EVIDENCE OF CLIMATIC EFFECT ON VISCOELASTIC ORTHOTROPIC MATERIALS: NUMERICAL INVESTIGATION OF THERMO-HYDRO LODINGS ON EUROPEAN WOOD SPECIES

Seif-Eddine Hamdi, Rostand Moutou Pitti, Malick Diakhaté, Manja Kitek Kuzman

EVIDENCE OF CLIMATIC EFFECT ON VISCOELASTIC ORTHOTROPIC MATERIALS: NUMERICAL INVESTIGATION OF THERMO-HYDRO LODINGS ON EUROPEAN WOOD SPECIES

Seif Eddine HAMDI
Université Clermont Auvergne, CNRS, Institut Pascal, F-63000 Clermont-Ferrand, France
E-mail: seif3eddine@yahoo.com

Rostand MOUTOU PITTI
Université Clermont Auvergne, CNRS, Institut Pascal, F-63000 Clermont-Ferrand, France
E-mail: rostand.moutou_pitti@uca.fr
CENAREST, IRT, BP 14070, Libreville, Gabon

Malick DIAKHATE
Université Bretagne Occidentale, FRE CNRS 3744, IRDL, F-29600 Morlaix, France,
E-mail: malick.diakhate@univ-brest.fr

Manja KITEK KUZMAN
University of Ljubljana, BF, Department of WST, Slovenia
E-mail: Manja.Kuzman@bf.uni-lj.si

Abstract

The mixed mode configurations coupling mechanical, hydric and thermal effects for viscoelastic orthotropic materials like wood is studied. The numerical application are proposed on european species (Abbie Miles alba). The analytical formulation of the energy release rate is introduced by A integrals generalized to mixed mode crack growth. The viscoelastic effects are introduced according to the generalized Kelvin Voigt model. This new formulation is based on conservation laws and real and virtual mechanical and thermal fields. The Mixed Mode Crack Growth specimen, providing the decrease of energy release rate during crack propagation, is considered in order to compute the various mixed mode ratios. The analytical formulation is implemented in finite element software Cast3m and the crack growth is obtained by testing the Griffith criterion rewritten in time domain under orthotropic configuration. As results, the evolution of energy release rate and the stress intensity factors versus crack length and hydric variations are computed for the proposed european wood species.

Key words: *mixed mode fracture; viscoelasticity; environnemental effects; european species.*

INTRODUCTION

Currently, worldwide, and arguably European industries, are showing increasing interest in wood based structures. Economic and environmental contexts have enabled the emergence of new markets for green constructions that have thus far been confined for steel and concrete based structures. The work on improving the mechanical properties of a tropical wood species, such as Okume (Aucoumea klaineana), Iroko (Milicia excelsa) and Padouk (Pterocarpus soyauxii) arguably offers many advantages, including lower cost and environmental impact (Nziengui et al. 2017). The benefits may also include energy savings, renewability of the resource, reducing the content of raw fossil materials and recycling (Odounga et al. 2017). However, wood materials also present drawbacks, such thermal and hydric sensitivity and multi-feature heterogeneity, compared with conventional civil engineering structures as steel and concrete. Fundamentally, the full potential of wood-based materials has still not been completely exploited because the relationships between fracture parameters at the microscale and macroscale behavior remain poorly described or integrated.

For civil engineering construction, wood is a traditional material that has been widely used for various types of structures. For example, there are about 27,000 timber bridges over a total of 40,000 bridges in Australia (Ranjith et al. 2011). By observing historical buildings around the world, it can be seen that wood-based structures guarantee a long-term service life with a high durability level. However, in timber structures, cracking initiation and propagation are frequently recognized as main causes leading to structural failure (Riahi et al. 2016). Mechanical behaviors of cracked timber structures are affected by environmental conditions: moisture, temperature, etc. These hydrothermal conditions could produce a higher risk of crack growth in timber structures (Dubois et al. 2009). The fracture studies in wood structure therefore should take into account these environmental conditions.

Wood is considered as an orthotropic hydro-mechanical material whose mechanical behavior strongly depends on the moisture content and the temperature. Taking into account humidity and temperature variation, the mechanical behavior assessment becomes more complex due to the coupling effect between the mechanical stress and the hydric state (thermos-hydro-mechanical behavior (THM)) (Moutou Pitti et al. 2009; Hamdi et al. 2009). The viscoelastic behavior of wood under variable humidity, known as the mechano-sorption behavior, induces different responses in the drying and in the humidification phase. However, in presence of climatic variations, the long terms load and especially the crack initiations, the mechanical behavior of wooden structures is found highly modified, disturbing their implementation and shortening their life in service. The effects of moisture changes on the propagation of cracks are not yet clearly identified. Therefore, it appears necessary to investigate the influence of the variable environment and crack growth process on the mechanical properties of wood structures.

Subsequent research has been performed by employing finite element calculations to determine the fracture mechanics parameters for a variety of wood species and for different grain orientations. Moutou Pitti et al. (2007a,b), showed that at least some of the assumptions underlying the use of the linear elastic fracture mechanics for wood, namely, the assumption of plane strain, and orthotropic and linear viscoelastic behavior, may be considered valid for wood characterization. However, very few studies were found in the literature on the development and the analysis of cracking process during the variation of temperatures and moisture in wood-based materials (Tjeerdsma et al. (1998); Triboulot et al. (1984); Popovic et al. (2006)). In this paper, a numerical analysis of a thermal expansion effect on crack growth in a wooden plate is discussed by using energetic approach. In the first section, the mathematical formulation of the invariant integrals, based on a conservative law approach, is introduced. A combination of real and auxiliary displacement fields (Noether (1971)), is employed in order to isolate different fracture modes by introducing a generalization of the virtual work principle. The Noether's theorem is used to define the general form of the A-integral. The generalization for a viscoelastic behavior is proposed in the second section. The numerical solution is based on a viscoelastic crack growth algorithm which computes step by step the viscoelastic response, the separation of the energy release rate and the crack growth process by remeshing. According to finite element method, the time domain resolution is given by the proposed algorithm. Finally, a numerical validation, based on a MMCG specimen under temperature and moisture variations, is presented. Results are presented in terms of a parametric analysis of the energy release rate evolutions versus time, during the crack tip advance, for different mixed-mode configurations in european and tropical wood samples.

MATERIAL AND METHOD

Numerical analysis and A-integral formulation

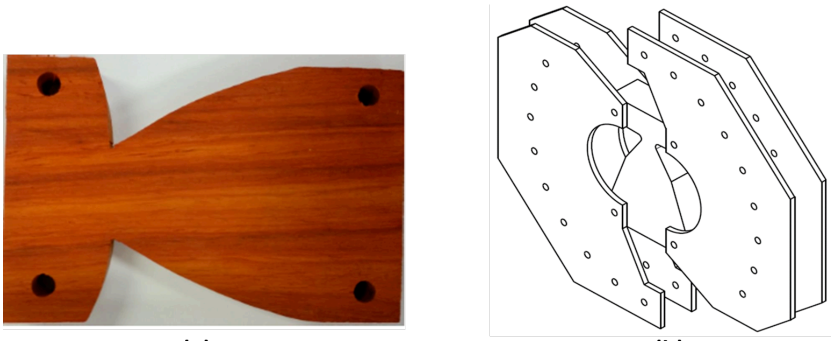
The formulation of the A-integral is based on the analytical work developed by Moutou Pitti et al. (2010), for mechanical and thermal loadings effects estimation. Considering a two-dimensional cracked volume $\mathbf{\Omega}$ with a rectilinear crack of length a, subjected to external loads σ^{∞} and γ^{∞}, applied far from the crack, and Γ a path which surrounds the crack tip oriented by the normal $\vec{n}$ of component $n_j, (\mathrm{j} = 1,2)$. With these considerations, according to Lagrangian Euleurian hypothesis (Donea et al. (1982)) and conservative laws (Noether (1971); Bui (2007)), in stationary crack, the A-integral is given by Moutou Pitti et al. (2010):

$$A = \int_{\Gamma} \frac{1}{2}\left[\sigma_{ij,k}^{v}\, u_i - \sigma_{ij}^{u}\, v_{i,k}\right]\theta_{k,j} dS - \int_{\Gamma} \frac{1}{2}\left[\gamma \vartheta_i \delta_{ij} v_{i,jk} \Delta T_{,j}\right]\theta_{k,j} dS + \int_{L} \frac{1}{2} F_i\, v_{i,j}\, \theta_j dx_1$$

where σ_{ij}^{u} and σ_{ij}^{ϑ} are stress tensor components deduced from the real displacement field u and the virtual displacement field ϑ, respectively. $F_1 = p$ and $F_2 = q$ on the upper lip and $F_1 = -p$ and $F_2 = -q$ on the lower lip. The first term of the A-integral is the classical term of the Mθ-integral which facilitate the separation of the contribution of each fracture mode, without resorting to separate the displacement field into a symmetric and antisymmetric parts. The second term of the A-integral deals with the temperature effect, including temperature gradients inducing thermal dilatation and contraction. The last term of the A-integral represents the effect of pressures p and q applied perpendicularly to the cracked lips. Note that, the mechanical load applied on the cracked lips can be induced by fluid action or contact between the crack lips during the crack growth process. The only restriction is the non-existence of friction or shear effects in the cracked lips.

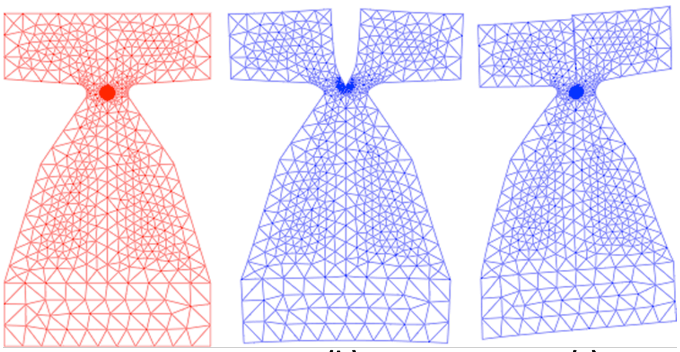
Mixed Mode Crack Growth specimen

The MMCG specimen of tropical wood sample presented in Fig 1a, is a combination of wood CTS specimen developed by DCB specimen Moutou Pitti et al. (2010), is used in order to obtain different mixed mode ratios and crack growth stability. The MMCG design stability is obtained by proposing a variable section. However, the geometry must concentrate the stress singularity around the crack tip in order to obtain an initial instability by using the arcan device, as depicted in Fig 1b. The numerical analysis is performed under plane stress conditions and based on the finite element mesh depicted in Fig 2a. For the numerical simulations, the A-integral method is implemented in the finite element software Cast3m (Cast3m (2010)). The external load is a creep loading applied to a perfect rigid arm with a chosen initial crack length of 40 mm is chosen. Points A_α and B_α with α = (1...7) are holes where forces can be applied with the angle β oriented according to the trigonometrically direction for different mixed-mode ratios. The pure opening mode is obtained by applying opposite forces in $A_1$and $B_1$with $\beta = 0^{\circ}$, as shown in Fig 2c. In the same way, loading points A_7 and B_7, with loading angle $\beta = 90^{\circ}$, are employed in order to impose a pure shear mode, as depicted in Fig 2c. Intermediate positions induce different mixed mode ratios.



(a) (b)

Fig. 1.
(a) MMCG wood specimen – (b) Modified Arcan fixture



(a) (b) (c)

Fig. 2.
(a) Finite elements mesh of the MMCG specimen – (b) Virtual displacements for opening mode – (c) Virtual displacements for shear mode

RESULTS AND DISCUSSION

Crack growth analysis under thermal loads

Considering physical phenomena inducing wood structures expands as the temperature rises, and restraint against contraction on subsequent cooling, cracks formation and development are initiated by various crack driving forces. In fact, when the crack became stable and had to be induced to propagate beyond it, this implied that the stable crack tip had been arrested at a zone of high toughness; in order to propagate further, the crack preferred the path of the least resistance, which bypasses the tough zone. Then, it is necessary to quantify the crack driving mechanisms such as temperature level and crack growth speed.

The simulation of a temperature dilatation effect on the energy release rate versus the crack growth speed and crack tip advance during mechanical loadings. the analysis deals with crack growth behavior during the heating process. Fig 3a and Fig 3b show the variation of energy release rate versus time and different crack tip advance for mixed mode during the heating process $(\Delta T = +20^{\circ} C)$ under creep loadings. The initial crack length is fixed to 40 mm. Successive cracks increments of $\Delta a = 1\ mm$ and $\Delta a = 8\ mm$ have been chosen and conducted up to a final crack length of $112\ mm$. In order to examine the uncoupling process, the simulation is limited to a mixed-mode configuration $(\beta = 45^{\circ})$. According to past simulations, the loading is constant with unitary opposing forces. For next results, the integration domain is based on crown C_6. The indicated time designates the corresponding simulations are proposed for different constant crack tip speed characterized by the imposed time increment step as shown in Fig 11. The results of part of the open mode presented in Fig 3a in terms of energy release rate versus time increment, shows that under higher temperature expansion a slow crack step advance leads to a higher crack driving force. Moreover, part of the shear mode presented in Fig 3b, shows a relative stability of energy release rate evolution over time, which illustrate the effect of a thermal expansion process in a progressive incohesion of cracked lips around the crack process zone.

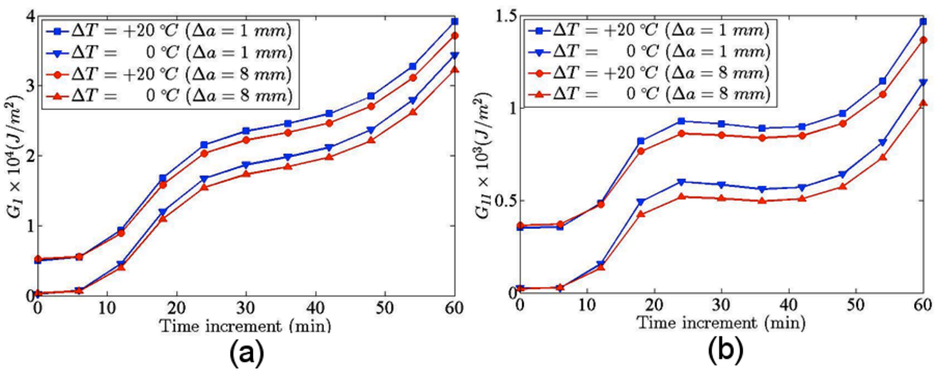


Fig. 3.
Energy release rate versus time and different crack tip advance (Δa =1 mm and Δa =8 mm), for mixed mode during heating process (ΔT =+20°C): Open mode part (a), Shear Mode part (b)

Crack growth analysis under hydrics loads

The analysis of cracks propagation of in mixed mode coupling the mechanical and moisture loads in the wood via the MMCG sample is carried out using an incremental finite element approach using the A- integral. This fact simultaneously leads to the possibility of separating the rupture process and the viscoelastic effect. The hydric fields calculated in the elastic phase before crack propagation are projected on the MMCG mesh in order to calculate the cohesion stress which incorporates this time a selected humidity variation. It should be noted that the viscoelastic procedure is applied before the next moisture step is taken into account and the cracking parameters in terms of viscoelastic energy release rate (G) are evaluated at each step until the test piece is ruined. The effect of Thermo-Visco-Hydro-Mechanical Load Coupling is observed in the wood material for all mixed mode configurations. In this case, Fig. 4a and 4b show the evolution of energy release rates in opening mode (GI), and shear mode (GII) as a function of crack length, for different moisture levels and different mixing rates using the invariant integral A. We note initially, a gradual growth of the development zone (growth phase of energy release rates) and, in a second phase, a stationary phase with a stabilizing changing release rate 'energy. More precisely, we observe, a higher rate of energy restitution for the mode II part (G_II), indicating that the cracking phenomenon is driven by this mode. It's to be noted that G increases in proportion to the moisture content with a higher proportion for ΔT = 30 °C.

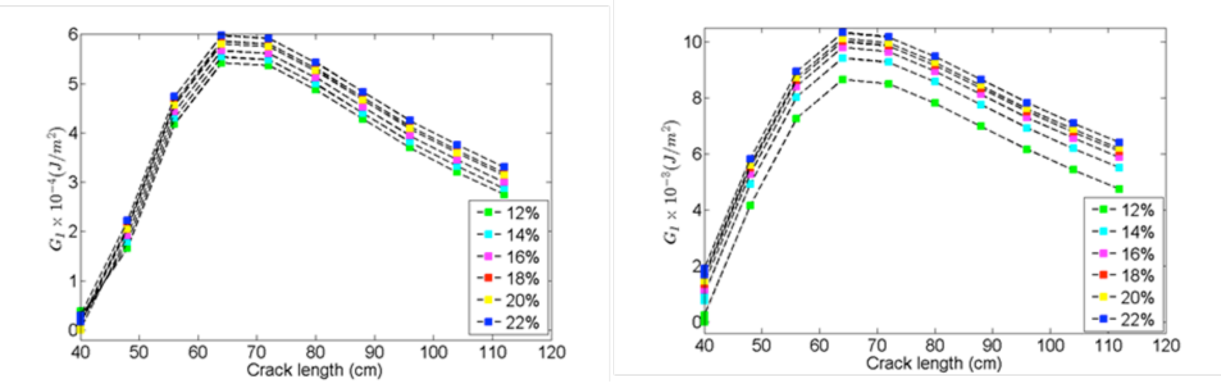


Fig. 4.
Effect of variation in moisture content (MC) on energy recovery rate (G) versus crack length: ΔT = 10 °C (a), ΔT = 30 °C (b).

CONCLUSIONS

This work attempted to numerically investigate the influence of temperature and moisture on crack driving forces of wood-based materials. An analytical formulation of the A-integral for mixed mode fracture separation in viscoelastic media was used. Crack driving forces are then estimated. Due to large differences in the conditions under which temperature and moisture levels can be compared and the variety of wood species, relaxation effects can be observed through the energy release rate evolution versus crack growth process. Then, it was possible to show a general trend, but not a universally valid description to what extent the wood behavior will change at a certain temperature level and what the impact is on the occurrence and development of cracks in wood subjected to thermal and hydrics loadings. In general, it could be concluded that thermo-hydro variation has a greater effect on the reduction of the mechanical proprieties of wood-based materials. However, a critical energy release rate that causes structurer failure and enhance crack growth dramatically, could not be stated, due to the time dependence behavior during wood heating and cooling, but also, no doubt, due to wood species behavior. An experimental procedure is planned in order to validate the numerical analysis. This procedure allows to measure the impact of Thermo-Hydro-Mecanical lodings on the structural collapse. In the end, all data obtained will be compared with results of the numerical model. Comparison of the results will help to refine the analytical and numerical models, and thus to extend their application to other types of wood species such as tropical wood.

ACKNOWLEDGEMENT

The authors wish to strongly acknowledge the National Agency of Research (ANR) for its financial support of this work through the project CLIMBOIS N◦ ANR-13-JS09-0003-01 labeled by ViaMeca.

REFERENCES

Bui H D, (2007) Conservation laws, duality and symmetry loss in solid mechanics. International Journal of Fracture 147; 163–172.

Cast3m, 2010. Cea / lams - scalay.

Donea J, Giuliani S, Halleux J, (1982) An arbitrary lagrangian-eulerian finite element method for transient dynamic fluid-structure interactions. Computer Methods in Applied Mechanics and Engineering 33; 689–723.

Dubois F, Moutou-pitti R, Husson J (2009) Thermodynamic approach about fracture modeling under mechano-sorptive loading. SEM Annual Conference, New Mexico, USA.

Hamdi S, Moutou Pitti R, Dubois F (2017) Temperature variation effect on crack growth in orthotropic medium: Finite element formulation for the viscoelastic behavior in thermal cracked wood-based materials. International Journal of Solids and Structures 115–116: 1-13.

Moutou Pitti R, Dubois F, Petit C (2010) Generalization of T and A integrals to time-dependent materials: analytical formulations. International Journal of Fracture 161: 187-198.

Moutou Pitti R, Dubois F., Petit, C., Sauvat, N., (2007a). Mixed mode fracture separation in viscoelastic orthotropic media: numerical and analytical approach by the Mθ-integral. International Journal of Fracture 145: 181-193.

Moutou Pitti R, Dubois F, Pop C, Sauvat N, Petit C. (2007b) Mv-integral for the crack growth in a viscoelastic media. Comptes Rendus Mécanique 335: 727–731.

Noether E, (1971) Invariant variations problem. Transport Theory Statistical Physics 1; 183–207.

Nziengui C, Ikogou S, Moutou Pitti R (2017) Impact of cyclic compressive loading and moisture content on the mechanical behavior of Aucoumea Klaineana Pierre. Wood Material Science & Engineering 1-7.

Odounga B, Moutou Pitti R, Toussaint E, Grediac M (2017) Experimental Fracture Analysis of Tropical Species Using the Grid Method. Springer International Publishing 8: 9-14.

Popovic Z, soskic B, Miris M. (2006) Effect of moisture and temperature on some mechanical properties of beechwood. Conference of Wood structure and Properties, Zvolen, Slovakia.

Ranjith S, Setunge S (2011) Deterioration Prediction of Timber Bridge Elements Using the Markov Chain. Journal of Performance of Constructed Facilities 27: 319-25.

Riahi H, Pitti RM, Dubois F (2016) Mixed-mode fracture analysis combining mechanical, thermal and hydrological effects in an isotropic and orthotropic material by means of invariant integrals. Theoretical and Applied Fracture Mechanics. 85: 424-434.

Tjeerdsma B, Boonstra M, Pizzi A, Tekely P, Militz H. (1998) Characterisation of thermally modified wood: Molecular reasons for wood performance improvement. Holz als Roh- und Werkstoff 56; 149–153.

Triboulot P, Jodin P, Pluvinage G. (1984) Validity of fracture mechanics concepts applied to wood by finite element calculation. J. Wood Science Technol 18; 51–58.