The viscoelastic properties of some Guianese woods

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Abstract

Samples of tension wood and opposite wood were obtained from four species (*Iyranthera sagotiana*, *Ocotea guyanensis, Virola michelii, Sextonia rubra*) growing in the tropical rainforest of French Guiana. Dynamic mechanical analysis was performed in the longitudinal dimension with samples in the green "never dried" condition. Temperature and frequency of the tests were regulated to be similar to conditions experienced by the living tree. Tension wood from the species containing a G-layer was found to have higher damping characteristics than opposite wood from the same species whilst no difference was found between the wood types of the non G-layer species. The research thus far does not permit a solid conclusion but speculation into the possible origin of these differences is drawn from the nature of the G-layer matrix.

Introduction

Reaction wood is formed in the cambium of living trees to readdress vertical orientation of the stem following mechanical stressing, often by weight overhang (e.g. irregular crown formation) or external environmental factors such as wind loading. Reaction wood changes with plant group and as such falls into two categories: compression wood or tension wood. Compression wood is formed by gymnosperms in the lower side of the leaning stem [1]. Tension wood is formed by Angiosperms and is, as the name suggests, found on the upper or tensile side. In biomechanical terms, tension wood corrects the stem verticality by creating a tensile force somewhat higher than that of the opposing (opposite) wood [2, 3]. The anatomical [4, 5] and mechanical properties [6, 7, 8] of tension wood can therefore be very different to those of the opposite wood in the same tree. Additionally the severity to which the tension wood is formed may affect the degree to which these properties vary [8]. Tension wood is further classified by the presence or absence of a gelatinous G-layer [9]. The G-layer is composed of highly crystalline cellulose aggregates, in which hemicelluloses and lignin occur in trace amounts [10]. As there is seemingly no difference in wood tensile stiffness between G-layer and non G-layer producing species, [11], the benefit of the G-layer to the living tree is currently not certain.

Wood is a polymeric composite material displaying viscoelastic behaviour [12], which by simple definition means that there is an elastic and viscous component to its mechanical behaviour. After unloading, purely elastic materials will return all of the energy imposed upon them whilst purely viscous materials will exhibit a delay in mechanical response and dissipate that energy. Viscoelastic materials will therefore return some of the imposed energy with a delay and dissipate the rest. Wood elasticity is mainly given by the stiffness and orientation of the crystalline cellulose microfibrils in the S_2 layer of the cell wall [13, 14], whilst wood viscosity originates from the lignin and hemi-cellulose matrix [12, 15]. Wood viscoelasticity is anisotropic and highly dependant on temperature and moisture content [12].

Viscoelastic properties of materials are commonly measured by dynamic mechanical analysis or DMA [16]. This technique can provide the conservative elastic modulus (E') and the damping coefficient or “tangent delta” (tan δ). From an experimental view, tan δ is the tangent of the phase angle between the oscillating applied stress and the resulting strain. Whilst an elastic only material will deform immediately and have no phase lag, a material with a viscous component will have a phase lag relative to the degree of viscosity. Consequently, a higher tan δ indicates a more viscous material. This study presents an investigation into the viscoelastic properties of tension wood compared to opposite wood in tropical rainforest species

Material and methods

Material

Sample trees were collected in the vicinity of the Paracou experimental field station in French Guiana. Four common species were chosen (*Table 1*) representing 2 groups of taxonomically similar species where one was thought to contain a G-layer whilst the other was not. To maximise the possibility of tension wood content, individuals with a crooked or sweeping stem form were sought. To verify the asymmetrical trunk stresses associated with reaction wood formation [17] growth stress measurements were performed at 8 points around the circumference at breast height [8] using the strain gauge method [18, 19]. Trees were then felled and 8 radial sections corresponding to the growth stress measurement locations were cut from each. To obtain tension wood, the section with the highest growth stress was taken and the section directly opposite in relation to the standing tree was used for opposite wood. 3 samples of dimensions 150 × 2 × 12 mm (LRT) were cut from the outer (bark) part of the tension wood and opposite wood sections of each tree. Sample material was maintained in the green state throughout the process by not being allowed to dry out. Anatomical measurements to confirm tension wood and identify fibre pattern (presence or absence of a G-layer) were carried out on adjacent sample material from one of the two sample trees per species [20]. Growth stress measurements and fibre characteristics are shown in *Table 1*.

Table 1 Sample material used in the study. GS = Growth Strain, TW = Tension Wood, OW = Opposite Wood

Family	Species	Tree	Tree diameter at breast height (cm)	GS TW (µstrain)	GS OW (µstrain)	Fibre Pattern
Lauraceae	*Sextonia rubra*	1	25	-2362	-328	G Thick
		2	21	-1657	-59	
	Ocotea guyanensis	1	19	-2097	-399	G Thin
		2	18	-2063	-718	
Myrsiticaceae	*Iyranthera sagotiana*	1	26	-1485	12	No G
		2	22	-822	-7	
	Virola michelii	1	36	-1708	45	No G
		2	29	-1699	-7	

Dynamic Mechanical Analysis

A Bose-Electroforce 3230 Dynamic Mechanical Analyser equipped with a submersible 450N load cell and a custom built water bath temperature controlled by a Huber Ministat cc3 was used for the DMA tests. Submerged samples were tested in tension at constant 30°C temperature, chosen to resemble that of the natural environment of the trees in the tropical rainforest. To commence a charge of quasi-static loading was imposed to verify that there will be no slippage of the sample in the clamps during subsequent loading used for the determination of mechanical properties. A static ramp test was performed on each sample prior to DMA analysis to determine the tensile Young’s modulus and the quantity of stress to produce 0.02% strain with amplitude of 0.03%. The DMA test was a sinusoidal loading applied at a frequency of 1Hz to represent the oscillation of the correct order for a standing tree whilst remaining in a frequency range where the DMA has a more accurate response. Tan δ was calculated by Fourier Transformation analysis within the integral BOSE WinTest^{TM} DMA Analysis software.

Statistical Analysis

In order to determine if there was a significant effect of wood type on the tensile modulus or tangent delta, analysis of variance was performed on the data grouped by species and wood type. An F-test was used to determine the significance (α = 0.05) of wood type on each variable and where appropriate a Tukey HSD test was used to examine the differences in means between wood types and within species.

Results and discussion

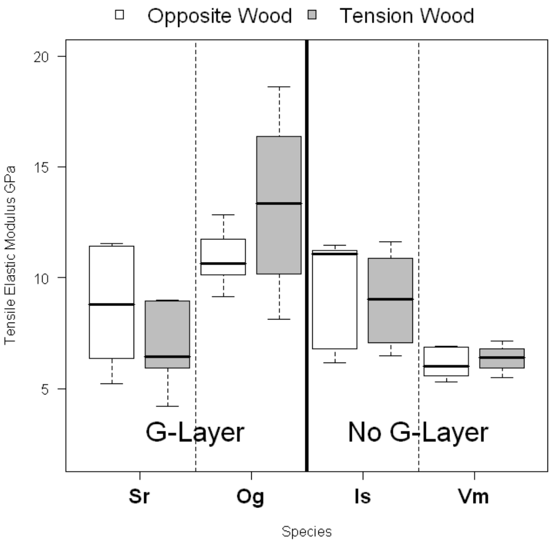

Fig. 1 Boxplot of tensile Young's modulus by species and wood type. Is = Iyranthera sagotiana, Og = Ocotea guyanensis, Vm = Virola michelii, Sr = Sextonia rubra . Significant differences (α=0.05) were found in green Young's modulus between tension wood and opposite wood of the G –layer species, Sr tension wood was less rigid than Sr opposite wood and Og tension wood was more rigid than Og opposite wood. No significant difference was found for the non G-Layer species.

With the exception of the *Virola* samples, there was a lot of variation in the tensile modulus (*Fig. 1*). Analysis of variance followed by the Tukeys HSD test (*Table* 2) showed that *the MOE* of *Sextonia* tension wood was lower than *Sextonia* opposite wood by 1.8GPa, whereas the inverse was true of *Ocotea* tension wood which was greater than *Ocotea* opposite wood by 2.4GPa. No significant difference (α = 0.05) was found between the tension wood and opposite wood of *Virola* or *Inga*. These results echo Ruelle et al. [7] who did not always find a significant difference between the air dry modulus of elasticity (MOE) of opposite wood and tension wood in Guianese species. Of the ten species studied by Ruelle et al. [7] only *Ocotea* was present in this study and the difference was in the same sense. Ruelle et al [7] presented a ratio of tension wood MOE over opposite wood MOE for this species equal to 1.28, the same ratio here was 1.22 and thus comparable though the effect of drying may change the ratio slightly. Ruelle et al. [7] also presented ratios less than one which showed the same trend for different species (*Virola surinamensis* and *Cecropia sciadophylla*) as the *Sextonia* here, i.e. the opposite wood was more rigid than tension wood. Neither the study by [7] nor these results can offer a definitive logic to the trends in longitudinal modulus within tropical species with reaction wood but do show the diversity of growth strategies and their underlying biomechanics in the tropical rainforest. It is important to note that the best comparison will be on the specific modulus to take account of density variations. The samples in this study are undergoing drying and further testing so that this comparison can be made.

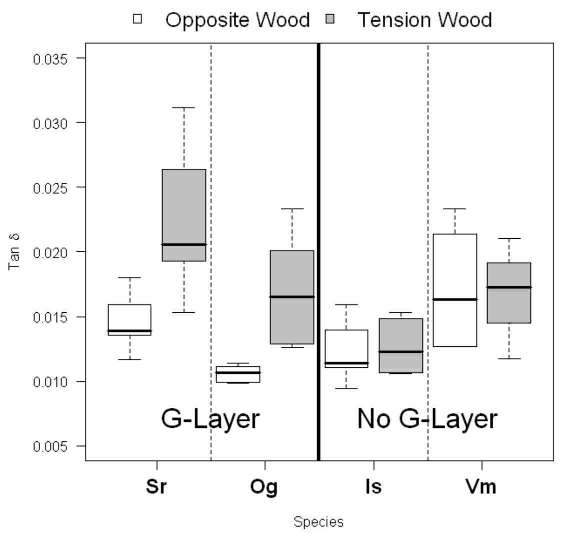

Fig. 2 Boxplot of tensile tangent delta at 1Hz by species and wood type. Is = Iyranthera sagotiana, Og = Ocotea guyanensis, Vm = Virola michelii, Sr = Sextonia rubra. Tension wood containing a G-layer was shown to have significantly (α=0.05) higher damping than opposite wood from the same species at a frequency of 1Hz There was no difference between tension wood and opposite wood from the non G-layer species.

Concerning the viscous part of this study, the measured tan δ are presented in *Fig. 2*. Both species which exhibited G-layer formation had a visibly and significantly higher tan δ in the tension wood as compared to the opposite wood (*Table 2*). The difference between the mean tan δ of the tension wood and opposite wood of both *Sextonia* and *Ocotea* was 0.0082 though the *Sextonia* samples did tend to have a higher tan δ in general. Differences between species were not assessed statistically due to the low number of sample trees. In contrast there was no visible or statistical difference between the tension wood and opposite wood of the species without a G-layer.

Table 2 Results from a Tukey HSD test examining the difference in Tensile Young's Modulus and Tangent Delta between the wood types of each species. OW = Opposite Wood, TW = Tension Wood, Is = Iyranthera sagotiana, Og = Ocotea guyanensis, Vm = Virola michelii, Sr = Sextonia rubra.

Parameter	**Difference in wood type within species**	**Difference in Means**	**p-value**
Tan δ	Is_TW - Is_OW	0,0002	1,0000
	Og_TW - Og_OW	0,0082	<0,0001
	Sr_TW - Sr_OW	0,0082	<0,0001
	Vm_TW - Vm_OW	-0,0008	0,9967
Tensile Young's Modulus (GPa)	Is_TW - Is_OW	-0,2563	0,9981
	Og_TW - Og_OW	2,4052	<0,0001
	Sr_TW - Sr_OW	-1,7837	0,0002
	Vm_TW - Vm_OW	0,2312	0,9996

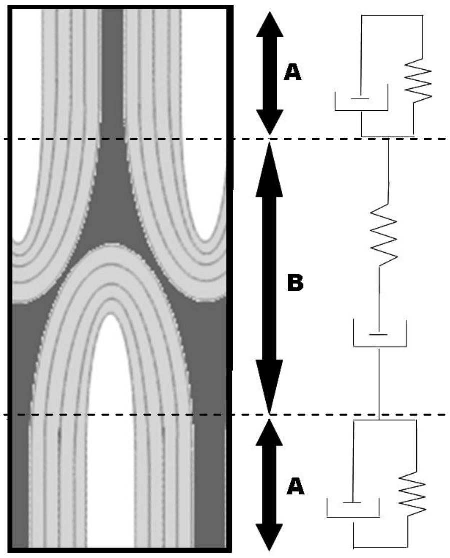

Fig. 3 Assumed fibres ends and rough viscoelastic models. Region A represents the axially aligned cell wall with a Hookian spring (mainly microfibrils) and a Newtownian dashpot (matrix) in parallel. Region B represents the region of vertical interaction between fibres were elastic rigidity may be lower due to increasing microfibril deviation from the vertical at the tapering fibre ends. In that region, constituent loading can be roughly seen to be in series with a lower spring stiffness (i.e. matrix, middle lamella and transverse microfibrils elasticity). The thickness of the middle lamella is thought to be constant and the varying thickness in this graphic is due to a limit of the current illustration technique.

□ Lumen
■ Middle Lamella
▥ Cell wall with microfibrils

The presence of a G-layer seems to indicate an increase in the viscosity of the material relative to the wood from the opposing side of the same tree. These experiments alone cannot offer a definitive origin of this phenomenon but there is room to speculate. Firstly it can be considered that the un-lignified gel-like matrix of the G-layer has properties different to those of the lignified wood cell wall (reviewed in [21]) and that consequently the gel matrix is more viscous. However, this corresponds only to region A of *Fig. 3* and it is difficult to imagine that this difference in viscosity would be detectible in the case where stress is longitudinally applied to the tension wood cell wall as the load should be mostly carried by the microfibrils, which are well aligned to the fibre axis, and not by the matrix. Logically, the mechanical properties of the matrix should be more apparent for longitudinal stress applied to a cell wall with high microfibril angle (MFA) and a resulting lower specific modulus. Again it will be important to observe the specific elastic modulus of these samples, as proposed earlier, in order to see clearly the difference in the cell wall longitudinal elasticity and its possible effect or correlation with the viscous response variations.

Independently of the how the mean MFA effects the viscoelasticity of the main body of the cell wall (region A of *Fig. 3*), it is not certain of how microfibrils are aligned at the tapered ends of wood fibres. It is plausible that the microfibrils follow the course of this taper and are thus, even in tension wood, less aligned relative to the vertical at these points (region B of *Fig. 3*). If this were to be the case, then at this interconnecting region, an applied axial stress would act across rather than along the microfibrils and therefore the mechanical properties of the matrix and/or the compound middle lamella (the interfusion of primary cell walls and the middle lamella after lignification) would become more important. This is illustrated with a viscous and elastic component in series in *Fig. 3*. With respect to the G-layer fibre, the properties of the chemically different matrix could become more pronounced at these points. Alternatively, in the G-layer there may be lower cohesion between fibres, caused by the lack of lignification for example, and consequently at the end the fibre would have lower axial rigidity than in normal wood, increasing the contribution of the viscous middle lamella. Some supportive evidence may be seen in Wimmer and Lucas [22] who showed quantitatively that the cell corner middle lamella was 50% less rigid than the S_2 layer in *Picea rubens* wood and that, visually, there seemed to be a larger remaining plastic (permanent) deformation in the cell corner middle lamella for the same imposed force. Further research is required in this area in order to further understand this phenomenon and should consist of anatomical studies of fibre ends coupled with micromechanics.

From the biomechanical point of view it can be proposed that the increased damping capability of the tension side of the stem could decrease the risk of fracture associated with a sudden jolt induced by a gust of wind for example. In this case it is not clear why some species have adopted the G-layer strategy in tension wood whilst others have not. On an evolutionary timescale it appears that both sets of species appeared at similar times [23]. On the other hand this increased damping could simply be the side effect or trade off of genetic mutation, the quantity of which is less important to the standing tree than architecturally related damping (e.g. [24, 25]).

Conclusion

The presence of a G-layer in the tension wood of the studied species was accompanied by an increased damping coefficient relative to the respective opposite wood. Hypotheses were put forward on the origin of this difference coming from the different chemical composition of the G-layer matrix or increased contribution of the middle lamella at fibre ends. A biomechanical implication was proposed in the damping of tension wood to an induced vibration and recommendations were made for future research.

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References

1. Timmel T.E., 1986. Compression wood in gymnosperms, Springer-Verlag,, New York, New York, USA.
2. Wardop A.B., 1964. The reaction anatomy of arborescent angiosperms. In: Zimmermann M. H. (Ed.) Formation of wood in forest trees, Academic Press, New York, pp. 405-456.
3. Fisher J.B. and J.W. Stevenson, 1981. Occurrence if reaction wood in branches of dicotyledons and its role in tree architecture. Botanical Gazette 142(1): 82-95.
4. Jourez B., A. Riboux, et al., 2001. Anatomical characteristics of tension wood and opposite wood in young inclined stems of poplar (Populus euramericana cv 'Ghoy'). Iawa Journal 22(2): 133-157.
5. Ruelle J., B. Clair, et al., 2006. Tension wood and opposite wood in 21 tropical rain forest species 2. Comparison of some anatomical and ultrastructural criteria. Iawa Journal 27(4): 341-376.
6. Coutand C., G. Jeronimidis, et al., 2004. Comparison of mechanical properties of tension and opposite wood in Populus. Wood Science and Technology 38(1): 11-24.
7. Ruelle J., J. Beauchene, et al., 2007. Comparison of physical and mechanical properties of tension and opposite wood from ten tropical rainforest trees from different species. Annals of Forest Science 64(5): 503-510.
8. Fang C.H., B. Clair, et al., 2008. Growth stresses are highly controlled by the amount of G-layer in poplar tension wood. Iawa Journal 29(3): 237-246.
9. Onaka F., 1949. Studies on compression and tension woodWood research bulletin, Kyoto University, Japan.
10. Daniel G., L. Filonova, et al., 2006. Morphological and chemical characterisation of the G-layer in tension wood fibres of Populus tremula and Betula verrucosa: Labelling with cellulose-binding module CBM1(HjCel7A) and fluorescence and FE-SEM microscopy. Holzforschung 60(6): 618-624.
11. Clair B., J. Ruelle, et al., 2006. Tension wood and opposite wood in 21 tropical rain forest species 1. Occurrence and efficiency of the G-layer. Iawa Journal 27(3): 329-338.
12. Navi P. and S. Stanzl-Tschegg, 2009. Micromechanics of creep and relaxation of wood. A review COST Action E35 2004-2008: Wood machining - micromechanics and fracture. Holzforschung 63(2): 186-195.
13. Cave I.D., 1968. Ansiotropic elasticity of plant cell wall. Wood Science and Technology 2(4): 268-&.
14. Salmen L. and I. Burgert, 2009. Cell wall features with regard to mechanical performance. A review COST Action E35 2004-2008: Wood machining - micromechanics and fracture. Holzforschung 63(2): 121-129.
15. Salmen L., 1984. Viscoelastic properties of insitu lignin under water-saturated conditions. Journal of Materials Science 19(9): 3090-3096.
16. Menard K.P., 2008. Dynamic Mechanical Analysis: A Practical Introduction, CRC Press, 240 p.
17. Trenard Y. and P. Gueneau, 1975. Relations between growth stresses and tension wood in beech. Holzforschung 29(6): 217-223.

18. Yoshida M. and T. Okuyama, 2002. Techniques for measuring growth stress on the xylem surface using strain and dial gauges. Holzforschung 56(5): 461-467.
19. Jullien D. and J. Gril, 2008. Growth strain assessment at the periphery of small-diameter trees using the two-grooves method: influence of operating parameters estimated by numerical simulations. Wood Science and Technology 42(7): 551-565.
20. Chang S.-S., B. Clair, et al., In print. Mesoporosity as a new parameter for understanding tension stress generation in trees. Journal of Experimental Botany.
21. Pilate G., B. Chabbert, et al., 2004. Lignification and tension wood. Comptes Rendus Biologies 327(9-10): 889-901.
22. Wimmer R., B.N. Lucas, et al., 1997. Longitudinal hardness and Young's modulus of spruce tracheid secondary walls using nanoindentation technique. Wood Science and Technology 31(2): 131-141.
23. Ruelle J., 2009. Personal Communication
24. Spatz H.C., F. Brochert, et al., 2007. Multiple resonance damping or how do trees escape dangerously large oscillations? American Journal of Botany 94(10): 1603-1611.
25. Moore J.R. and D.A. Maguire, 2008. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. Tree Physiology 28(1): 75-83..