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Model of Surface Strain/Stress in a Tree Stem

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EXECUTIVE SUMMARY

Trees are submitted to mechanical forces throughout their lifetime. Loads can be either short-term, *e.g.* rock impacts or wind, or long-term, *e.g.* gravity. In both cases, mechanical loading has strong effects on the normal development of the tree and may contribute to the initiation of abnormal tissues such as compression wood. In order to evaluate those effects, it is necessary to first determine the type and magnitude of the loads applied during growth history to the cambial region, which is the thin layer where wood formation takes place.

This study is part of a series of models developed to mechanistically simulate the biophysical environment in which tree cambium develops.

A numerical model was developed to simulate mechanical stresses and strains that occur at the periphery of a tree stem as the tree grows. The model is based on the Finite Element Method, a common engineering approach used to study the behaviour of large mechanical structures. The method was adapted to account for the fact that the tree structure changes over time. The model was integrated to the ‘Mechanobiology of wood formation’ framework. Simulations were carried out using data provided by a process-based growth model, CABALA (CSIRO).

A mechanical model is available to predict growth stresses and strains occurring at the surface and also inside a single, growing tree stem. Such a model makes possible integrating mechanical influences into models of cambial growth and wood formation. Alternatively, the model may serve as a basis to study stability of standing trees or to predict warp caused by releasing growth stresses when stems are being processed.

INTRODUCTION

Like light environment or water and nutrients availability, mechanical forces shape the tree during its lifetime (Mattheck and Breloer 1995). Many types of mechanical loads apply to trees. Short-term loading will cause a temporary deformation of the tree structure. While the load magnitude can be high enough to cause an irreversible deformation, *e.g.* toppling, or structural collapse, *e.g.* uprooting, deformation will be elastic most of the time and the tree will return to its rest position. The loading can be said to be short-lived when the duration of load application is significantly less than that of cell maturation. Even though the stimulus does not last, cell growth can respond to transient mechanical loading (Braam 2005, Telewski 2006). The phenomemon is known as thigmomorphogenesis (Jaffe *et a*l. 2002). Tree growth response to the stimulus mainly consists of a temporary cessation of shoot elongation and an increased radial enlargement (Coutand and Moulia 2000, Telewski 2006). From a mechanical point of view, the key sensed variable is the longitudinal deformation in the cambial zone, the region where the wood is being formed (Coutand and Moulia 2000).

Long-term loading happens when load duration is similar or higher to that of cellular maturation. Cells thus form and develop under the direct, physical influence of such forces. This is the case of gravity for instance. A well-known adaptation to long-term loading is the formation of reaction wood in trees to re-orient shoots and minimize weight action. Telewski (2006) proposed a unified hypothesis in an attempt to present the morphological responses to both short- and long-term mechanical loads as being the same. The hypothesis mainly proposes that duration, intensity and frequency of the applied load are responsible for the observed differences in the nature of the growth response to mechanical stimuli. Another type of loading exists in trees and is endogenous, induced by the secondary growth process. Cells of normal wood tend to shrink when maturing. Because those cells are rigidly linked to previously formed (and dead) wood material, the deformation cannot freely take place, therefore inducing forces in the tree. Stresses associated with those forces are commonly referred to as growth stresses (Archer 1987, Okuyama *et al.* 1994).

Accounting for the mechanical environment of the cambium produces benefits such as an improved representation of the wood formation process with respect to both production rate and resource quality. Simulation of stresses accumulating during tree growth is also beneficial for better wood processing practices. Modelling tree mechanical behaviour can also contribute to wind risk management research.

This work presents a numerical model developed to handle the particularities of the tree structure. In a first phase, mechanical simulations were done assuming short-term loading of the tree. Then tree behaviour was simulated when submitted to the incremental loading of self-weight associated with growth. Finally, the action of maturation strains developing in the growing layer of material was included in the model, and test simulations were carried out.

Modelling the growth feedback to mechanical loading is not within the scope of this milestone. The present mechanical model was developed as a component of the *Mechanobiology of Wood Formation* modelling framework (Intensive Forest Systems, objective 2).

METHODS

Short-term mechanical loading

The Finite Element Method (FEM) is employed in order to calculate the mechanical response of a tree stem to an instantaneous load. The cambial surface is provided by the surface evolver component of the framework. The surface is transformed into a three-dimensional mesh of solid elements using routines already developed for the xylem transport model. Mesh is generated through Delaunay triangulation of the domain (Fig. 1). Alternatively, a bounding box can be defined by the user to extract a section only of the tree stem. The mesh representing the stem or the stem section is then translated to the input file format of ABAQUS (Simulia inc., Providence RI, USA), which is a commercial Finite Element code. Tests were carried out by applying compression on the top part of a stem section to simulate the effect of temporary snow loading. Of course, other load direction or magnitude can be specified.

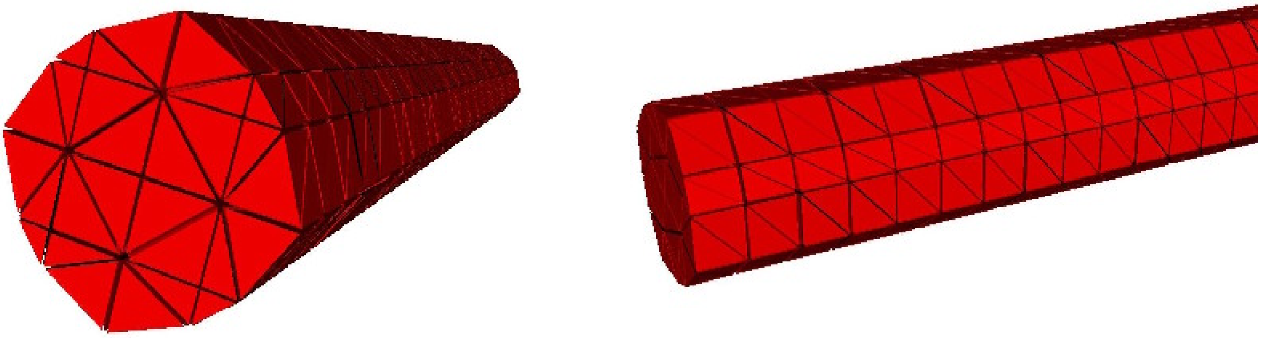

Figure 1: Delaunay triangulation of an idealised tree stem section: a) top view and b) side view.

Diagram 1 summarises the functions available with the mechanical component. The component can be invoked at the end of any growth cycle after radial enlargement has taken place. The duration of the growth cycles is a parameter dependent of the growth component, not the mechanical one.

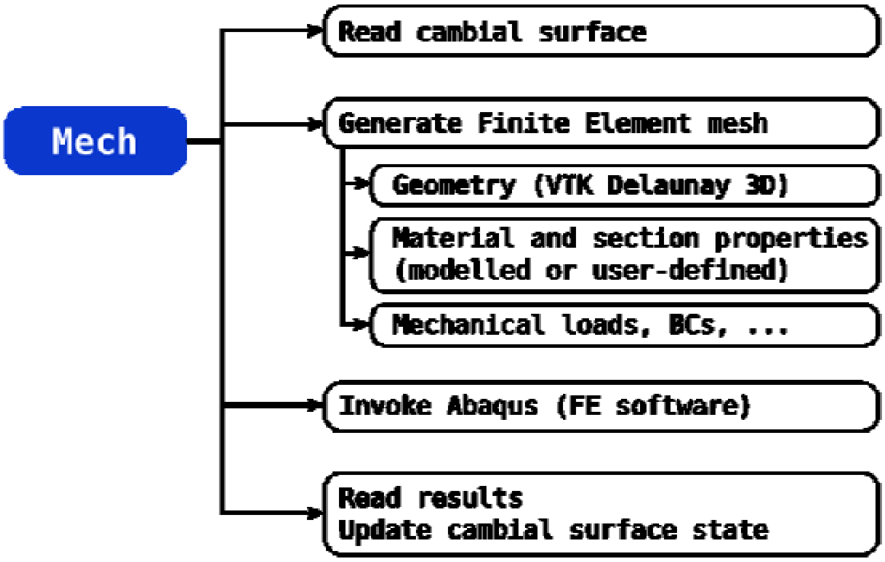

Diagram 1: Structure of the mechanical component (Mech) module

Long-term incremental loads – Self-weight and maturation

To simulate the effects of long-term loading on the tree structure, the FEM was adapted to deal with load increments associated with material produced during the last growth cycle. The approach used here is the incremental FE formulation proposed by Fourcaud and Lac (2003). Details are provided in the seminal paper and consequently are not reproduced here. Essentially, the equations of mechanical equilibrium are re-written as a function of displacement and force increments occurring at each growth cycle. Retrieving the current displacement/force at any point in the stem can be performed by cumulating the respective increments from the time of formation to the current simulation time.

Numerical simulations were carried out using a radiata pine growth scenario generated by CABALA (CSIRO). Stem and crown mass are among the growth data provided by CABALA at every step of tree growth. Due to the current lack of predictive models of wood properties in the *Mechanobiology* modelling framework, the stem material is assigned values that are issued from radiata pine literature and that are constant over the domain. It is by no mean sufficient to represent patterns of wood properties as they occur in real trees, but it is inconsequential for the development of the surface stress/strain model. Meshing was performed using the same tools as for short-term loads. The load cases of self-weight and maturation strain have been simulated separately. Calculations have been made on a 40-cm-long stem section centred at breast height. Stem weight above the considered section is taken into account. At each growth cycle, stress and strain increments calculated by ABAQUS are written to a .dat file which is parsed so increments can be stored in a grid available to all other modules of the modelling framework.

RESULTS

Short-term loading

Figure 2 shows vertical displacements under a) a compression load evenly applied at section's end, and b) volume forces as caused by gravity. Although not shown, deformations and stresses are also calculated. Of particular interest, b) shows a non-linear variation in displacement. This is because every infinitesimal volume in the log is submitted to its own weight and the weight of the column of material above itself. The associated deformations (derivative of displacement) and stresses (proportional to deformation over cross section area) vary linearly (not shown), increasing towards the fixed end of the stem section. This illustrates that, stress-wise, a cylinder of constant section is not as adapted to gravity loading as a tapered one. With an increasing section, diameter towards stem base would keep the stress constant over the length of the section.

a) **b)**

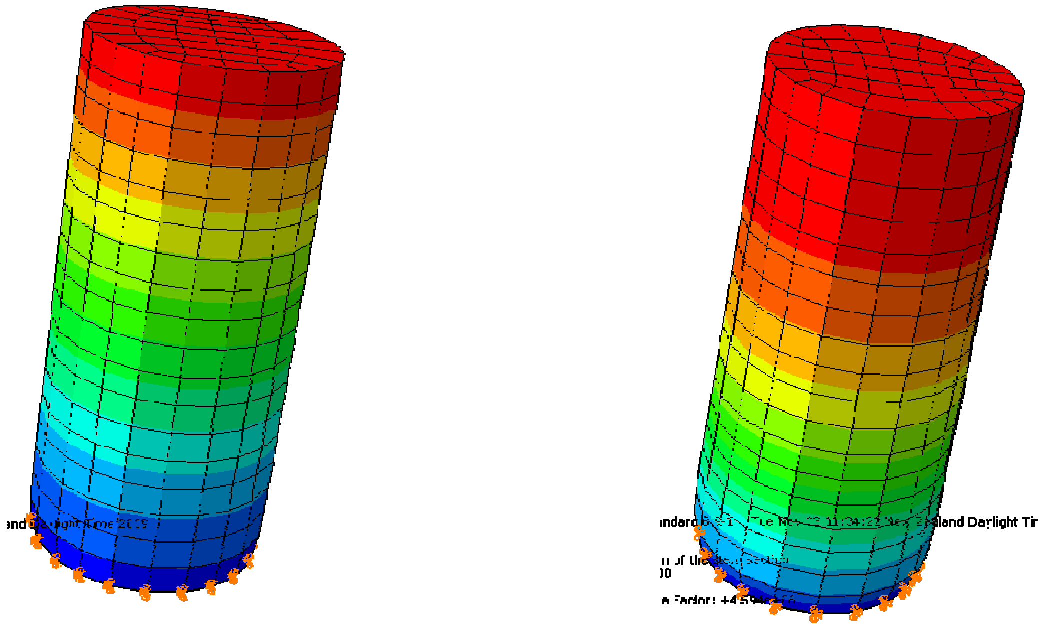

Figure 2: Longitudinal displacement caused by a) compression of section top face and b) gravitional loading. Displacement amplitude is indicated by the color scale, from null displacement (blue) at the bottom end where the stem section is fixed, to maximal displacement (red) at the free end.

As based on a full 3D description of the stem, the approach becomes computationally intensive for fully grown trees and/or trees described at high spatial resolution.

Self-weight

Figure 3 shows cumulated deformations and stresses in the stem cross-section at breast height of a 15-yr-old radiata pine. Profiles shown are representative of tree growth with a peripheral zone that is submitted to only the latest weight increment whereas the pith is submitted to all the successive weight increments since it was initiated. Given that no radial gradient in material properties was considered, the central area deformation peak is probably underestimated. The model would be able to describe that aspect if more precise patterns of wood properties were available.

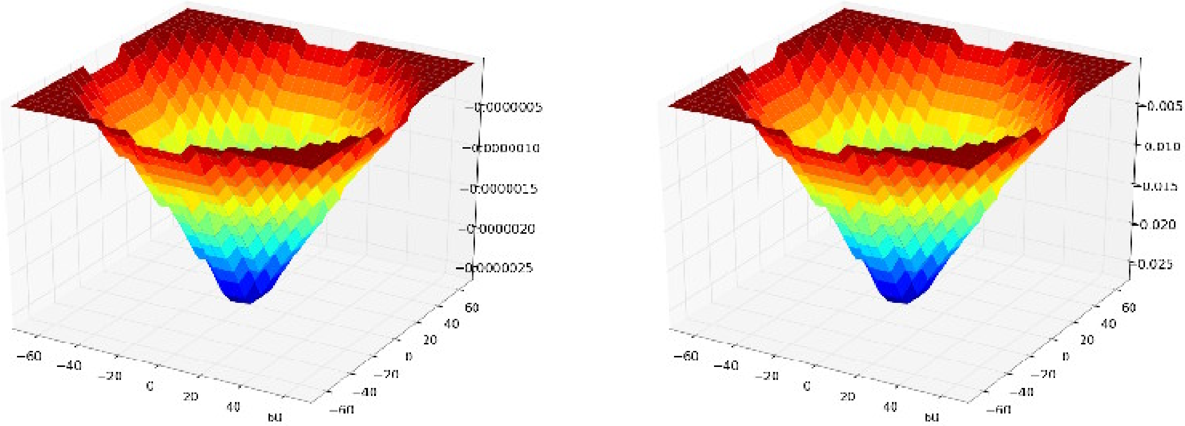

Figure 3: Cumulated a) deformations (x10^3) and b) stresses (GPa) in the stem cross-section at breast height. Profiles correspond to self-weight loading (weight of the stem only). X and Y axes correspond to coordinates (mm) in the stem cross-section.

Maturation strain

Figure 4 shows cumulated deformations and stresses calculated under the forces associated with cellular maturation in the cambial zone. Computations were performed until tree age reached 12 years. Maturation-induced strain and stress profiles are also characteristic of growth without development of reaction wood. Modelling the effect of compression wood (CW) can be done by assigning a different value of initial deformation to the material in the area where CW occurs.

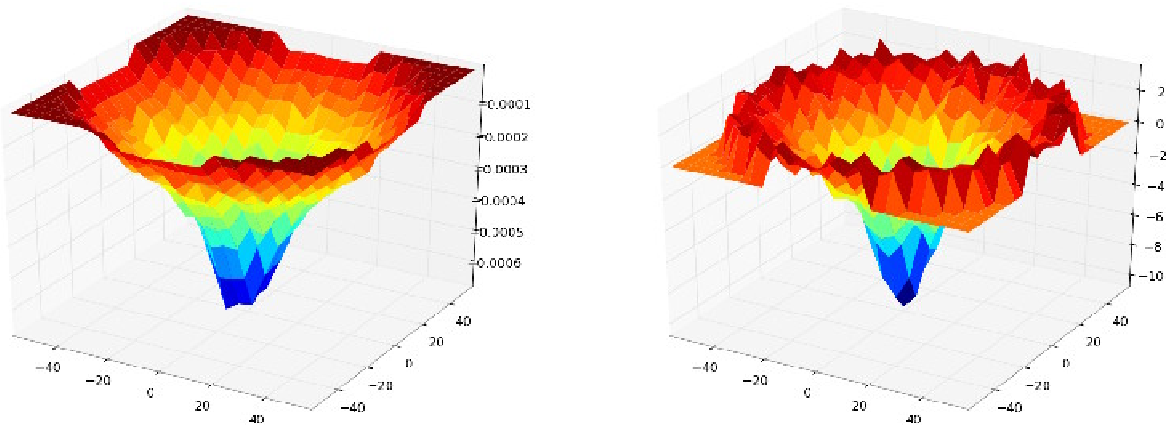

Figure 4: Cumulated longitudinal a) deformations (-) and b) stresses (Mpa) in the stem cross-section located at breast height under the action of forces induced by cell maturation. X and Y axes correspond to coordinates (mm) in the stem cross-section.

CONCLUSION

A mechanical model was developed to predict stress/strain acting at the periphery of a tree stem where new material is being accreted. The model can also predict stress/strain patterns within tree stems at high spatial resolution. Predicted quantities can be used as input to drive growth rate and wood properties models since mechanical environment is known to affect these.

Beyond benefiting wood formation models, the mechanical module could be employed to help in designing tools geared towards assessing wind risk in plantation forests, or to include the effects of growth stresses for appraising quality of products processed.

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