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Numerical investigation of climate change impacts on European wood species vulnerability

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Abstract

Moisture levels are considered as a critical environmental impacting factor for wood and its components, as the moisture content (MC) influences virtually all the physical and mechanical properties. Adsorbed moisture is known to cause significant dimensional changes, as well as changes in mechanical properties such as the modulus of elasticity, stress factors and brittleness. In green wood, water droplets moved away from the cell lumens around the crack tip. Drying of wood induces micro-cracking and crack bridging as toughening mechanisms. To quantify the effect of humidity, fracture patterns and properties at various moisture levels are numerically investigated. Finite element simulations were performed on a modified Douglas Mixed-Mode Crack Growth specimen (MMCG). The crack growth process as well as the opening crack under temperature and moisture variations were calculated under various mixed mode ratios, and mixed modes energy release rates were evaluated. The distributed damage patterns in the most stressed regions between the area where concentrated force is applied and the notch plane where the fracture initiates is also taken into account in this study.

Keywords: Fracture mechanisms; moisture; finite element analysis; numerical modelling; solid wood.

1. 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

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thus far been confined for steel and concrete based structures. The work on improving the mechanical properties of wood based materials, 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. 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.

Moisture damage driven failure in wood based-structures is commonly induced by micro-cracks occurring under repeated moisture cycles loadings. In fact, combining with mechanical solicitations as fatigue, overload or creep loading, the environmental actions like hydric or temperature play an important role in the propagation of these micro-cracks in the material.

To predict the crack growth process, many numerical methods were developed to characterize the mechanical fields around the crack tip. The most popular is the J-integral proposed by Rice (1968), based on the assessment of the strain energy density and Noether's theorem (Noether et al. 1918). This method is inefficient when dealing with mixed mode crack growth problems because it is necessary to separate the displacement field into a symmetric and antisymetric parts. To circumvent this difficulty, Chen and Shield (1977), have developed the M-integral in order to separate fracture modes based on a bilinear form of the strain energy density with virtual mechanical fields.

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. (2010); Hamdi et al. (2017)]. 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.

In recent work, a new analytical formulation of A-integral developed by Moutou Pitti et al. (2010), and implemented in finite element software for moisture effects investigation by Hamdi et al. (2017), is proposed. This formulation takes into account the viscoelastic behaviour, the effects of thermal load, induced by temperature variation, and complexes boundaries conditions, such as contact between crack lips during crack growth process.

This paper deals with the effect of Moisture Content (MC) variation in mixed mode configuration using non-dependent integral approach in room temperature. The first part of this paper deals with the mathematical formulation of the invariant integrals T and A taking into account. Simultaneously, the energy release rate in mixed mode is proposed according to the real and virtual stress intensity factors. In the second section, the background of Mixed Mode Crack Growth (MMGC) specimen is proposed. The last section proposes the numerical routine and some results of viscoelastic energy release rate versus moisture content evolution in wood material.

2. Materials and methods

2.1. Mixed-mode fracture 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. In order to implement the A-integral in a FEA software, it is easier to take into account a surface domain integral. Within this context, the curvilinear path is transformed into surface domain by introducing a vector field $\vec{\theta}$. This mapping function is continuously differentiable and takes these values: $\vec{\theta} = (1, 0)$ inside the ring **S**, and: $\vec{\theta} = (0, 0)$ outside it. Hence, the use of the Gauss-Ostrogradsky theorem (Hamdi et al. (2017)), enables us to obtain the following A-integral given by:

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

where $F_1 = p$ and $F_2 = q$ represent the loads applied to the upper crack edge, and $F_1 = -p$ and $F_2 = -q$ the loads applied to the lower crack edge. 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. θ is a continuous and derivable scalar field. It forms a crown around the crack tip. The factor γ introduces the elastic modulus versus temperature variation ΔT in plane strain. For the orthotropic material, the value of γ depends on the direction of the material, since the engineering constants are not the same for all directions. δ is the Lagrangian representation of the bilinear form of strain energy density. The first term of eq **Erreur ! Nous n'avons pas trouvé la source du renvoi.** is the classical term of the Mθ-integral (Moutou Pitti et al. (2010)), which facilitates the separation of the contribution of each fracture mode, without resorting to separate the displacement field into 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, where L_p is the integration path. 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.

In the orthotropic case, the mechanical behavior of an anisotropic material is described by the stress-strain relationship $\epsilon_i = \sum_j E_{ij}\, \sigma_{ij} + \sum_j \alpha_i\, \Delta T$, where E_{ij} are the contracted notations of the compliance tensor S_{ijkl} that depend on modulus and Poisson coefficients in longitudinal, transversal, radial directions; and α_i are thermal expansion coefficients in longitudinal (α_1) and transversal (α_2) direction of wood. In the case of two-dimensional anisotropic elasticity problems, the components ϑ_1 and ϑ_2 of the near tip displacement field are expressed as (Moutou Pitti et al. (2010)):

$$\vartheta_1 = K_I \sqrt{\frac{2r}{\pi}}\, \Re\left[\frac{1}{\mu_1 - \mu_2}\left(\mu_1 p_2 \sqrt{cos\,\varphi + \mu_2\, sin\,\varphi} - \mu_2 p_1 \sqrt{cos\,\varphi + \mu_1\, sin\,\varphi}\right)\right]$$
$$+ K_{II} \sqrt{\frac{2r}{\pi}}\, \Re\left[\frac{1}{\mu_1 - \mu_2}\left(p_2 \sqrt{\cos\varphi + \mu_2 \sin\varphi} - p_1 \sqrt{\cos\varphi + \mu_1 \sin\varphi}\right)\right] \quad (2)$$

$$\vartheta_2 = K_I \sqrt{\frac{2r}{\pi}}\, \Re\left[\frac{1}{\mu_1 - \mu_2}\left(\mu_1 q_2 \sqrt{cos\,\varphi + \mu_2\, sin\,\varphi} - \mu_2 q_1 \sqrt{cos\,\varphi + \mu_1\, sin\,\varphi}\right)\right]$$
$$+ K_{II} \sqrt{\frac{2r}{\pi}}\, \Re\left[\frac{1}{\mu_1 - \mu_2}\left(q_2 \sqrt{\cos\varphi + \mu_2 \sin\varphi} - q_1 \sqrt{\cos\varphi + \mu_1 \sin\varphi}\right)\right] \quad (3)$$

where (r, φ) represents the polar coordinate system of a point P_n in the neighborhood of the crack tip. k is a coefficient such as $k = 3 - 4\,\vartheta$ in plane strain and $k = \frac{3-4\,\vartheta}{1+\,\vartheta}$ in plane stress. μ_1 and μ_2 designate the roots of the characteristic equation, which is given in the following general form, in the case of elastic anisotropic material:

$$\mathrm{E}_{11}\mu^4 - 2\,\mathrm{E}_{16}\mu^3 + (2\,\mathrm{E}_{12} + \mathrm{E}_{66})\mu^2 - 2\,\mathrm{E}_{26}\mu + \mathrm{E}_{22} = 0 \quad (1)$$

The parameters p_j and q_j, $(j = 1{,}2)$ in eqs. **Erreur ! Nous n'avons pas trouvé la source du renvoi.** and **Erreur ! Nous n'avons pas trouvé la source du renvoi.** are given respectively by:

$$p_j = E_{11}\mu_j^2 + E_{12} - E_{16}\mu_j \text{ and } q_j = E_{12}\mu_j + \frac{E_{22}}{\mu_j} - E_{26} \quad (2)$$

Knowing the material properties, the singular stress field near the crack tip can be easily obtained from the near tip displacement field defined by equation **Erreur ! Nous n'avons pas trouvé la source du renvoi.**, and the stress-strain governing the mechanical behavior of the material.

According to the definition of the energy release rate G, the superposition principle (Hamdi et al. 2017), the virtual stress tensor components σ_{ij}^v are proportional to the virtual thermal stress intensity factors ${}^AK_I^v$ and ${}^AK_I^v$, which characterize the virtual open and shear modes, respectively. Moreover, the A-integral, like the M-integral, can be physically interpreted as a particular definition of real stress intensity factors ${}^AK_I^u$ and ${}^AK_{II}^u$. The mixed-mode separation can then be obtained by performing two distinct computations of ${}^AK_I^u$ and ${}^AK_{II}^u$ for special values of ${}^AK_I^v$ and ${}^AK_I^v$, such as:

$${}^AK_I^u = 8\frac{A\left({}^AK_I^v = 1, {}^AK_{II}^v = 0\right)}{C_1}; \quad {}^AK_{II}^u = 8\frac{A\left({}^AK_I^v = 0, {}^AK_{II}^v = 1\right)}{C_2} \quad (6)$$

where C_1 and C_2 indicate the reduced elastic compliances in the opening and shear modes, respectively. The thermal energy release rates, in each specific fracture mode ${}^AG_I$ and ${}^AG_{II}$, are ultimately given by the following expression:

$${}^AG_I = C_1\frac{\left({}^AK_I^u\right)^2}{8} \quad \text{and} \quad {}^AG_{II} = C_2\frac{\left({}^AK_{II}^u\right)^2}{8} \quad (7)$$

${}^AG_I$ and ${}^AG_{II}$ will be used in section **Erreur ! Nous n'avons pas trouvé la source du renvoi.** in the reliability analysis to determine the probability of failure.

2.2. Mixed-mode crack growth specimen

The MMCG specimen of 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. The numerical analysis is performed under plane stress conditions and based on the finite element mesh depicted in Fig 1(a-c). For the numerical simulations, the A-integral method is implemented in the finite element software Cast3m. 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 Aα and Bα 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 A1 and B1 with β=0°, as shown in Fig 1(b). In the same way, loading points, with loading angle β=90°, are employed in order to impose a pure shear mode, as depicted in Fig 1(c). Intermediate positions induce different mixed mode ratios.

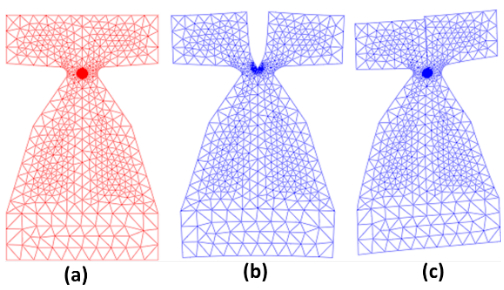

Fig. 1. (a) Finite elements mesh of the MMCG specimen; (b) Virtual displacements for opening mode; (c) Virtual displacements for shear mode.

3. Results and discussion

Considering physical phenomena inducing wood structures restraint as the moisture rises, and expands against contraction on subsequent heating, 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 moisture level and crack growth speed.

The experimental setup is composed of a wooden specimen with an Arcan steel system (the set constitutes the Mixed-Mode Crack Growth or MMCG specimen under moisture loadings, is simulated by finite elements model. The analysis of cracks propagation in mixed mode coupling the mechanical and moisture loads via the MMCG sample is carried out using an incremental finite element approach based on 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.

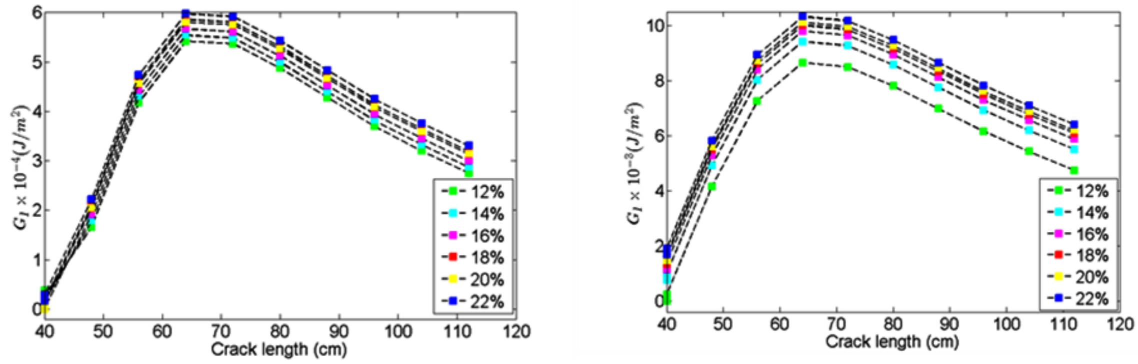

Fig. 2. Evolution of GI (a) and GII (b) versus crack length for different moisture variation.

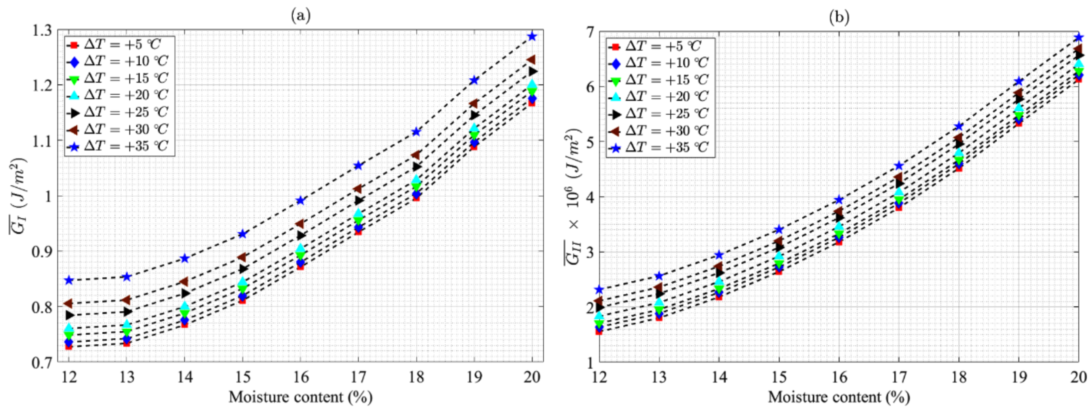

Fig. 3. Evolution of GI (a) and GII (b) versus moisture content for different temperature variation.

The effect of Thermo-Visco-Hydro-Mechanical Load Coupling is observed in the wood material for all mixed mode configurations. In this case, Fig. 2(a) and Fig. 2(b) 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. The effect of moisture variation on mixed modes energy release under temperature variation is depicted in Fig. 3(a) and Fig. 3(b). Results show important information about the influence of moisture content on fracture toughness of this tropical wood specie in constant and variable environments. More precisely, we observe, a higher rate of energy restitution for the mode II part (GII), 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 $\Delta T = 30$ °C.

4. Conclusion

This work attempted to numerically investigate the influence 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 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.

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