Experimental Fracture Analysis of Tropical Species Using the Grid Method

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Chapter 2
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Abstract The fracture processes of three tropical species: *Aucoumea klaineana*, *Malicia excelsa* and *Pterocarpus soyauxii*, are investigated with the grid method. These species are widely used in many sub-tropical countries, in timber building construction, as well as in semi-finished products and paper fabrication. However their fracture behaviour must still be investigated, data being scarcely available on this subject. Modified Mixed Mode Crack Growth specimens are used in order to obtain a stable crack growth evolution in opening, shear and mixed mode ratios. The images of the grid are analysed to provide the crack opening displacement and the crack tip location. The stress intensity factors and the critical energy release rates for each species are then obtained by using the compliance method in imposed displacement. The semi-experimental energetic method is also applied in order to show the efficiency of the proposed technique to characterize the fracture properties of the tropical species under study.

Keywords Mixed mode crack growth • Tropical wood species • Compliance method • Grid method

2.1 Introduction

Today, wood is one of the solutions that sustainably limits global warming of our planet. In Central Africa and particularly in equatorial regions, the forest plays a key role in this regulation. In the case of Gabon, the recent decision of stopping the exportation of tropical species has opened the way to their local extension and to their more widespread use in local individual and industrial buildings. However, the mechanical behavior of local species largely depends on temperature and humidity variations, which can impair their structural efficiency, and thus lead to sudden failure during their service life. Studying failure of tropical wood is crucial to know their behavior and guide local people in their choice of building materials other than concrete and steel. This would also contribute to the sustainable development discussed during the COP21 meeting in Paris last year [1].

This paper is focused on the study of the initiation and the crack propagation at room temperature of the following tropical species: Iroko (*Pterocarpus soyauxii*), Padouk (*Malicia excelsa*) and Okume (*Aucoumea klaineana*). A short review of the literature shows that few studies and data related to failure of this type of wood material are available. Similar studies deal with temperate species as Douglas, Maritime pine and Abies Alba mills, using Compact Tension Shear (CTS) specimens [2–4], Double Cantilever Beam (DCB) specimens [5], Mixed Mode Crack Growth (MMCG) [6] specimens and TDCB specimens [7]. In the present work, tropical wood specimens are investigated with the grid method [8–11].

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The first part of this paper presents the materials and methods applied for this experimental campaign. The background of the grid technique in order to record the crack tip position during the test is recalled. The origin and the characteristics of the tropical wood species are also described. The experimental devices are detailed. Experimental results are given in term of force-displacement curves and the crack tip location. The second part shows the fracture analysis by computing the critical energy release rate at the failure point using the compliance method.

2.2 Materials and Method

2.2.1 Wood Specimen

The dimensions of the CTS specimens are $105 \times 105 \times 12.5\ \text{mm}^3$ (see Fig. 2.1a). A typical Padouk specimen is shown in Fig. 2.1b. The main difference between the three species is their density: Okume (density = 0.44) is less dense than Iroko (density = 0.64) and Padouk (density = 0.79). It means that during cracking process, Okume exhibits a quasi-brittle behavior. For all the specimens, the initial crack length $a = 25$ mm is at mid-height and oriented along the fiber direction. The initial crack is completed by a notch (length: 3 mm) with a cutter in order to initiate correctly crack propagation. A grid, with a regular pitch of 200 µm, is transferred on one face of the specimen (see Fig. 2.1b).

2.2.2 Devices of the Experiments

The experimental device is shown in Fig. 2.2. A 200 kN Zwick/Roel testing machine was used for the tests. A camera was fixed on a tripod at a distance of 67.5 cm from the specimens in order to shot grid images during the tests.

A miniature steel Arcan fixture was used to load the specimens. The grips were equipped with a fixed lower frame. A mobile upper part allowed to apply the Arcan system in various mixed mode configurations. The testing machine, driven with imposed displacements, was equipped with force and displacement sensors in order to obtain force-displacement curves. The cross-head speed was 0.005 mm/s, and the acquisition rate of the camera was 1.35 frames/s. To minimize image noise, each image was averaged with 8 frames. The sample was illuminated by three flexible optical arms powered by a cold light source KL 2500 LCD. A SIGMA 105 mm objective was mounted on the camera.

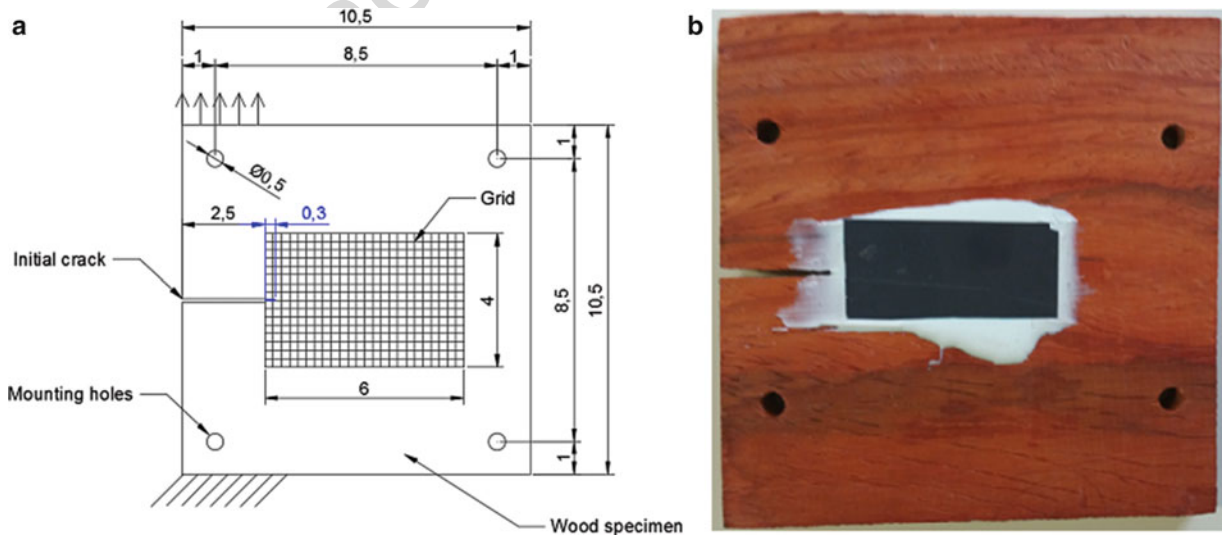

Fig. 2.1 (**a**) Dimensions of the wooden specimen fitted grid; (**b**) wooden specimen with grid (Padouk)

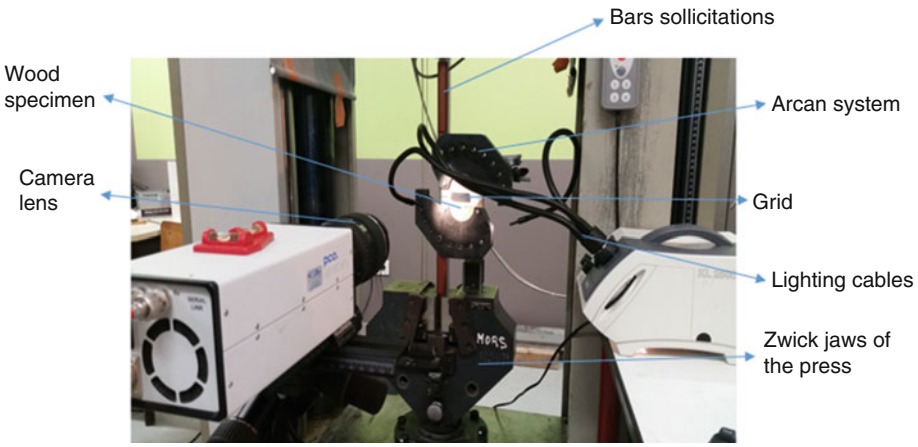

Fig. 2.2 Experimental device

2.3 Results

2.3.1 Force-Displacement Curves

Figures 2.3, 2.4 and 2.5 show the force-displacement curves for Okume, Iroko and Padouk species, respectively. Note that the fracture toughness is not considered here due to the sudden failure observed for the CTS specimens. Indeed, for this kind of specimen, we do not observe a crack growth process, thus the critical force F_{CO} is equal to the load at failure F_{RO}. The crack growth observed here is only due to the uncohesion of wood fibers at the tip. For Okume, the force at failure is equal to $F_{RO} = 147\,\text{N}$, which corresponds to a global vertical displacement $d_O = 0.35\,\text{mm}$. The sudden decrease of load represents the dissipation energy during crack propagation. Due to its low density, failure occurs suddenly.

In the case of Iroko (see Fig. 2.4), the failure force is equal to $F_{RI} = 375\,\text{N}$, which corresponds to a global vertical displacement of Iroko $d_I = 0.39\,\text{mm}$. Padouk, Fig. 2.5, has the most important fracture toughness: $F_{RP} = 569\,\text{N}$, which corresponds to the maximal displacement of Padouk $d_P = 0.69\,\text{mm}$. Before failure, we can see some energy dissipation at about $d_I = 0.39$ and 0.65 mm. According to the high density of this specimen, the stable crack growth process is observed after the fracture point, between the displacements of Padouk $d_P = 0.75$ and 0.85 mm.

2.3.2 Crack Length-Images Curves

Figures 2.6, 2.7 and 2.8 show the evolution of the crack vs. image number (and thus time) for Okume, Iroko and Padouk, respectively. Okume presents a sudden crack growth due to instantaneous failure corresponding to the maximum range of $a = 11$ mm (see Fig. 2.6). However, the observation of the Iroko curve (see Fig. 2.7), shows that the maximum crack length is $a = 16$ mm after 350 images. Note that this phenomenon is not only due to the bridging fibers during the increase of the load, but also to the peculiar properties of tropical species. Padouk (see Fig. 2.8), exhibits the maximum crack growth, with about $a = 32$ mm (image #285). In this case, the sudden bridging of the fibers is very marked at about image #240.

2.4 Fracture Analysis

In this part, the critical value of the energy release rate of the three species was calculated using the compliance method, Eq. (2.1). These results are calculated with the force at failure, and with the corresponding value of the crack length a

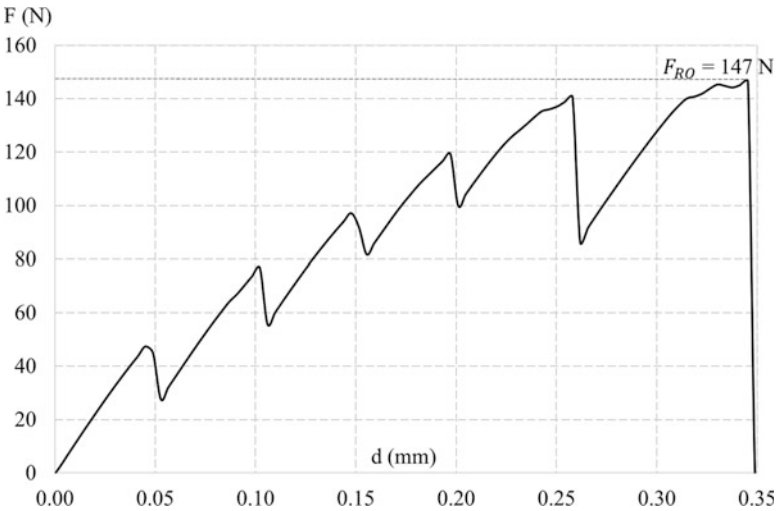

Fig. 2.3 Force-displacement curve for Okume (F_{RO} = failure force of Okume)

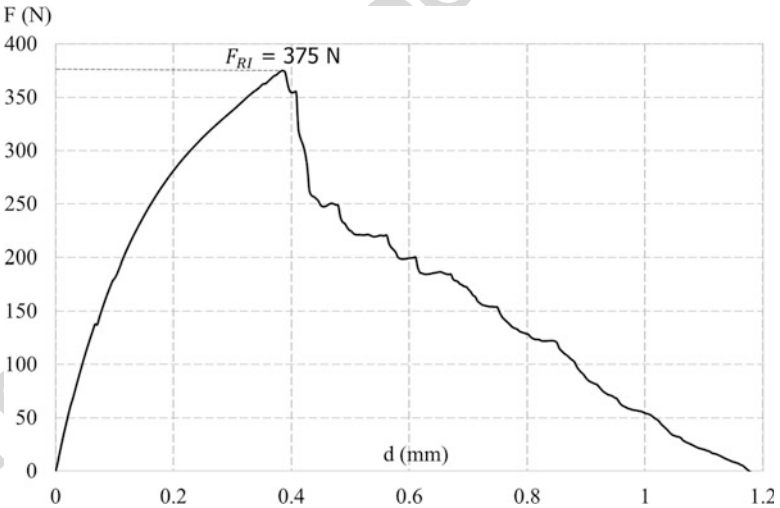

Fig. 2.4 Force-displacement curve for Iroko (F_{RI} = failure force of Iroko)

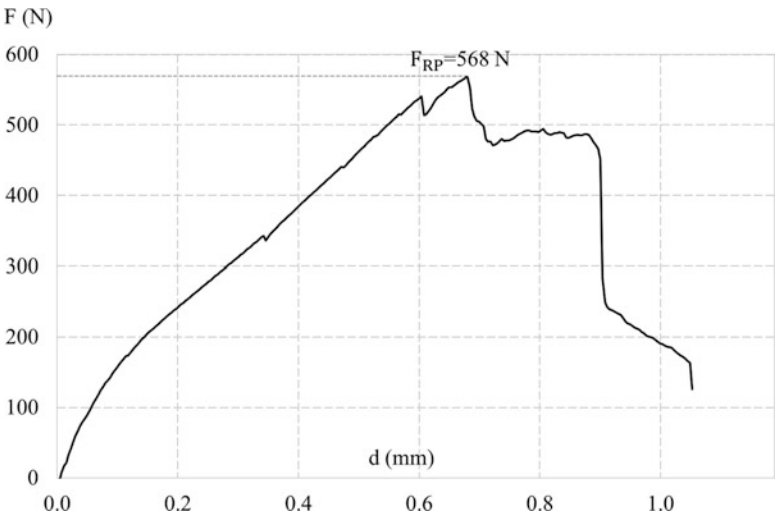

Fig. 2.5 Force-displacement curve for Padouk (F_{RP} = failure force of Padouk)

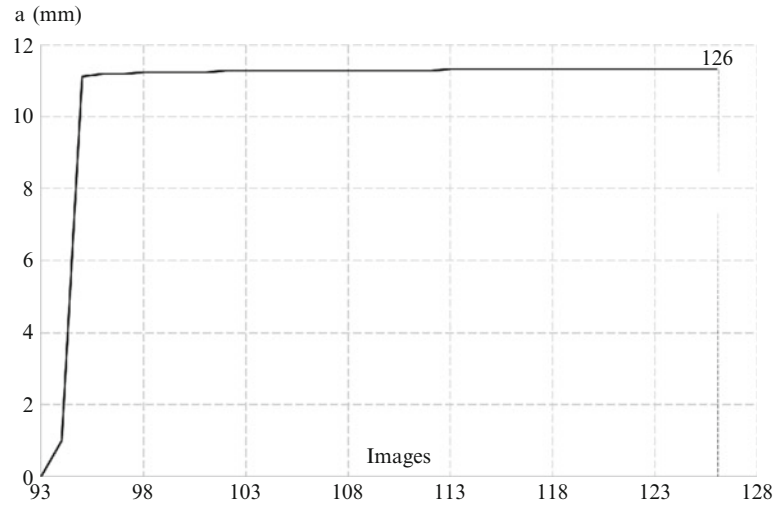

Fig. 2.6 Crack length—image number for Okume

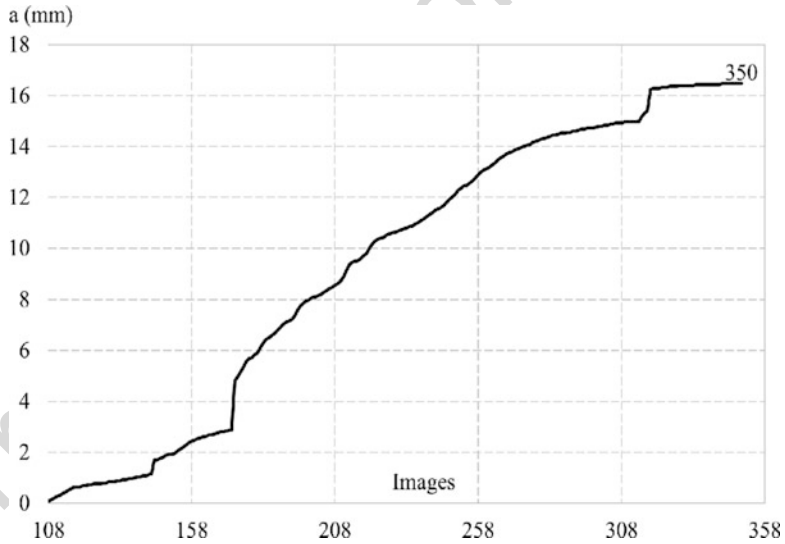

Fig. 2.7 Crack length—image number for Iroko

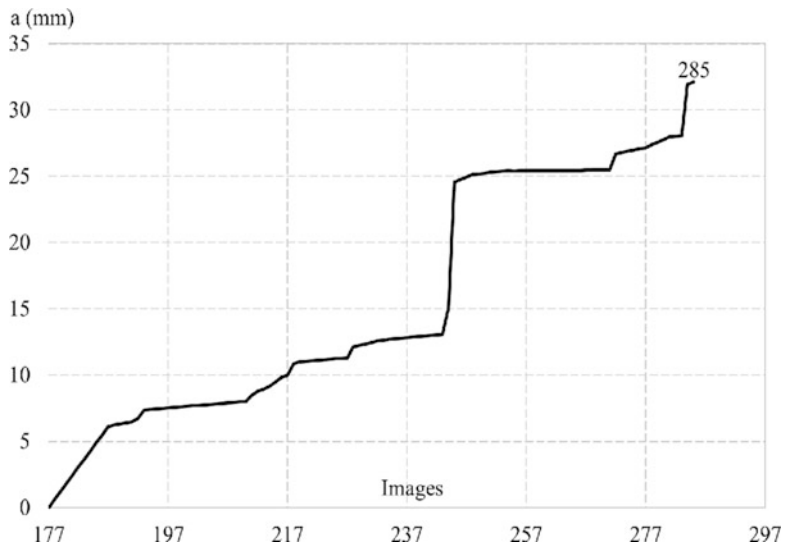

Fig. 2.8 Crack length—image number for Padouk

t.1 **Table 2.1** Critical energy release rate G_C

t.2 Wood species	Density	Crack length a (mm)	Compliance C (N/m)	Rupture force F(N)	Critical energy release rate G_C (J/m^2)
t.3 *Aucoumea klaineana* (Okume)	0.44	28	2.38E−06	147	82
t.4 *Milicia excelsa* (Iroko)	0.64	28	1.03E−06	375	234
t.5 *Pterocarpus soyauxii* (Padouck)	0.79	28	1.22E−06	568	632

$$G_C = \frac{F_C^2}{2b} \cdot \left(\frac{\partial C}{\partial a}\right)_d \tag{2.1}$$

where F_c is the critical load inducing a crack propagation length, b is the thickness of the specimen, and C denotes the compliance at imposed displacement. The results obtained are summarized in Table 2.1.

The values of density given by CIRAD [12] show that Padouk is denser than Iroko and Okume (see Table 2.1). Indeed, Okume is considered as a very light wood, Iroko as medium light wood and Padouk as medium-heavy / heavy wood. The present results show that the higher the density, the higher the value of the energy release rate. Thus the energy release rate value of Padouk is 2.5 times greater than that of Iroko, and that of Iroko is also more than 2.5 times that of Okume (see Table 2.1).

2.5 Conclusion

Tests were performed on three wood tropical species. The grid method was applied in order to follow the crack tip evolution during the test in opening mode. The critical energy release rate was obtained with the compliance method. It has been observed that the fracture toughness of Padouk is higher than that Iroko and Okume. In further work, the tests will be performed in mixed-mode configuration and for various orientations of the fibers.

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