Chapter 1
Experimental Investigation of the Impact of Localized Spectrum Analysis Method on Fracture and Hygro-mechanical behavior of Wood

Loic Chrislin Nguedjio, Rostand Moutou Pitti, Benoit Blaysat, Pierre Kisito Talla, Fréderic Dubois, and Naman Recho

Abstract This study highlights the potential of the Localized Spectrum Analysis (LSA) method to experimentally identify the wood fracture parameters under coupled hygro-mechanical loading. Specifically, the study investigates how moisture variations influence the critical values of the energy release rate that drive crack initiation and propagation in different fracture modes, including opening, shear, and mixed modes. To achieve this goal, this experimental Localized Spectrum Analysis, image-correlation technique is employed to capture displacement and strain fields during instantaneous fracture tests under varying mode mixity ratios. Wood specimens are prepared in a Mixed Mode Crack Growth (MMCG) geometry, their lateral faces coated with a permeable white paint, followed by the application of a periodic checkerboard pattern. After being conditioned under controlled climatic environments long enough to ensure internal moisture diffusion, the specimens are subjected to fracture tests. Critical forces and crack opening displacements are recorded, and the energy release rate is evaluated via the compliance method at different internal moisture contents. Force–crack opening curves as a function of moisture content, as well as energy release rate–crack length relationships, are finally established, providing new experimental insights into the role of moisture in the fracture behavior of wood.

Keywords Localized Spectrum Analysis · moisture content · wood · energy release rate · MMCG specimen

Introduction

The dimensional variations of wooden structural elements induced by moisture adsorption and desorption phenomena are among the main causes of degradation in wood structures [1, 2]. Variations in moisture content lead to deformations in the form of swelling or shrinkage, depending on whether the wood adsorbs or desorbs moisture. When these hygro-induced deformations are restrained, moisture-induced stresses develop and may cause crack initiation or the propagation of pre-existing cracks [3], particularly due to excessive transverse tensile stresses. It therefore appears essential, in light of the above, to account for the impact of moisture variations when computing fracture parameters of wood materials.

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In experimental fracture mechanics, image analysis and non-destructive testing techniques are increasingly used to characterize fracture parameters. Among the most recent techniques, the Grid Method can be cited [4, 5]. This method has been used not only for the physico-mechanical characterization of wood [6], but more importantly for the determination of fracture parameters [7, 8, 9]. However, this technique has shown some limitations, particularly related to the application of the grid on the specimen surface, which complicates data analysis and interpretation.

The Localized Spectrum Analysis (LSA) image processing method has been introduced as an improvement over the Grid Method [10, 11, 12]. In particular, it enables the direct measurement of displacement and strain fields on the surface of the tested specimen, while also eliminating the need for a physical grid by directly printing the periodic pattern onto the specimen surface. In the literature, only a limited number of studies have employed the LSA method to determine wood fracture parameters. These include the works of Biyo'o *et al.* [13, 14] on Cameroonian tropical woods and those of Houngbegnon *et al.* [15, 16] on woods for mobility applications.

However, the application of LSA requires a preliminary surface treatment of the specimen, consisting of applying a paint layer and engraving a periodic pattern by laser thermal processing. The research question addressed here concerns the impact of this surface treatment on surface moisture exchanges, which define the boundary conditions governing moisture transport and thus directly influence the displacement and strain fields. The works of Nguedjio *et al.* [2] have provided some initial insights into this issue. The application of LSA in wood fracture mechanics under variable moisture conditions therefore remains a significant scientific challenge. Although numerical studies already exist [17, 18, 19], the experimental issue remains critical.

The objective of this work is thus to determine the impact of the LSA treatment surface on moisture diffusion of the tropical wood *Khaya ivorensis*.

Experimental Method

Specimen preparation

Khaya ivorensis, also known as African mahogany, is a valuable wood species, highly appreciated for its aesthetic and mechanical properties (Fig. 1). The *Khaya ivorensis* tropical wood species used in this study was harvested from the Ouémé-Supérieur forest, located in southern Benin. The samples were taken from the trunk of a tree approximately 30 m in height and 1 m in diameter. After felling, the wood was sawn and cut into boards, then naturally air-dried for one month under tropical climatic conditions. At a moisture content of 12%, *Khaya ivorensis* exhibits an average density of 770 kg/m^3, which is stable and provides high mechanical strength [15, 16].

Bars (see Fig. 2a) were subsequently cut and machined to standardized dimensions in order to obtain the geometric shape



(a) (b)

Fig. 1 Tropical *Khaya invorensis* species : (a) Trunk; (b) Longitudinal-Radial plane.

suitable for Mixed Mode Crack Growth (MMCG) tests (see Fig. 2b). The specimens cut in the MMCG geometry were then prepared to enable optical measurement of mechanical fields using the LSA method. This preparation consists in coating the specimen surface with a thin layer of paint (see Fig. 2c), followed by laser engraving of a periodic checkerboard pattern (see Fig. 2d). Fig. 2e shows the surface condition of the specimens after engraving. The contrast created by this pattern allows the cameras to visualize the various displacement fields during the tests. Both engraved and non-engraved specimens were then immersed in water for a period of five days to ensure humidification. After humidification, the specimens were removed from the water and regularly weighed during the drying phase in order to evaluate the desired internal moisture content prior to each crack growth test.

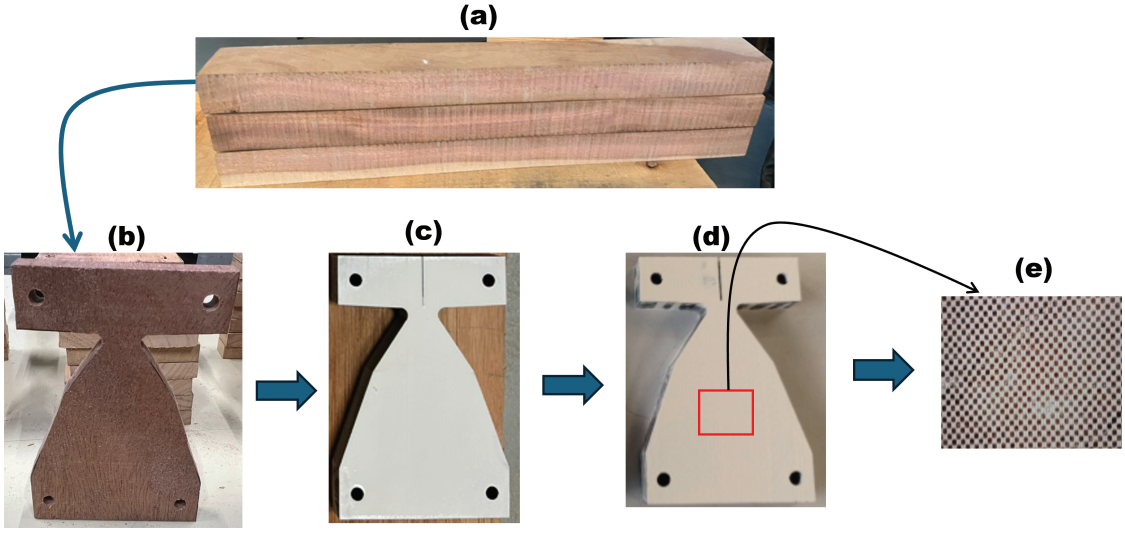


Fig. 2 Specimen preparation : (a) initial wooden bar; (b) MMCG specimen; (c) paint layer in the surface; (d) checkboard pattern; (e) final surface state.

Experimental setup

A Zwick/Roell tensile–compression testing machine, with a maximum loading capacity of 200 kN and equipped with a 50 kN load cell, was used to perform the experiments. A camera mounted on a tripod was used to capture images of the checkerboard pattern during the tests. Light projectors were arranged to enhance the illumination of the specimen surfaces in order to obtain high-quality images. Fig. 3 presents the complete experimental setup. The movable crosshead of the testing machine (upper grip) was displacement-controlled at a rate of 0.05 mm/s and was equipped with a force sensor.

The mechanical loading of the humidified specimens was carried out using the Arcan testing device. The fixation holes make it possible to impose the desired fracture mode, ranging from the opening mode (Mode I, 0°) to the shear mode (Mode II, 90°); any other loading angle is considered as mixed-mode loading. Fig. 4 highlights this testing method.

Impact of the LSA on the hygro-mechanical behavior of wood : Results and discussion

In order to prepare the specimens for crack propagation tests under variable humidity conditions, *Khaya ivorensis* wood samples, either modified by the LSA treatment (KHg) or left unmodified (KHng), were immersed in water until reaching approximately 60% moisture content (i.e., above the Fibre Saturation Point). The specimens were then removed from water and allowed to dry. Figs. 5 and 6 present the humidification–drying kinetics and the corresponding moisture rate evolutions, respectively.

Fig. 5a shows that the average moisture content increases with time for both modified and unmodified specimens, reflecting the progressive absorption of water. However, the unmodified specimens exhibit a higher moisture uptake compared to the LSA-treated ones, indicating a reduction of the incoming moisture flux at the surface of the engraved specimens. This observation is consistent with the results reported by Nguedjio *et al.* [20], who estimated a reduction factor of approximately 2.3 in the incoming water flux at the surface of LSA-treated *Khaya ivorensis* specimens.

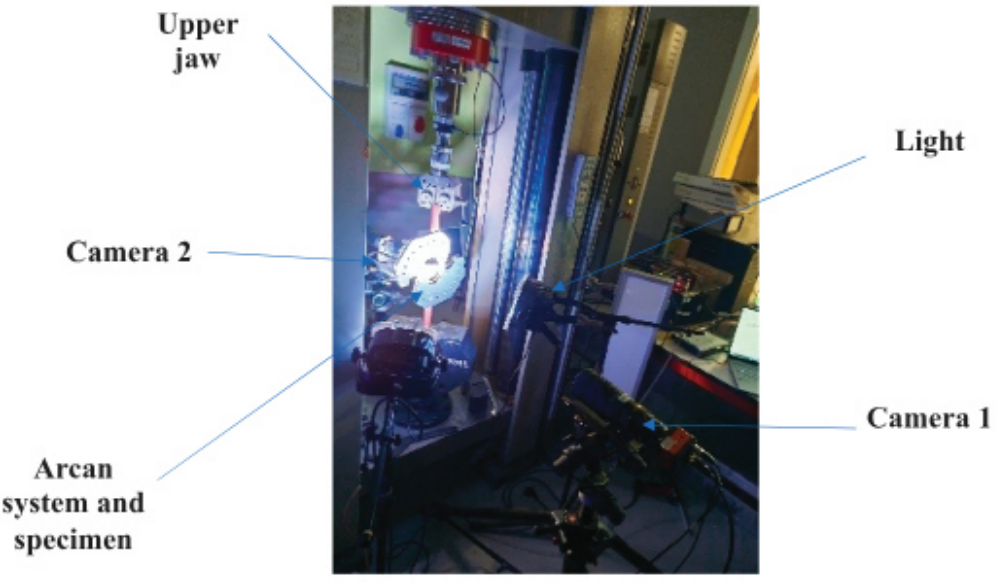
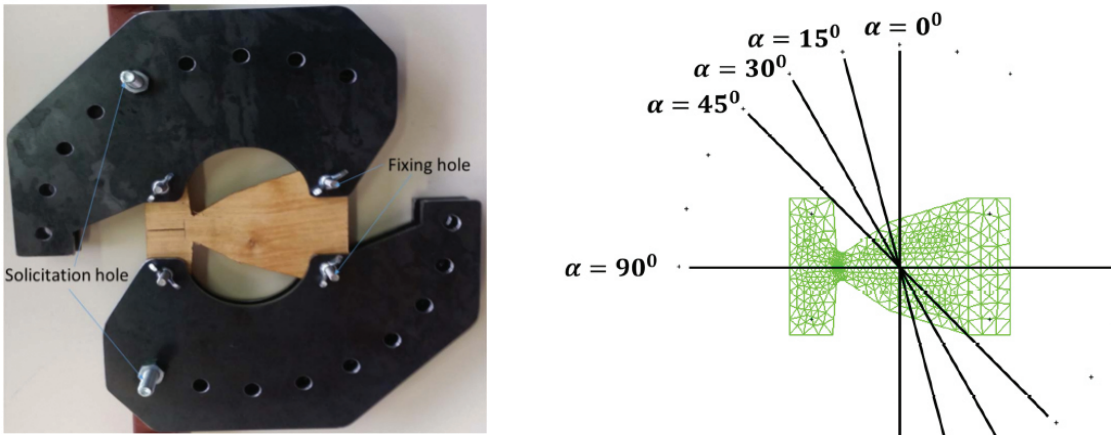


Fig. 3 Experimental test machine [15]

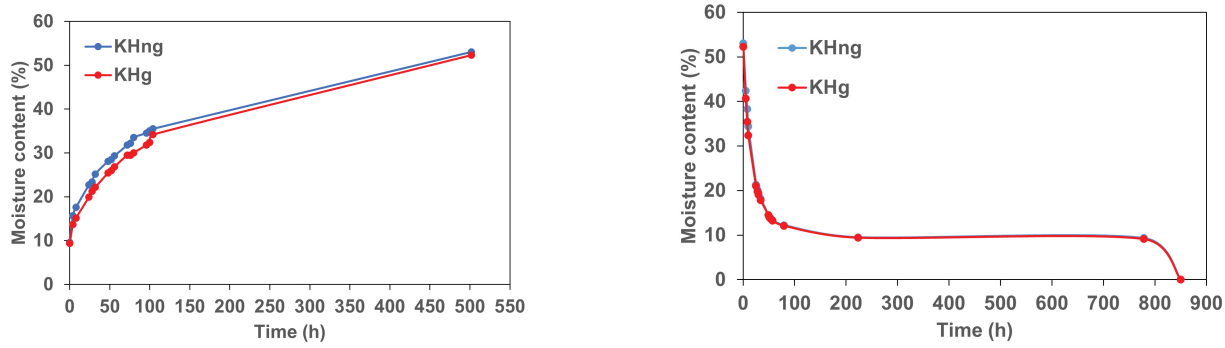


(a) (b)

Fig. 4 (a) Fixing Arcan system; (b) loading angle.

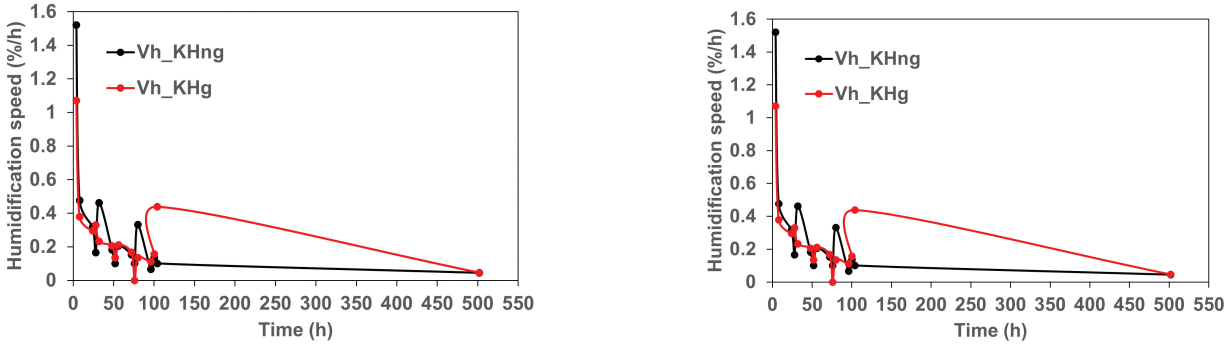
Fig. 5b illustrates the evolution of moisture content during the drying phase. As expected, the moisture content decreases progressively with time, corresponding to gradual water loss. The drying kinetics appear nearly identical for both categories of specimens, suggesting that the surface treatment (paint coating combined with the laser-engraved checkerboard pattern) does not significantly hinder desorption compared to absorption. Since the imposed treatment mainly affects the surface, the drying process being primarily governed by internal moisture diffusion is less impacted. This indicates that the intrinsic moisture diffusivity of the wood is not significantly altered by the LSA treatment.

The humidification rates shown in Fig. 6a exhibit pronounced initial peaks, with a lower maximum value observed for the treated specimens. This reflects the resistance to water penetration induced by the surface motifs. The humidification rate then progressively decreases, indicating a slower moisture penetration from the surface toward the core of the wood. The observed fluctuations may be attributed to the natural micro-heterogeneity of wood, but more importantly to preferential penetration paths, including the initial notch acting as a crack starter, as previously illustrated in the MMCG specimen geometry. These fluctuations are more pronounced during humidification than during drying (Fig. 6b). Indeed, during drying, moisture is already distributed within the bulk material and the process becomes mass-controlled. In contrast, humidification is a surface-controlled process, strongly influenced by the surface barrier introduced by the LSA treatment.



(a) (b)

Fig. 5 Sorption-Desoption of *Khaya invorensis* species : (a) Humidification phase; (b) Drying phase.



(a) (b)

Fig. 6 Speed of Sorption-Desoption of *Khaya invorensis* species : (a) Humidification phase; (b) Drying phase.

Conclusion and Future Work

The impact of the surface treatment (paint coating combined with a periodic checkerboard pattern deposited by laser printing) applied to MMCG-shaped tropical wood specimens of *Khaya ivorensis* was investigated in order to assess its influence on the moisture absorption and desorption properties of this wood species. The ultimate objective is to analyze the potential repercussions on the energy release rate during crack propagation tests under variable humidity conditions. Preliminary results indicate that this specific surface treatment, required for hygromechanical testing based on LSA image analysis, affects both the water ingress and egress processes. Untreated specimens exhibit faster moisture absorption, whereas treated specimens show increased resistance to water penetration at the surface. During the drying phase, however, the kinetics are nearly identical for both configurations, a result further confirmed by the corresponding absorption–desorption rate profiles.

Ongoing investigations involving hygromechanical crack propagation tests will aim to elucidate the influence of moisture variations on the energy release rate.

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