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BIOMECHANICAL PERFORMANCES OF TREES IN THE PHASE OF ACTIVE REORIENTATION

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Abstract

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The purpose of the present paper was to investigate the accumulation of growth stresses in a cross section of a tree in active reorientation process and its biomechanical performances i.e. up-righting efficiency and stem flexibility. Effect of two factors was analysed in details: occurrence of juvenile wood and viscoelasticity of wood tissues. In a phase of active reorientation, wood tissues close to the pith are submitted to significant levels of compressive stresses. Production of juvenile wood in earlier stage of a tree life seems to increase the stem flexibility during active reorientation for both softwoods as well as hardwoods. Concerning the viscoelasticity of wood tissues, only minor effect has been observed in softwoods while an important positive impact has been pointed out in hardwoods. Set of simulations with increasing level of maturation strains in reaction tissues indicated possible trade-off between the stem flexibility and the up-righting efficiency.

tree reorientation, stem flexibility, up-righting efficiency, juvenile wood, viscoelasticity

During its life, a tree is submitted to an incremental diameter growth together with an increase of external forces, mainly due to the weight of its crown. To improve the stiffness of newly formed cells, wood tissues are pre-stressed during their maturation. Due to the lignin deposition, the newly formed wood cells have a tendency to shrink along the fibres however this deformation is restricted by older (already stiff) wood layers thus inducing considerable pre-stresses in the new layer. Asymmetric distribution of pre-stresses around its circumference allows the tree to control the verticality of its stem and the shape of branches (Archer, 1986).

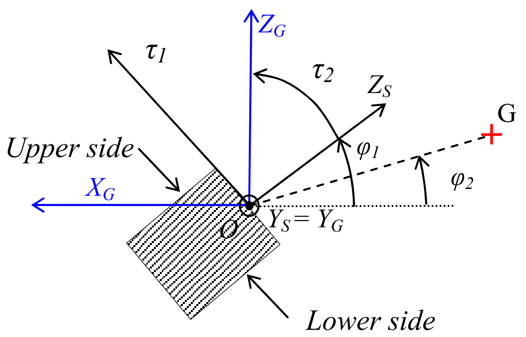
It is well known that the distribution and magnitude of growth stresses depends on the relative speed of loading and of secondary wood formation. However, the viscoelastic nature of wood introduces an additional time dependency through the differential relaxation of various tissues. This aspect is only poorly documented and probably introduces a significant bias in the biomechanical models used for tree assessment or growth description.

Mechanical analysis of progressively loaded growing structure submitted to maturation strains was done by Fournier (Fournier *et al.*, 1991a; Fournier *et al.*, 1991b). Alméras (Alméras *et al.*, 2005) investigated the impact of maturation strain and Young modulus differential between normal and reaction wood and of the growth eccentricity on the efficiency of reorientation process. Finite element method was also applied to analyse the shape regulation in trees (Fourcaud & Lac, 2003). However only few modelling approaches take into account viscoelastic properties of wood (Gril & Fournier, 1993) and no references were found about the influence of juvenile wood transition.

In the present study, we have investigated the accumulation of growth stresses in a tree stem based on simple cross-section model allowing general distribution of wood properties. The aim was to investigate the impact of viscoelasticity of wood tissues and juvenile wood occurrence on the reorientation process. Further, the impact of the growth eccentricity was investigated. Presented simulations are based on estimated values of wood properties that will be replaced, when available, by experimental data.

MATERIALS AND METHODS

A simple model based on beam theory has been developed to simulate the dynamics of the stem reorientation and the evolution of its flexibility. The analysis focused on a small stem portion, a "cross section" represented in Fig. 1 that can be located at the base of a trunk or a branch, or any given position of a standing tree. In the current version of the model, the up-righting process is not interactive with the environment (initial and final positions of the stem are imposed) so that we can use it only to test qualitatively some hypothesis about up-righting strategies. In presented simulations, the up-righting reaction at the base of a tilted tree was analysed allowing the curvature only along Y-axis.



1: *Description of the section geometry. O(Xs, Ys, Zs) is the reference system corresponding to a given section, with Zs equal to the local pith orientation n; O(X_G, Y_G, Z_G) is the reference system corresponding to the tree; O: biological centre of the section; G: centre of mass of the upper part of the tree; φ1: tilt angle of the section; φ2: tilt angle of the tree.*

I: *Set of tree leaning parameters used for modelling the up-righting reaction of tilted trees. RW: reaction wood, OW: opposite wood.*

Growth scenario for tilted tree	
Angle at the section φ_1 (deg)	60
Radial Growth Evolution: $R = R_0*(RN/R_0)$^(n/N)	
Initial radius R_0 (cm) Rinal radius RN (cm)	1 5
Growth Raction	
RW extension (deg) OW extension (deg)	90 60
Loading history	
Angel of the center of mass φ_2 (deg) Evolution of load: $P = 14.1*R^{2.6}$	75

General description of the section geometry allows to simulate general distribution of wood properties (elastic, viscoelastic and yield stresses) so that the occurrence of juvenile and reaction wood could be taken into account. Viscoelastic properties of wood were described through a rheological model of 2 Kelvin elements in series, each of them associated with a characteristic time and a delayed modulus. Estimates of all parameters used for simulations are summarised in Table II and will be replaced, when available, by experimental data.

Growth eccentricity was taken into account through the eccentricity index representing the ratio of the distance between the centres of two successive layers and difference of their radius. In simulations for the tilted tree, it was set to ±2/3 while the straight tree did not exhibit any growth eccentricity. Moreover, the distribution of maturation strains in vertically growing trees was supposed to be homogeneous while in tilted trees the contrast between the opposite and the tension/compression wood was essential.

The *up-righting efficiency* was investigated through the total change in curvature at the end of the simulated period. The maximal increment of curvature that a tree was able to withstand without failure was called *flexibility* and represented a kind of a security factor. Both, up-righting efficiency and flexibility were expressed in degrees of curvature along Y-axis per meter of tree stem. When the computed stress at a given position of the cross-section reached the yield stress in compression or in tension, this was considered as a *weak point*, i.e. the point where the failure will appear at first.

Growing period of 200 weeks was considered and analysis was applied to a tree in juvenile stage where the need of reorientation is crucial for the tree positioning in the canopy. At first, simulations omitting the occurrence of juvenile wood and viscoelasticity were performed. Afterwards, corresponding parameters were introduced one by one in order to assess their effect. During the second set of simulations, we investigated the influence of eccentric growth and maturation stress on biomechanical performances and finally we analysed the relation between up-righting efficiency and stem flexibility.

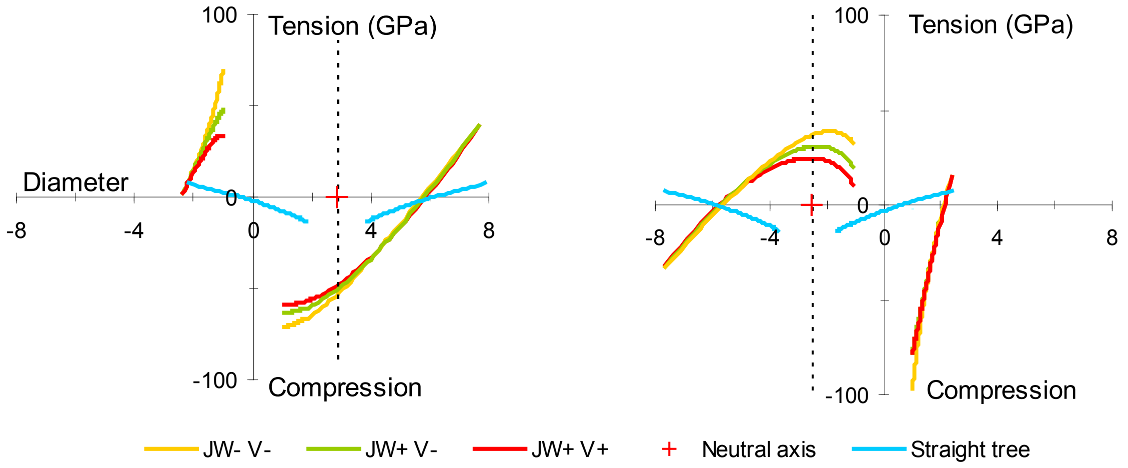
RESULTS AND DISCUSSION

Stress profiles in trees exhibiting eccentric growth and location of weak points

First, simulation for a straight and vertically growing tree with circular section and without occurrence of reaction wood was performed to obtain some reference value (blue profiles in Fig. 2). Afterwards, simulations on a tilted tree in a reorientation process were done. We could see that during the up-righting process, wood tissues close to the pith are submitted to very high levels of compressive pre-stresses (Fig. 2). The maximal value of compressive stress is up to 4 times larger inside a cross section of a tree in reorientation process than in the section of a straight growing tree.

II: *Estimates of parameters used in presented simulations. NW: normal wood; TW: tension wood; OW: opposite wood; CW: compression wood; MOE: elastic modulus in longitudinal direction; MORC: yield stress in compression; MORT: yield stress in tension.*

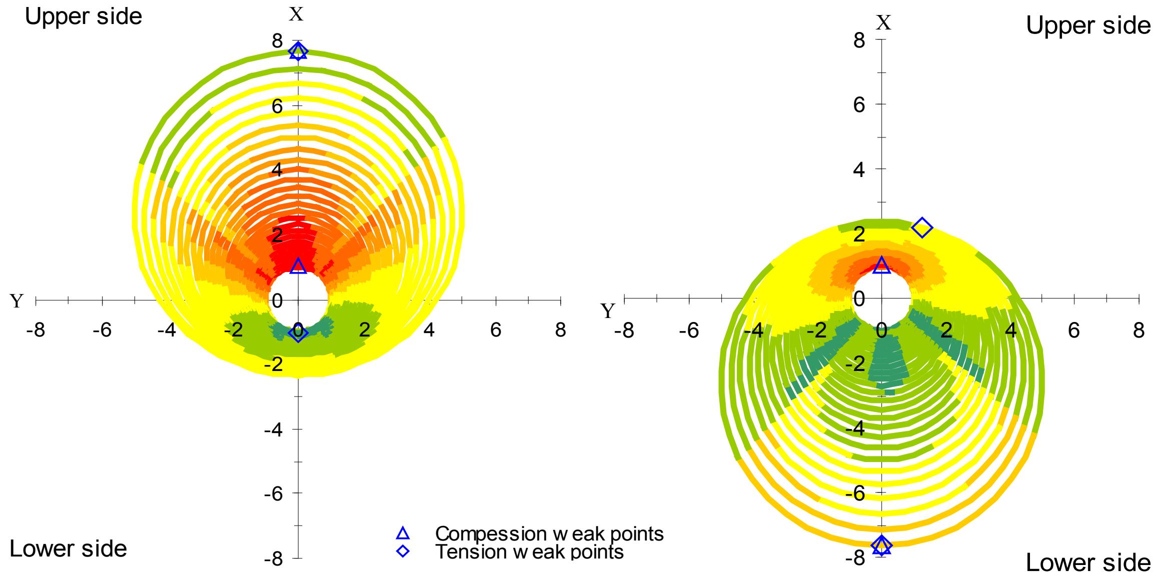
Softwood	**NW**	**CW**	**OW**		**NW**	**CW**	**OW**
Mat. strain (με)	−500	2500	−1000	**Viscoelastic properties**			
MOE (GPa)	$E = E0 + (EN-E0)*n/N$			First visco-elastic modulus (GPa)			
E0 =	12	10	15	E10 =	50	120	30
EN =	16	15	18	E1N =	75	160	60
MORC (MPa)	−100	−80	−120	First relaxation time (weeks)			
MORT (MPa)	160	200	120	τ10 =	20	20	20
Hardwood	**NW**	**TW**	**OW**	Second visco-elastic modulus (GPa)			
Mat. strain (με)	−500	−2500	0	E20 =	50	120	30
MOE (GPa)	12	15	10	E2N =	75	160	60
MORC (MPa)	−100	−80	−120	Second relaxation time (weeks)			
MORT (MPa)	160	200	120	τ20 =	200	200	200



2: *Stress distribution along a diameter, as a function of the distance to the pith, for a hardwood (left) and a softwood (right) in reorientation process; JW: effect of juvenile wood is taken (+) or not (−) into account, V: effect of viscoelasticity is taken (+) or not (−) into account; +: location of bending axis; blue curve represents a stress profile in a straight tree (simulation accounts for viscoelasticity and the occurrence of juvenile wood), its pith (dashed vertical line) is located at the neutral axis.*

In softwoods, the occurrence of juvenile wood allows to reduce markedly the magnitude of pre-stresses (−19.3% near the pith). Has double effect: separately it viscoelasticity increases slightly the stress level near the pith (+0.3%), but in combination with juvenile wood the impact is opposite (−20%). In hardwood, the maximal stress level is lower than in softwood, and is further reduced by the occurrence of juvenile wood (−11%) and viscoelastic relaxation (−8%).

It is also interesting to notice the positioning of weak points in bending within the cross-section. In a straight growing tree, weak points are always located at the periphery of the stem. For trees in reorientation process this is not always true (Fig. 3). For both simulated scenarios (hardwood and softwood), the weakest points in tilted trees were located in the area close to the pith that exhibited high levels of compressive pre-stresses. Consequently, if a tilted tree is submitted to a sudden change in curvature (e.g. because of wind), the failure would appear at first in compression close to the pith.



3: *Stress distribution and location of weak points in a hardwood (left) and in a softwood (right): section exhibits an important eccentricity (e = ± 2/3) with occurrence of juvenile and reaction wood; red areas represent maximal compressive stresses, green areas maximal tensile stresses*

Impact of viscoelasticity and juvenile wood occurrence on biomechanical performances of a tree in reorientation process

Table III shows biomechanical performances of trees in active reorientation process (high eccentricity and level of maturation strain). Simulation on a reference straight tree has pointed out that neither juvenile wood nor viscoelasticity have any influence on the stem flexibility because weak points are located on the periphery of the stem. For both softwoods and hardwoods, the up-righting efficiency is nearly the same and stem flexibility falls down due to the up-righting reaction. However in comparison to softwood the hardwood stem remains more flexible.

III: *Summary table of biomechanical performances*

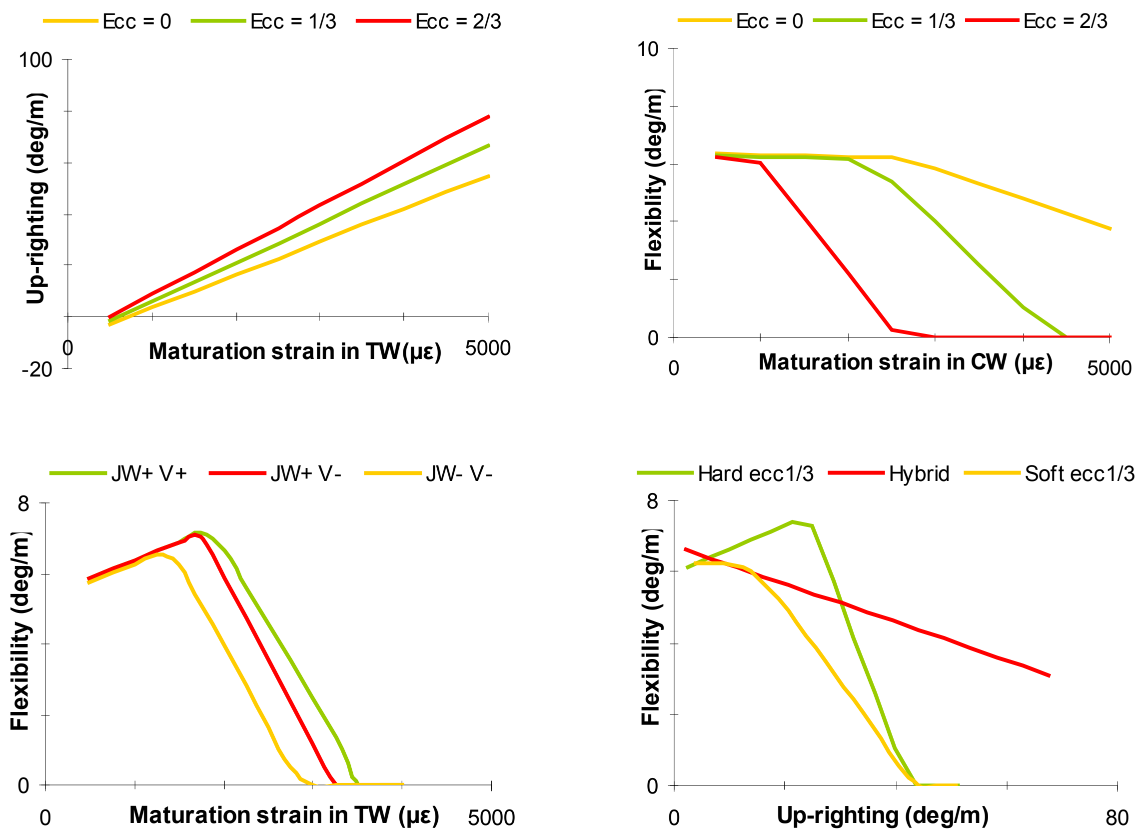
	Straight tree	Tree in a stage of intensive re-orintation			
	Soft/Hard	Softwood	Softwood (JW)	Softwood (V)	Soft. (JW + V)
Up-righting (deg/m)	0.0	31.1	30.1	38.0	35.2
Flexibility (deg/m)	7.69	0.0	0.17	0.00	0.24
		Hardwood	Hardwood (JW)	Hardwood (V)	Hard. (JW + V)
Up-righting (deg/m)		31.2	32.1	34.2	34.6
Flexibility (deg/m)		1.64	3.53	2.74	4.56

Legend: The same as for figure 2

Juvenile wood improves slightly (3%) the efficiency of the reorientation process in hardwoods, but has an opposite effect in softwoods. The increase of flexibility due to the juvenile wood is a direct consequence of the reduction of the maximal compressive stress in weak points. Because of the relaxation of the central part of the stem, viscoelasticity increases essentially the up-righting efficiency of both hardwoods and softwoods. It has also a positive impact on the hardwood flexibility. The combination of both factors is beneficial especially for the flexibility parameter.

The magnitude of maturation stresses in reaction wood and growth eccentricity has a proportional effect on the efficiency of the up-righting process (Fig. 4a). However if the reaction of the stem is too strong in term of maturation strain, the loss of stem flexibility is substantial (see Fig. 4c). The trade-off between flexibility and efficiency of the up-righting process seems to limit the magnitude of maturation strain to about 3000 με. Eccentric growth is a limit-ing factor especially for softwood stems (Fig. 4b). For a given eccentricity, the occurrence of juvenile wood combined with the viscoelasticity of wood allows the tree to use higher pre-stresses in reaction wood and consequently to speed up its reorientation process (Fig. 4c).

Finally, we tried to compare the efficiency of uprighting process of hardwood and softwood with a virtual specimen (Fig. 4d). This "hybrid" is able to produce both types of reaction wood (compression and tension wood) at the same time and avoid in this way the critical eccentric growth. Surprisingly, the flexibility of its stem is not significantly lower than for hardwood and is already higher than for softwood. We suppose that other disadvantages or natural limits may exist, explaining why we can not find this kind of behaviour in the nature.



4: *Effect of maturation strain of reaction wood on biomechanical performances. (a) Relationship between the maturation strain of tension wood (με) and the curvature induced by the reorientation process (ecc: index of eccentricity). (b) Relationship between the flexibility of a softwood stem and the maturation strain of compression wood for various values of eccentricity (c).Relationship between the stem flexibility and maturation strain of tension wood (with ecc = +2/3); (d) Relationship between flexibility and up-righting efficiency of a softwood, a hardwood and a hypothetical hybrid.*

SUMMARY

Accumulation of the growth stresses and efficiency of reorientation process were investigated through a model of a cross-section based on the beam theory. General description of the section geometry allows simulation of a general distribution of wood properties taking into account the growth eccentricity, the occurrence of juvenile and reaction wood and the viscoelasticity of wood tissues.

First observation that we could made was significantly higher level of pre-stresses in trees in reorientation process exhibiting eccentric growth compared to straight growing trees with circular section. Consequently, when submitted to external bending loads such as wind, so called weak points (points where the failure appear at first) were situated near the pith and not at the periphery of the stem as it was the case in the straight growing trees.

Occurrence of juvenile wood produced in earlier stages of a tree life revealed to improve the stem flexibility during the reorientation process. Due to the relaxation of the central part of the stem, vis-

coelasticity increased essentially the up-righting efficiency of trees in reorientation. Its impact on the stem flexibility was minor in softwoods but important in hardwoods. Set of simulations with increasing level of maturation strains in reaction tissues indicated possible trade-off between the stem flexibility and the up-righting efficiency.

Even if performed simulations have pointed out some interesting results, presented conclusions are heavily dependent on used parameters and in consequence need to be confirmed by using reliable experimental data especially for viscoelastic properties and yield stress in compression and tension.

SOUHRN

Biomechanické parametry stromů ve stadiu aktivní reorientace

Předložená práce se zabývá akumulací růstových napětí podél průřezu stromu ve fázi aktivní reorientace. Dynamika procesu reorientace je posuzována pomocí dvou kritérií: účinnosti vzpřimovací reakce a zůstatkové pružnosti kmene. Obecný popis geometrie průřezu a distribuce mechanických vlastností umožňuje modelovat excentrický růst, vliv výskytu juvenilního a reakčního dřeva a implementovat model viskoelastických vlastností dřeva.

Ve fázi aktivní reorientace jsou pletiva nacházející se v blízkosti dřeně vystavena vysokým tlakovým napětím (až čtyřnásobek maximálního tlakového napětí v rovně rostoucím stromu), která mohou vést ke vzniku vnitřních trhlin. Výsledky simulací ukázaly, že tvorba juvenilního dřeva v ranném stadiu růstu stromu má za následek zvýšení pružnosti kmene a tedy snížní rizika vzniku vnitřních trhlin jak u jehličnanů, tak u listnáčů. Pozitivní vliv viskoelasticity na pružnost kmene byl výrazný u listnáčů a téměř zanedbatelný u jehličnanů. Díky relaxaci růstových napětí ve středové části kmene má viskoelasticita kladný vliv na účinnost vzpřimovací reakce. Série numerických simulací reorientačního procesu s rostoucí úrovní růstových napětí v reakčním dřevu ukázala, že pravděpodobně existuje kompromis mezi účinností vzpřimovací reakce a zůstatkové pružnosti kmene.

reorientace stromu, pružnost kmene, účinnost vzpřimovací reakce, juvenilní dřevo, viskoelasticita

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