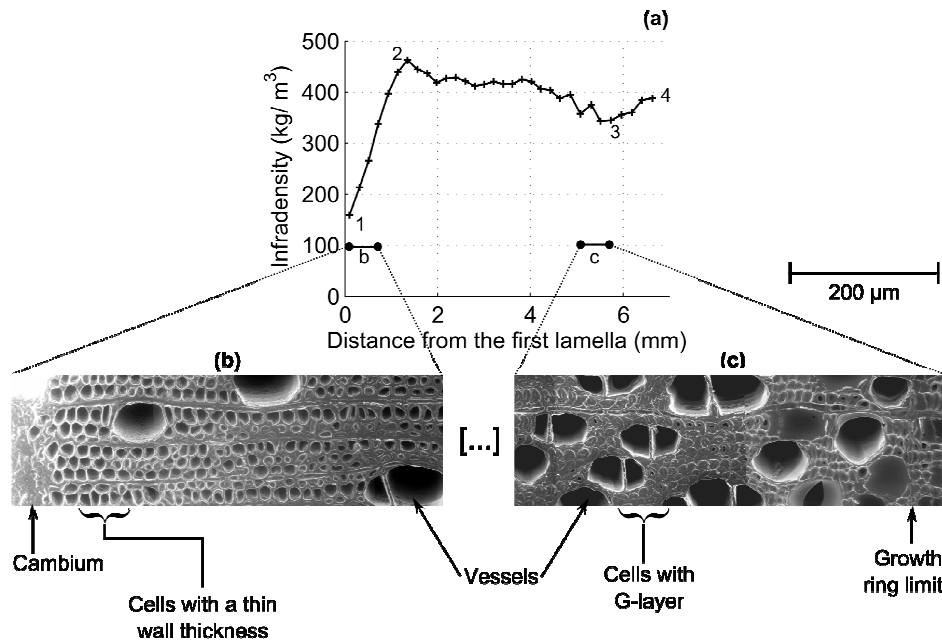


FIG. 1 – (a) Typical infradensity curve depending on the radial distance from the first lamella. (b) ESEM observation of the near cambial zone. (c) ESEM observation of the growth ring limit zone.

3.2 Cyclic tensile tests

Figure 2a and 2b presents typical stress/strain curves obtained with different poplar TW lamellas. For TW lamellas, strain/stress curves consistently presented strain hardening behaviour. Moreover, the shape of the stress/strain curves can be significantly different from one lamella to another. Indeed in this example, a lamella located at a distance of 2.8 mm from the cambium (figure 2b) presented a higher strain-hardening behaviour than a sample located at a distance of 1.4 mm from the cambium (figure 2a). Furthermore, as a difference with TW samples, samples of wood located into the previous annual ring (called Normal Wood NW) exhibited strain softening behaviour and a brittle failure (figure 2c).

Because of the strain-dependent behaviour, we could not study green wood stiffness regardless of applied strain (or stress). This conclusion led to the specific experimental protocol defined previously, for which cycles with increasing loads scan the range of possible strains. However we noticed that TW exhibited a linear shape of the loading phase of each cycle. Thus, for each cycle of each sample stiffness was calculated by linear interpolation over the reloading phase. The reloading phase was defined as the region between zero load and the maximum strain value obtained from the previous cycle. Therefore, for each sample, stiffness depends on the cycle being considered. We call this stiffness “Cycle Stiffness in the Reloading Phase” (CSRP).

In order to characterize stress/strain curves easily, the CSRP was plotted according to the maximum strain applied during the previous cycle for each lamella. A typical curve is presented in figure 2e. It shows a linear relationship between CSRP and maximum applied strain. The entirety of the tested sample presented such linear behaviour. Hence it is possible to characterize each sample by the two parameters of the linear curve: the slope and the y-intercept. We have called these parameters gradS for the slope of the linear curve and S0 for the y-intercept. gradS represents the stiffness gradient of the wood according to the applied deformation whereas S0 corresponds to the initial stiffness before loading. These parameters enable us to visualize variation in TW mechanical properties along the radius, regardless of the applied strain.

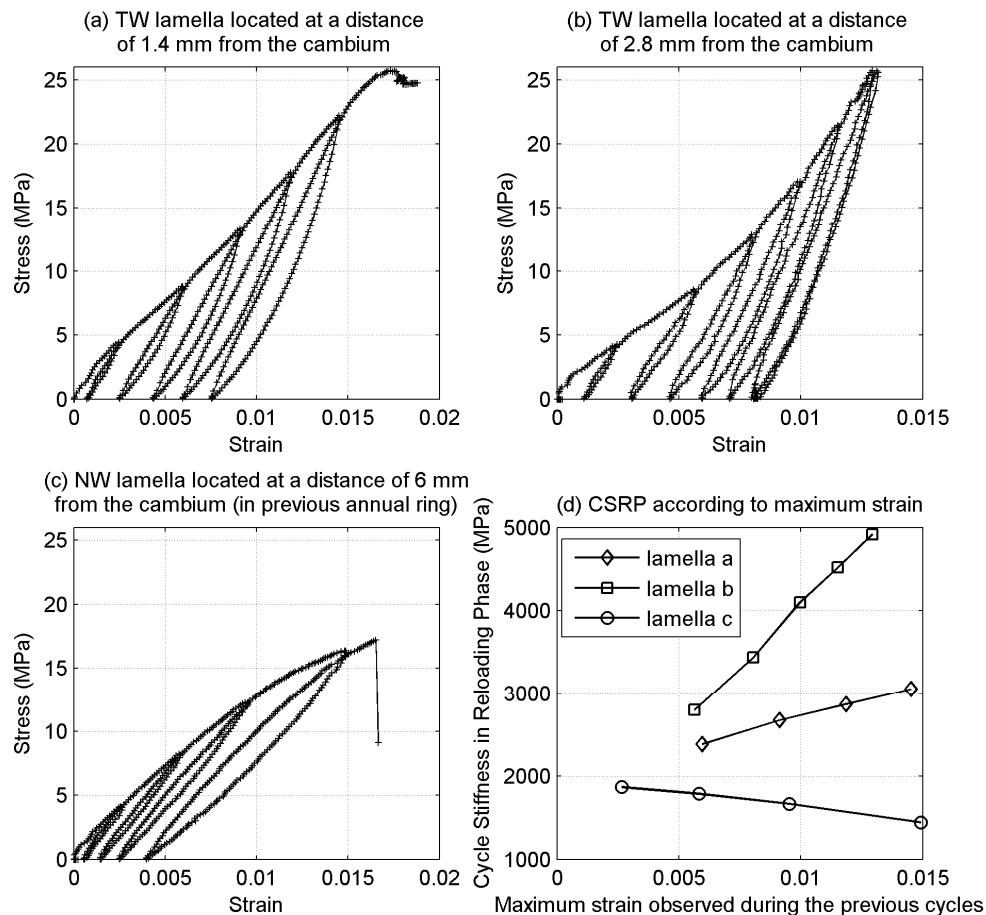


FIG. 2 – Chosen stress/strain curves of TW of a free tree lamella cut at a distance of (a) 1.4 mm from the first lamella; (b) 2.8 mm; (c) 6 mm, (d) Cycle Stiffness in Reloading Phase plotted according to the maximum strain observed during the previous cycles, obtained thanks to each curve (a), (b) and (c).

Figure 3 presents independently gradS and infradensity variations as a function of the radial distance from the first lamella for TW and OW samples, for a free tree and for a staked tree felled at the end of the growing season. No clear pattern was observed with S0. On the contrary, gradS variations along the radius of the tree were significant. Firstly, gradS was positive for TW until a given depth into the radius of the tree which corresponded to the decrease in infradensity (i.e. the growth ring limit). Then, in the growth ring limit region, there was a discontinuity in the TW curves and gradS suddenly decreased to negative values. This shows that TW of the last growth ring exhibited strain hardening behaviour whereas the wood of the previous growth ring showed strain softening behaviour. For TW of staked-tilted tree, gradS tended to increase when it came closer to the growth ring limit discontinuity, whereas its infradensity tended to decrease. The TW of a free tree presented very different behaviour, since there was a peak in gradS located at a distance of 2.4 mm from the first lamella. After this peak, gradS decreased to reach a more or less constant value which was similar to the initial value observed before the peak. It then decreased suddenly to a negative value in the growth ring limit region, like the TW of the staked tree. While the TW gradS of the free tree exhibited such high variations, its infradensity remained constant. From a global point of view, there was no significant statistical relationship between gradS and infradensity for TW.

Considering OW in figure 3, gradS was negative for the free tree as for the staked tree, and gradS variations were very low compared to those of TW. Hence OW exhibited strain softening behaviour which remained unchanged along the radius of the tree. Moreover, gradS values were similar to those of the NW of the previous annual ring. As was the case for TW, there was no statistical relationship between gradS and infradensity for OW.

These comments are applicable to all the tested trees. Especially TW of the free trees exhibited a peak in terms of gradS in a same region distant of 2 to 3 mm from the cambium. No peak was observed for staked-tilted trees.

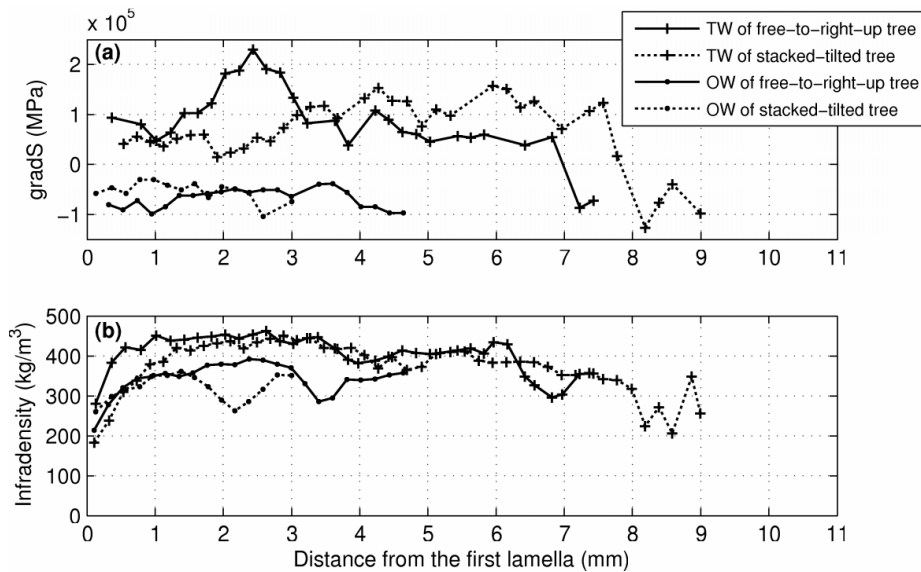


FIG. 3 – Typical TW radial evolution of (a) gradS and (b) infradensity of tension wood and opposite wood of a free tree and a staked-tilted tree

4 Discussion

The comparison between TW and OW highlights the profound difference in mechanical behaviour between these two materials extracted from the same living tree. Gilani and Navi in [12] have put forward an isotropic damage model of a cell under tension which could explain this difference by complex process mixing MFA changes and multi-damaging of the lignin and hemi-cellulose matrix. In this model, MFA reduction increases stiffness, whereas damage to the matrix leads to the opposite effect. Hence, in the present work, TW behaviour could be explained by the reduction in MFA, which would be preponderant compared to damage. Otherwise, for OW samples, damage would overcome the effect of MFA reduction and, as a consequence, stiffness would decrease as applied strain increases. This model refers to the behaviour of a single fibre considered as a hollow cylinder, whereas the samples tested in the present study contain several fibres. Despite the fact that the MFA reduction model could explain, qualitatively, the TW and OW behaviour observed in the present study, we suspect structural effects to be significant in the behaviour of the whole sample under longitudinal tension.

Despite the complex mechanical behaviour of green wood, this study highlights that the strain hardening behaviour of TW presents a linear relationship between CSRP and maximum applied strain. Since gradS does not depend on the applied strain, it allows the mechanical behaviour of a sample to be characterized irrespective of tensile test conditions (especially applied strain). Because the experimental protocol used is strictly the same for the entirety of the tested samples, changes in gradS can only be explained by changes in the composition or the structure of the wood. As a consequence, gradS is an appropriate indicator of the mechanical properties of maturing cells.

Infradensity is usually employed as an indicator of wood stiffness. In the present study, infradensity ranged from a very low value in the first lamella (i.e. cambium or close to it) to a maximum at a distance of less than 1.5 mm from the first lamella. Hence the maturation zone should be limited to this region. However, considering the gradS of TW from free trees (figure 3), a significant increase appears at a distance of 2 to 3 mm from the first lamella, in a zone where there is no significant variation in infradensity. As no infradensity variation must signify no material addition, gradS variation must be caused by micro-structural changes in cells. Moreover, no statistically significant relationship was found between gradS and infradensity for either TW or OW. As a result, infradensity is not a sufficient parameter to evaluate the mechanical behaviour of green wood.

The gradS peak, located at the same distance from the cambium for all the free trees, indicates unusual behaviour in the maturation process. This highlights the fact that important changes in the mechanical properties of free trees appear after cell wall thickening. As previously mentioned, we suspect the micro-structure of the wood to be responsible for changes in gradS, but the reasons for these changes remain enigmatic. Moreover, no variation in gradS appeared clearly for staked-tilted trees while they underwent

gravitropic stress and produced TW. Thus, the gradS peak observed for free trees may be related to the righting-up process itself.

Infradensity and gradS variations are large in a zone situated several millimetres away from the cambium, which lead to large temporal variations in these parameters. Hence we conclude that maturation is not an instantaneous phenomenon and that cells undergo a temporal evolution in their properties. As a consequence, mechanical pre-stresses in trees must also not appear immediately. To our knowledge, such temporal evolutions are not taken into account in biomechanical models of tree re-orientation. Their importance may be not negligible, as suggested by Coutand et al. [5]; the accuracy of these models could be improved thanks to the results of the present study.

5 Conclusion

In this study, longitudinal mechanical tensile tests and infradensity measurements were performed on a large quantity of thin green wood samples which were representative of the last growth ring of tilted poplar trees. They highlighted the particularly complex mechanical behaviour of green wood, such as permanent sets in terms of displacement and strain-dependent stiffness. TW samples presented strain hardening behaviour whereas OW of the last growth ring and NW of the previous growth ring presented strain softening behaviour. In spite of this, the experimental protocol used allowed us to define a mechanical quantity (gradS) which characterizes the radial mechanical evolution of TW in the last growth ring.

Infradensity measurements performed on the tested samples did not show a statistical relationship with gradS, which lead to the conclusion that infradensity (i.e. the quantity of wood) is not sufficient to evaluate the mechanical properties of green wood. Moreover, this study shows that important changes in the mechanical properties of free trees appear after cell wall thickening, whereas infradensity remain constant in this zone. The reasons of this behaviour remain unknown, but we suspect micro-structural changes occurring during cell maturation and righting-up process to be responsible for this.

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