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STUDY OF THE MECHANICAL BEHAVIOR AND MULTISCALE SIMULATION OF THE CRACK PROPAGATION IN A BILINGA WOODEN BEAM

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The mechanical behavior of local wood species (Bilinga) in the south west region in Cameroon during rainy and dry seasons and the mechanical behavior of wooden beam under bend loading are studied. The three points flexural tests were used to determine the mechanical properties of the wood under study. ANSYS 2020 R1 finite element (FE) software is used for numerical simulations at a macroscopic level using one of the newer technologies called Smart crack growth, which was introduced in the 2019 version. The geometry was modeled in SolidWorks with an initial crack length of 4 and 8 mm introduced in each sample and then imported to ANSYS workbench for further analysis with ANSYS which has all the tools to perform linear fracture. The stress intensity factor (SIF) determines the fracture toughness of a material which is subjected to linear-elastic fracture mechanics (LEFM) where a variable of the critical stress intensity is denoted as K_{Ic} . The fatigue crack growth was modeled using Paris' law. The crack growth was simulated based on Mode I crack specimen with an initial crack length of 4 and 8 mm, respectively. The stochastic multiscale modeling of crack growth on meso- and microscale is used to compare the crack growth rate in the approach of a heterogeneous material and taking into account the microstructure and fracture mechanism of the Bilinga wood. The results of stochastic modeling of the crack growth in the array of cracks and pores of a characteristic size shows that the simulation is close to FE-modeling results. Therefore, the stochastic simulation of the crack growth in wood at meso- and microscale shows the lower local stress intensity factors and slower crack growth due to the existence of the scale-time hierarchy. The crack growth rate v_{cr} at a macroscale ranges within $0.845 - 0.9 \times 10^{-3}$ m/sec which corresponds to the macroscopic value of the fracture toughness K_{Ic} .

Keywords: wood; viscoelastic material; main crack; secondary cracks; mechanical behavior; Bilinga; FE-modelling; experimental study; structural approach; stochastic modeling.

Introduction

Bilinga is considered one of the most valuable woods because of its unusual strength and resistance, excellent flexibility and decorative appearance. It is widely used in marine and onshore construction. It is used for planed veneer, interior and exterior cladding panels, joinery, sleepers, posts, carpentry and piling structures of piers, wharves, platforms, window sills, various furniture and parquet. It is used for decorative finishing of interiors and exteriors of premises, terraces and garden objects; it is excellent for covering of floors in residential and industrial premises, vehicles and contain-

ers. Due to the high tannin and natural oil content in the wood, Bilinga is resistant to the most diverse weather and climatic conditions, sunlight and seawater. This is why it is excellent for the construction of bridges and seagoing vessels, especially playboats and their decks.

Bilinga wood is very strong and hard, it surpasses oak wood in all technical parameters except the aspect of splitting and resistance to impact loads. Its density at standard humidity can range from 740 to 810 kg/m³. Bilinga is highly water- and fire-resistant, so it is suitable for use in a variety of temperature and humidity ranges. It is considered



Fig. 1. Sample piece: (a) raw material, (b) prepared sample for mechanical characterization

one of the most resistant of the existing breeds, as it is practically unaffected by attacks from insects, termites and even sea grinders, and also resists the appearance of fungi on its surface also.

The mechanical behavior of this wood is quite complex due to its anisotropic nature [1]. The fracture behavior also is commonly accepted as a quasi-brittle behavior in which a softening zone called Fracture Process Zone (FPZ) exists ahead of the crack tip [2]. However, micro-cracks, which can propagate and cause failure, are commonly found in all timber structures. Failure is principally a result of fatigue. Fatigue is the process of progressive localized irreversible change in a material, and may culminate in cracks or complete fracture if conditions that are initiated or propagated on the process persist [1]. The viscoelastic behavior of wood under varying moisture phenomenon as well as the coupling phenomenon between the temperature and the moisture transfer in this wood material is often explained [3]. However, most models do not consider the crack growth in the structure. Combining mechanical solicitation like fatigue, overload, or creep loading and environmental actions like hydro or temperature will play an important role in the growth of these micro-cracks in structural materials [4]. To determine the behavior of cracks in wooden beams, many numerical methods are used to characterize the stress around the crack tip which one of them is the J -integral developed by J. Rice in 1968 [5]. For elastic and visco-elastic material the SIF approach of NLFM could be used. The first part of this paper presents the material and method used in this work. The mathematical formulation of J -integral to determine the stress intensity factor around the crack tip, the energy release rate calculated using the result from the laboratory experiment with respect to mode I specimen is presented in the second part. In addition, the Kelvin Voigt Model was used to model the viscoelastic material [6]. The third part of the paper presents the FE numerical modeling of the wooden bulk deformation under the three-point bend loading at the macroscale, and the stochastic modeling of crack growth by the mechanism of

crack and pores coalescence on the microscale of Bilinga wood material.

Experimental materials and methods

A material for the study was raw and prepared Bilinga wood samples (Fig. 1).

The flexural testing machine used in carryout the three-point bending test; it is equipped with a camera that records every detail such as fracture appearance and breakage point. Universal hydraulic grips with a set of wedge members is used to carry out bending test, compression test, etc. High stiffness frame with minimum deflection at maximum load (0.9 mm). Upper/lower rollers: 160 mm. Ram travel: 110 mm.

Electronic balance of type XPR5003S used to take measurement like the mass of the samples, moisture content, etc. Its maximum capacity is 5.1 kg, readability of 1 mg and with a minimum weight (USP, 0.1, typical) 6 g.

Laboratory electric oven used in drying the wood in order to prepare it for physical characterization. It has a power rating of 2.0 – 2.2 kW, which means its consumption is from 2000 to 2200 W.

Material Preparation. A selection of Bilinga wood was done in the midst of rainy season with a temperature range of between 24 – 28°C with 1889 mm of accumulated precipitation in the month of August. It was termed BI-R-A-NC (Bilinga rainy season of specie A without initial crack), while another specie of wood was harvested in the dry season i.e. in the month of February with a temperature range of 28 – 34°C and with 167 mm of accumulated precipitation. It was also termed BI-D-B-NC (Bilinga dry season of specie B without initial crack). 10 specimens were prepared for each specie for characterization. In this paper, the specimen preparation is subjected to rigorous and precise process such as an accurate alignment of the specimen in the tangential and longitudinal directions of wood, a check on the exactness of the length, width and thickness of all the samples of both species is done. For the physical characterization, the dimension of the specimens was (20 ×

$\times 20 \times 360$ mm and $20 \times 20 \times 20$ mm). Specimens were stored into an electric oven for 24 hours to attain different Relative humidity; the oven was conditioned under a constant temperature (200°C). The equilibrium moisture content of the specimen was obtained when its weight between 2 days did not change, with a reasonable tolerance of (0.05 g). For the investigation of the crack propagation, an initial crack of 4 and 8 mm was induced on each specimen on each of the specie then was simulated with specimens without any initial crack.

Physical Properties study. These studies were carried out at ENSET Douala in the Forest Engineering laboratory. This part is about studying the variability of density. These characters are essential to judge the quality of the wood and its classification for a given use.

The oven drying method is the standard way of determining wood moisture content. With this method, 10 specimens of each species of wood measuring $20 \times 20 \times 20$ mm were initially weighed on an electronic scale balance and then dried in an oven at $103 \pm 2^\circ\text{C}$ for 24 hours. Drying continues and measurement is taken until all the specimens completely dried off, i.e., when no further weight loss occurs. The formula below is used in determining the water content:

$$MC = \frac{m - m_0}{m_0} \times 100 \%, \quad (1)$$

where m is the average of the mass of specimen before submerged in water while m_0 is the average of the mass of the dried specimen.

In order to determine the density, ten specimens for each species were submerged into distilled water. To determine the volume (V_S), Archimedes method was used which consists of weighing an empty container of water on a scale and recording its mass M_1 then immersing each of the specie inside the distilled water for at least 4 hours and then taking the mass gain to have M_2 and in the end differentiate between the two masses as indicated by the equation $V_S = M_1 - M_2$ [7].

Mechanical Properties. In this study, the woods studied are of section ($20 \times 20 \times 360$ mm) with moisture content of 12% water oven dry and 14% water oven dry. The tests have carried out on 10 specimens per species. We determined the flexural modulus of elasticity E_f (MPa) and the energy re-

lease rate G (J/m^2). The tests have carried out according to standard NFB 51-008 (Table 1).

The principle of the simple bending test is to determine the maximum load at which failure will occur of a material sample on two supports with an application at mid-distance of the supports to one constant speed on a sample. The load has applied continuously to a speed equal to 2 mm/min. we simultaneously measure loads and displacement up to rupture of the sample.

The modulus of elasticity. The modulus of elasticity (E_f) calculated on the principles of the standard NFB 51-016 (1987) [7]. It is a function of the load, the displacement and the coefficient of rigidity. The recording of the “force-deflection” curve makes it possible to calculate inside of the linear zone the flexural stiffness K :

$$K = \Delta F/m_0 \times 100\%, \quad (2)$$

$$E_f = \frac{L^2}{4bh^3} K. \quad (3)$$

Energy of rupture: J ($\text{N} \cdot \text{m}$). The displacement force curves obtained during the three-point bending of the two species having a notch $a_1 = 4$ mm, $a_2 = 8$ mm, in calculating the area between the two force displacement curves. To do a graphical calculation the tool was used (Origin Pro 2019b). It allows calculating the area using the option (analysis, calculation, integral). The results obtained are in ($\text{N} \cdot \text{mm}$), these are the values of J (energy of rupture), we divide it over the thickness of the sample piece ($e = 20$ mm) times the depth of the notch, which gives the rate of energy release G in (J/mm^2) [8].

Critical stress intensity factor (fracture toughness). It has shown that in mode I the value of K_{Ic} can be determined from the energy refund rate. G_{Ic} (Specific energy of rupture or energy of propagation crack) by the formula below [9]:

$$K_{Ic} = \sqrt{E_f G_k}. \quad (4)$$

Here K_{Ic} is the critical stress intensity factor, E_f — the elasticity modulus.

Numerical modeling. In order to analyze cracked timber structures under real service conditions, the moisture content level in wood during the loading must be considered in the framework of fracture mechanic. On the other hand, the main problem is the coupling between the hydride state

Table 1. Characteristics of samples by the mechanical properties

Origin of Sample	Types of test	Number of samples	Dimension, mm	Geometry
Bi-R-A-NC	Flexural	10	$360 \times 20 \times 20$	longitudinal
Bi-D-B-NC	Flexural	10	$360 \times 20 \times 20$	longitudinal

and the mechanical state in the material, as well as the coupling between the configuration with and without the crack propagation. In this paper, in order to have a better comprehension of the loaded structure behavior, the modeling of the cracked structure taking into account the moisture variation is proposed and studied.

The size of a flaw in any material is an important variable in fracture analysis, as is the stress on the flaw and the fracture toughness of the material, which replaces material strength in fracture calculations. The stress intensity factor (SIF) determines the fracture toughness of a material subject to linear-elastic fracture mechanics (LEFM); the SIF variable represented as KIC. For elastic-plastic fracture mechanics (EPFM), fracture toughness determined by the energy required to grow a crack, represented by JIC, also known as the *J*-integral parameter. Fatigue crack growth modeled by using Paris' law as seen below [10]:

$$da/dN = C(\Delta K_I)^m.$$

(5)

The numerical simulation has done with the help of a finite element software ANSYS workbench 2020 R1. With the help of the most recent technology of ANSYS workbench call Smart crack growth that has introduced from the 2019 version of ANSYS. The geometry had modeled in SolidsWork with initial cracks of 4 mm and 8 mm introduced in each sample and imported to ANSYS workbench and further analysis with ANSYS mechanical that has all the tools to perform linear fracture, all geometry data have found in table below.

Geometry and Meshing generation. The geometry was model using SOLIDWORKS 2017, the solid was model base on the characteristic of sample used for the experimental study, the file format and geometry characteristic is found in Table 3 with intial cracks of 4 and 8 mm were intoduced to models and saved in IDES file format where it can be open and be read in ANSYS (Table 2).

Because of the existence of crack tip singularity, the usual elements surrounding the crack tip should be generated refined mesh in order to derive reliable stress intensity factor results. ANSYS requires the part structure body with cracks should be meshed with tetrahedron elements, while other bodies without cracks can be set arbitrary element types. Meanwhile, the crack mesh generation set-

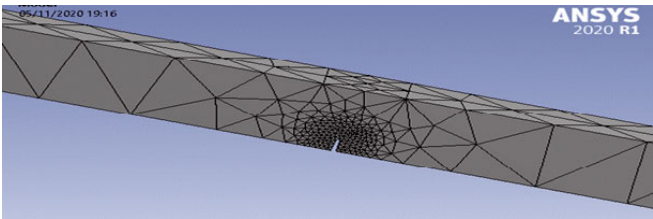


Fig. 2. Meshing of solid in ANSYS workbench

tings of Work bench are more convenient than settings under ANSYS classic analysis environment, because under Work bench environment mesh refinement of the crack tip is automatically to generate after accomplishment of mesh generation for the whole body (Fig. 2).

SMART simulation is the latest in a long line of ANSYS innovations designed to solve the critical issue of crack initiation, growth and fracture in product design. Meshing around the crack tip after each iteration concentrates the computing power where it is needed most, making SMART simulations faster and easier to scale up for larger projects. Using UMM (unstructured meshing method) for meshing eliminates costly preprocessing time and produces a test mesh that is just as accurate as a time-consuming hex mesh. The algorithm below gives the different step to carryout crack propagation on ANSYS workbench. Many applications of the same approach have a good implementation in modern education and industry [11 – 16].

Table 2. Geometrical information for solid model in ANSYS

File Type	IGES
Length Unit	Millimeters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	360 mm
Length Y	20 mm
Length Z	20 mm
Properties	
Volume	1.4393e+005 mm ³
Mass	1.1298 kg
Scale Factor Value	1

Table 3. The mechanical properties and crack parameters obtained from experimental results

Region	Number of samples	Modulus of elasticity, MPa	Critical stress intensity factor, MPa · m ^{1/2}	Energy release rate, J/m ²	Energy of Rupture, kJ/m ²
BI-R-A	10	8.828	16.347	134,428	1875.12
BI-D-B	10	6.7415	9.478	145,575	1276.25

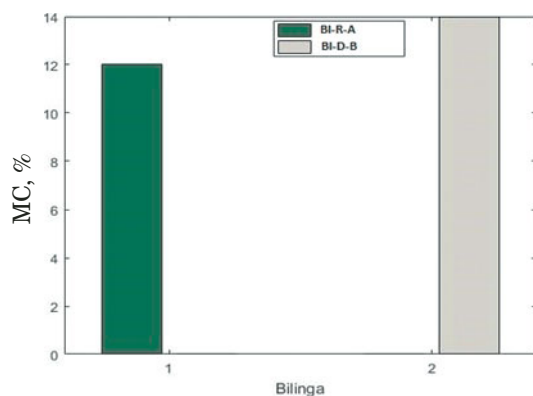


Fig. 3. Relative moisture content

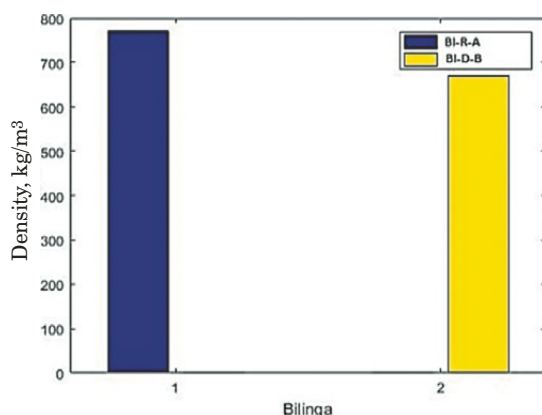


Fig. 4. Density chart for species

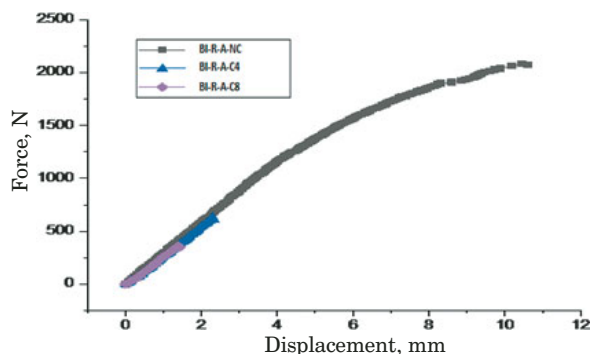


Fig. 5. Force displacement curve for Bilanga BI-R-A

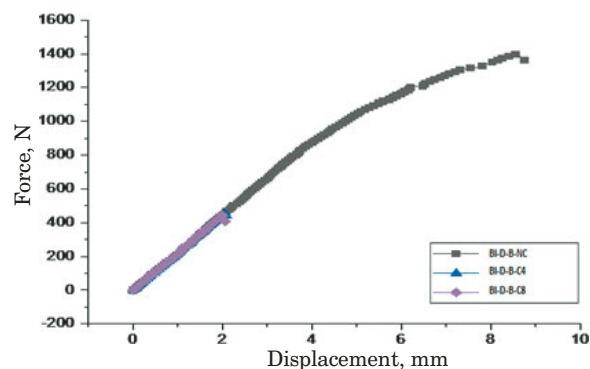


Fig. 6. Force displacement curve for Bilanga BI-D-B

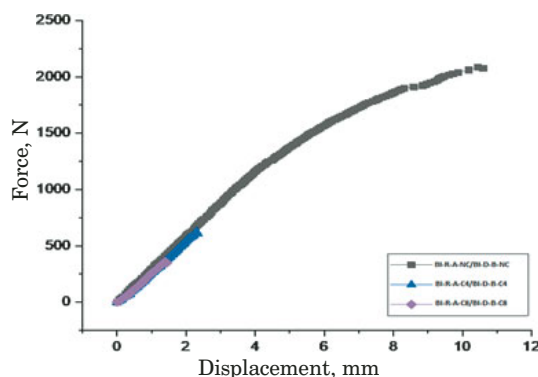


Fig. 7. Force displacement curve for both probes of different Bilanga wood species

Mechanical Properties. The curve on Fig. 5 represents species of type BI-R-A-NC with no initial crack and specimens with initial crack of 4 mm and specimen with 8 mm initial crack.

Figure 6 represents a behavior of a species of type BI-D-B-NC with no initial crack and specimens with initial crack of 4 mm and specimen with 8 mm initial crack.

The curve on Fig. 7 represents the displacement versus force for the both different species Bilanga wood probes. It has shown that the deformation curves are same.

Mechanical properties and crack parameters from experimental result are shown in Table 3.

It can be noticed that the Bilanga of the both species whether those without initial crack and those with initial crack when they are mesh together shows no variation in elasticity.

The fracture energy is proportionally reversed to the notch depth. The energy release rate of Bilanga in the rainy season of species A is lower than Bilanga of the dry season of species B.

Energy release rate was calculated from the experimental data and the value is presented below.

The critical stress intensity factor (fracture toughness) is a parameter that amplified the magnitude of the applied stress that includes the geo-

Experimental result and discussion

Physical Properties. We can see that Bilanga from south west harvested in the dry season has a higher relative moisture content which is 14% and that harvested in the same region but during the rainy season has only 12% (Fig. 3).

The density of both species was determined and presented on the diagram on Fig. 4.

Meanwhile that which is harvested in the rainy season has a higher density value than that of the dry season.

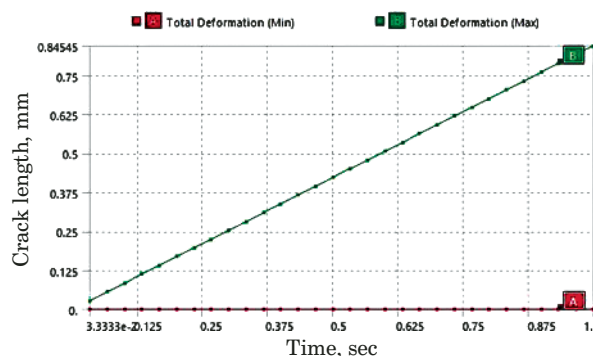


Fig. 8. Crack length versus time

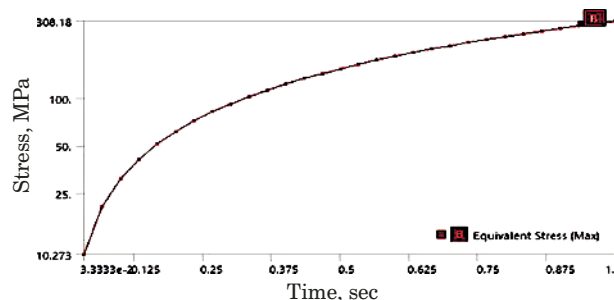


Fig. 9. Equivalent stress curve versus time

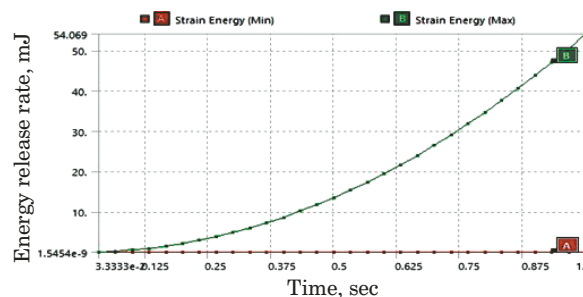


Fig. 10. Strain energy

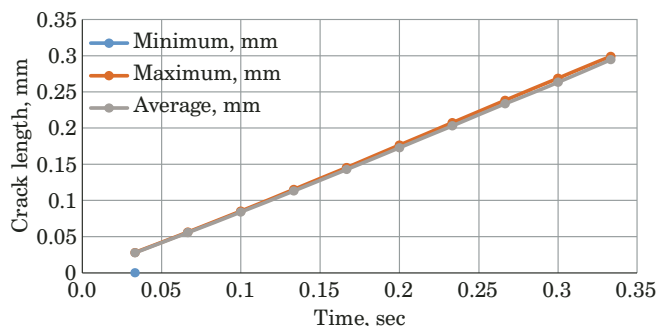


Fig. 11. Calculated curves of the crack length versus time

metrical parameter (load). The stress intensity in any mode situation is directly proportional to the applied load of the material.

Figure 8 shows the crack length displacement against time line. So, the crack tip velocity calculated as 0.845 mm/sec.

Equivalent stress considers different effects resulting from multi axial residual stress states (Fig. 9).

Strain energy is a type of potential energy that is stored in a structural member as a result of elastic deformation. Figure 10 represents a time dependence curve of the strain energy.

The crack propagation was simulated base on numerical data collected from laboratory experiment and the simulation was based on 6 contours and the result is represented on Fig. 11. The crack growth velocity could be calculated as $v_{cr} \approx 0.90$ mm/sec = 0.9×10^{-3} m/sec.

Figure 11 represents the rate of growth of crack with respect to time, the graph shows that at the beginning of the crack tip where that crack start at zero will increase progressively at 0.333 and then propagate to a length of 0.35 mm. This explains the resistance of the material under study. The stress concentration on the crack tip was also determined and presented on Fig. 12.

Multiscale Stochastic Modeling of Crack Growth. The FE-modeling based on isotropic solid concept does not take into account the structural heterogeneities and anisotropy of the properties of

a natural material such as wood, even soft wood [17]. So, one need to verify the structural modeling to estimate the key fracture parameters.

The microstructure of Bilinga wood well known by the several museum researches. We use images of the microstructure of tangential section of Opepe, Bilinga (Lat. *Nauclea diderrichii*), by Hans Beeckman, Royal Museum of Central Africa, Belgium, and cross-section by M. E. Bakker, Naturalis Biodiversity Center (Fig. 13a), and Frances Whinder & Peter Gasson, Royal Botanic Gardens — Kew (Fig. 13b).

In general, the wood is loaded crosswise to the growth of the fibers trough the tangential section because of high strength and processing technology reasons. So the crack growth in the cross section will be faster than in the tangential section of the wood due to big pores (up to $\varnothing 200 \mu\text{m}$) coalescence. In the case of the tangential section, however, cracks will be slower because of the time needed to have the crack to be form and for it to grow, which will also subsequently merge into the main crack (Fig. 14). The size of crack will start from 50 to $200 \mu\text{m}$. The vessels (micropores) size is about 10 m here.

Stochastic Modeling of the Crack Growth on Microscale. Although LEFM does not provide for the consideration of levels in a solid, the multiscale description must be introduced for at least a brief theory of crack dynamics. For the verification of the crack growth rate by structural multi scale sto-

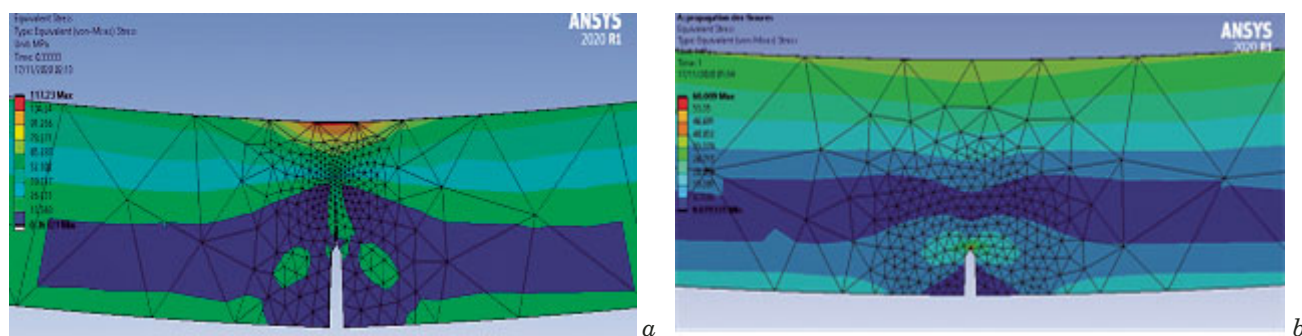


Fig. 12. Distribution of the equivalent stress (*a*): initially concentrated on the crack tip; (*b*): at the crack tip during propagation (ANSYS Smart Crack modeling results)

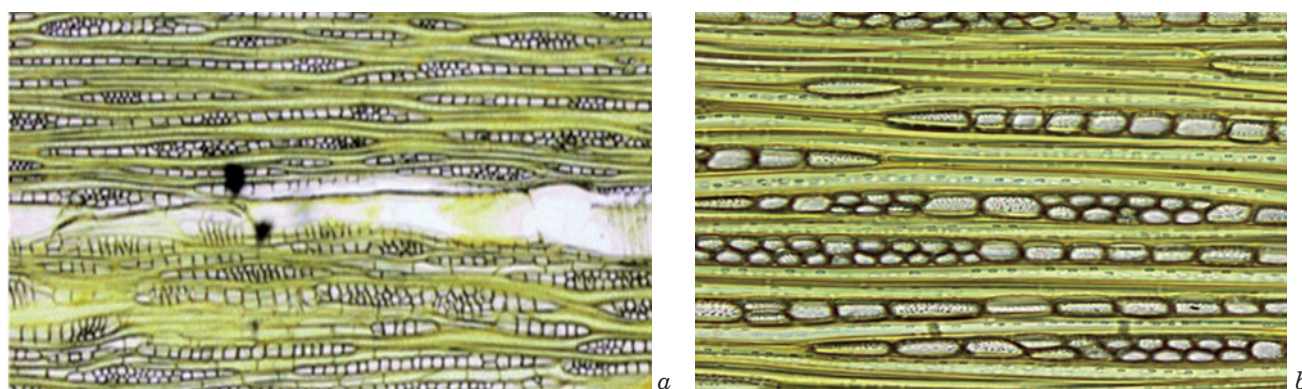


Fig. 13. Microstructure images of Bilinga wood (tangential section): *a*) 3.0 mm wide, *b*) 800 μm

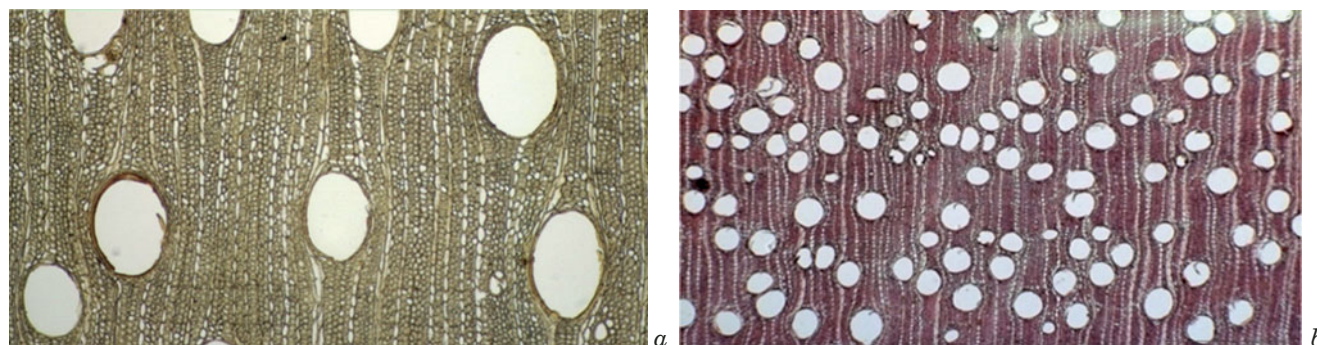


Fig. 14. Microstructure images of Bilinga wood (cross section): *a*) 2.0 mm wide, *b*) 6.0 mm wide

chastic modeling is necessary to qualitatively and quantitatively evaluate the fracture mechanism of wood [18]. When we consider the first mode, i.e., mode I, which is the (opening mode) crack and applying on the bending and loading process on the sample, where the external normal stress is perpendicular to crack [19].

For the Bilinga wood, the stochastic fracture modeling based on the mechanism of viscous coalescence of pores (vessels) by the small crack growth across the fibers was used [20]. Scheme of multiscale quasi3D-modeling presented on Fig. 15.

A scale-time hierarchy according the proposed system-structural approach [21 – 23] reflects the

dependence of the local approach by LEFM relation:

$$\delta_c = \frac{2K_{Ic}}{\pi\sigma_c^2}; \tau_c = \delta_c/c.$$

Here c is the elastic wave velocity in direction of loading, for wood $c \approx 4000$ m/sec, δ_c , τ_c is the size and time of the scale; so for mesoscale the $\tau_c \sim 10^{-5}$ sec, and for microscale $\tau_c \sim 10^{-7}$ sec.

However, the fracture mechanism at microscale would be different and described by short crack growth law. The large variability of crack growth rates at different scales is a result of microstructural influence on the local crack driving force. To do

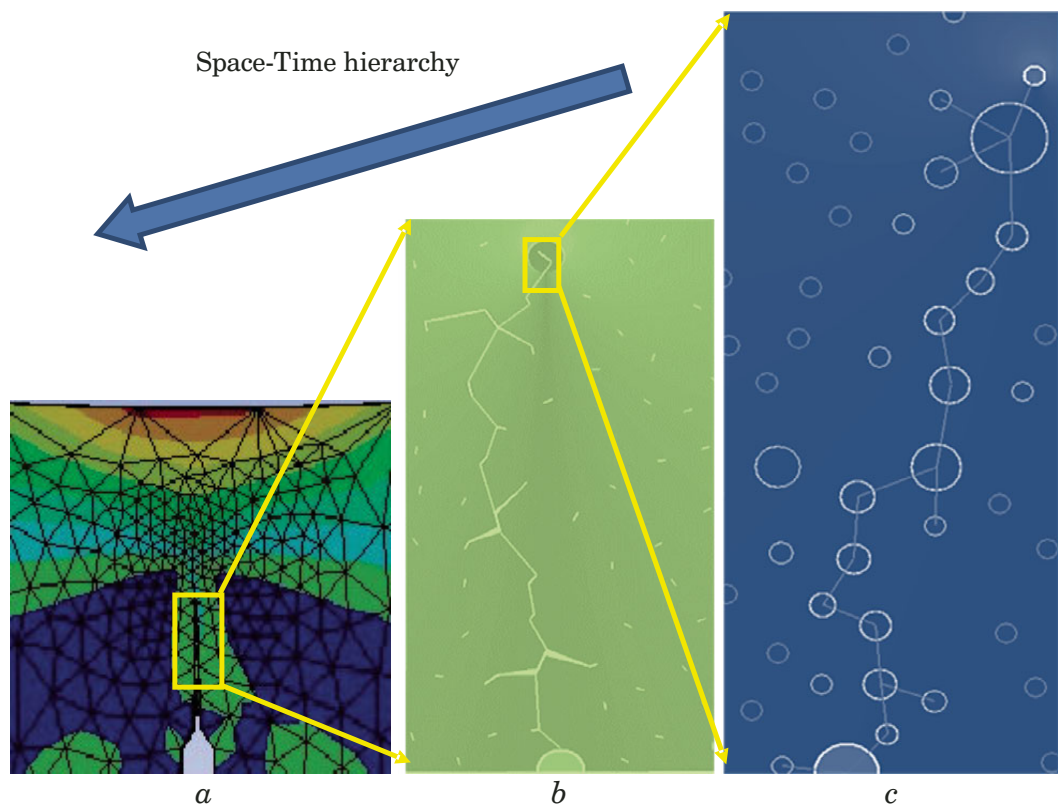


Fig. 15. Scheme of crack growth modeling based on multiscale quasi-3D-modeling: *a*) FE-model realized by Smart Crack ANSYS approach (main crack at macroscale); *b*) stochastic modeling of the main crack growth (crack branching at mesoscale ~0.1 mm); and *c*) stochastic modeling of the crack tip coalescence with micropores (wood vessels on microscale ~1 – 10 μm)

accurately prediction of the crack growth rate on microscale, a local rather than a far field driving force must be used. The question is that for the wood, the growth patterns of short cracks have not been sufficiently investigated, and we have to assume the mechanism of growth and coalescence of micropores based on images of microstructural sections (see Figs. 13 and 14).

The results of main crack growth visualization on mesoscale by the mechanism of short cracks coalescence presented on Fig. 16.

The calculated crack growth rates at different local stress intensities K_I used by stochastic model shown in Table 5.

Therefore, stochastic simulation of crack growth in the wood at mesoscale and microscale shows the lower local stress intensity factors and slower crack growth due to existence of the scale-time hierarchy. The crack growth rate at macroscale is equals $v_{cr} = 0.845 - 0.9 \times 10^{-3}$ which corresponds to macroscopic fracture toughness K_{Ic} .

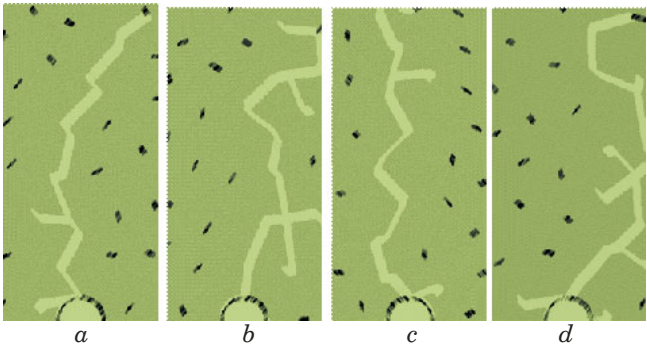


Fig. 16. Crack growth visualization from the pore Ø20 μm from the bottom of area on mesoscale. The calculated area is 1200 × 1200 μm. Distance between the cracks is 25 μm. Normal distribution of the cracks with a standard deviation of 1 μm and K_I , MPa/m^{0.5}: *a*) 35.0, *b*) 36.0, *c*) 37.0, *d*) 38.0 (see Table 5)

The micropores coalescence mechanism used for simulation of short crack growth at microscale (Fig. 17).

Table 5. Crack growth rate v_{cr} calculated by stochastic model

Scale	Meso ($\delta_c \sim 100 \mu m$)				Micro ($\delta_c \sim 10 \mu m$)			
K_I , MPa · m ^{-0.5}	35.0	36.0	37.0	38.0	53.0	54.0	55.0	56.0
v_{cr} , m/sec	1.8×10^{-4}	2.3×10^{-4}	3.5×10^{-4}	4.7×10^{-4}	1.5×10^{-5}	5.6×10^{-5}	1.3×10^{-4}	5.5×10^{-4}

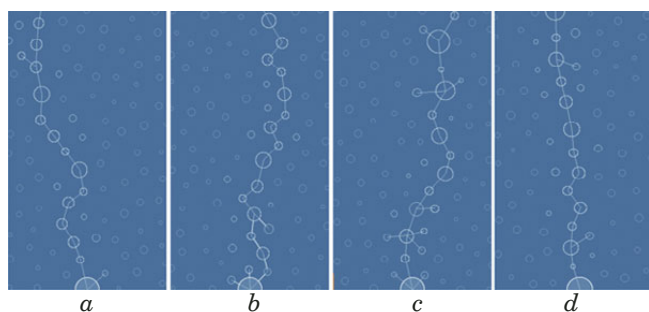


Fig. 17. Visualization of the crack growth by micropores ($\varnothing 5 - 10 \mu\text{m}$) coalescence from the crack tip on microscale (bottom). The calculated area is $760 \times 380 \mu\text{m}$. Distance between the cracks is $10 \mu\text{m}$. A normal distribution of the cracks with a standard deviation of $1 \mu\text{m}$ and K_I , $\text{MPa}/\text{m}^{0.5}$: a) 53.0, b) 54.0, c) 55.0, d) 56.0 (see Table 5).

CONCLUSION

The purpose of this research was to consider a multiscale modeling of a wooden beam and to study the effects of crack and its propagation using a finite element program ANSYS and own stochastic algorithm code. The same species of wood from the same region of Cameroon harvested in two different seasons were used for the experimentation to find out if their different seasons will influence their strength. The simulation was calibrated and modified based on experimental result. Finding out the critical energy rational value for which the fracture mode to match with available experimental result and material properties was one of the main points of focus. A study was carried out in order to compare the cracks of the different samples with an initial crack of 4 mm on the specimens of the two species with that of initial crack of 8 mm also applied on the specimens on the two species. The rate of crack growth was verified with the application of micro scale by structural stochastic modeling. A method is proposed in order to analyze the crack growth of timber structures under environmental conditions in which moisture effect is integrated into the Fracture Process Zone (FPZ), so that the coupling between the mechanical behavior of wood and the crack growth process can be expressed. The stochastic simulation of crack growth in the wood at mesoscale and microscale shows the lower local SIF and slower crack growth due to existence of the scale-time hierarchy. Crack growth rate at the macroscale corresponds to non-local macroscopic SIF. It is confirms the reliability of the method and allows us to talk about the possibilities of widespread application of a multiscale and multilevel approach in modeling materials and technologies.

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Conflict of interest

The author declares no conflict of interest.

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