3D crack growth monitoring in wood-based materials by means of X-ray computed microtomography and 2D DIC analysis method

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Abstract:

Crack initiation and growth in wood-based materials, commonly employed in buildings and civil engineering structures, still generate considerable inspection and repair costs besides the fact that is one of the most important factors involved in structural failure. X-ray computed microtomography (X-ray CT), which provides 3D images with a high level of detail at both the micro- and macro-scales, is frequently used as a non-destructive technique. In this work, the propagation of a 20 mm initial crack in Mixed-Mode Crack Growth (MMCG) wood samples was tracked using high-energy X-ray CT. Crack growth data were then determined from 3D tomography reconstructions. 2D crack tracking data measurements from fracture surface were performed using 2D Digital Image Correlation (DIC) analysis method. The collected 3D measurements were compared to those obtained from 2D DIC analysis and conventional mechanical tests in order to measure long and small crack growth. The observed results demonstrate that X-ray CT and surface tracking analysis using DIC can be successfully combined to study the crack propagation.

Résumé:

L'initiation et la croissance des fissures dans les matériaux à base de bois, couramment employés dans les structures et les ouvrages de génie civil, génèrent toujours des coûts d'inspection et de réparation considérables, outre le fait que c'est l'un des facteurs les plus importants impliqués dans les défaillances structurelles. La microtomographie à rayons X (XCT), qui fournit des images 3D avec un haut niveau de détail aux échelles micro et macro, est fréquemment utilisée comme technique non destructive. Dans ce travail, la propagation d'une fissure initiale de 20 mm dans des échantillons de bois a été suivie par la méthode XCT. Le suivi de la propagation en surface des fissures a été effectué en utilisant la méthode de la corrélation d'image numérique 2D (DIC). Les mesures 3D collectées ont été comparées à celles obtenues à partir de l'analyse 2D DIC et des essais mécaniques conventionnels, afin de mesurer la croissance des fissures. Les résultats observés démontrent que l'analyse par rayons X et la technique de suivi de surface par DIC peuvent être combinées avec succès pour étudier la propagation des fissures.

Keywords: Crack growth monitoring; wood-based materials; X-ray computed microtomography; 3D image analysis; DIC analysis

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 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 [9]. The benefits may also include energy savings, renewability of the resource, reducing the content of raw fossil materials and recycling [1]. 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.

Concerning materials, X-ray CT and digital image correlation (DIC), are frequently used as non-destructive techniques. Both 3D and 2D imaging techniques provide useful morphological descriptions of crack growth evolution [2, 3]. The principle of absorption of X-ray CT consists of reconstructing the attenuation coefficient from the attenuation measurements of an X-ray beam passing through the sample at different viewing angles. Differences in the linear attenuation coefficient among the fibers are responsible for X-ray image contrast, which enables the creation of two-dimensional images of the internal structure of the object. The reconstructed consecutive slices provide a 3D volume visualization with high resolution, thereby enabling morphological measurements of microstructure parameters such as porosity, effective area or crack length in a heterogeneous material [4, 5].

Given that small changes in on-site conditions (temperature, relative humidity, Internal moisture, etc.) have the potential to affect the morphological and mechanical characteristics of in-service wood-based structures [6], the objective of this study was to investigate the performance of the X-ray CT and DIC image analysis methods for damage monitoring applied to tropical wood specimens. The Mixed-Mode Crack Growth or MMCG [7], is used to show the accuracy of the 2D and 3D imaging techniques for measuring differences in crack tip advance. Therefore, the advantages and limitations of both methods are presented and discussed regarding the properties of the analyzed tropical wood samples.

2 Materials and methods

2.1 Wood samples and MMCG specimen

The wood specimens with dimensions 105x70x15 mm^3, depicted in Fig. 1 (a), are tested. An initial crack length ai = 22 mm is machined along the longitudinal direction (see Fig. 1 (a)). On one face of the specimen a speckle is deposited, see Fig. 1 (a). The values of the densities of the Okume, the Iroko and the Padouk are of 0.44, 0.64 and 0.79, respectively. The internal moisture content of all specimens is for Okume 9.12, it is 7.94 for Iroko and 7.29 for Padouk. The room temperature (T) is 21 °C and the relative humidity (RH) is 35%. Four washers in galvanized steel of a diameter of 6 mm were used to reinforce the holes, through which the load is applied, as shown if Fig. 1 (a). The lower and upper parts of the specimen have also been reinforced by thin aluminum plates. The camera was placed at 675 mm of the specimen in order to record crack tip progress. Displacement and strain fields were deduced from the recorded 2D images using the DIC method. The MMCG specimen and the experimental device are presented, Fig. 1 (b).

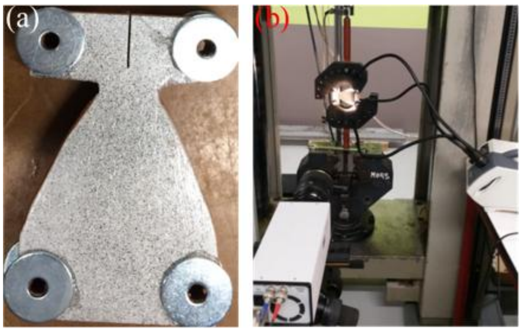


Fig.1: MMCG wood samples (a); Experimental set up (b)

2.2 X-ray microtomography

A Skyscan 1174 X-ray microtomograph was used for microtomographic acquisitions. The instrument is a high-resolution X-ray tomograph scanner with a closed X-ray micro-focus source for non-destructive three-dimensional (3D) microscopy. The maximum peak voltage of the Skyscan 1174 X-ray source is 50 kV with a maximum power of 40 W; it has a tungsten reflection target and a focal spot of 5 µm. The detection system consists of a 14-bit cooled CCD camera coupled to a scintillator by lenses with 1:6 zoom ranges. Multiple 2D X-ray projections are stored while the sample is rotated. The internal structures are reconstructed as three-dimensional images, which are then used to analyze the morphological and topological parameters of the object [2]. The process is non-destructive and requires no special preparation of the specimen. The Skyscan 1174 microtomograph can acquire images with a minimum pixel size of 6 µm. The investigated cracked wood samples extracted from MMCG specimens (Fig. 2. a), were glued on a metallic container (Fig. 2. b). This sample holder was placed between the X-ray source and detector. To obtain high-resolution images using X-ray CT, the magnification of the system was set so that the container remained within the field of view of the detector for the full rotation cycle. Projection images were taken every 0.4° rotation step over 360°. After reconstruction, a 3D volume was obtained in consecutive slices throughout from the 2D cross-sectional images of the investigated wood samples.

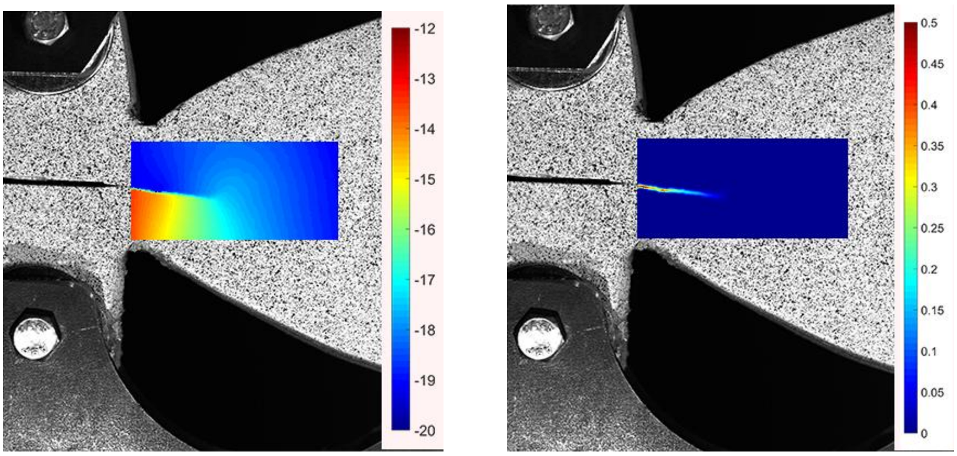
(a) ***(b)***

Fig.2: 3D image acquisition protocol by X-ray microtomography (from right to left): Cutting of the specimen and location of the sample, sample of wood to be scanned by XCT.

3 Results and discussion

3.1 Crack length and crack opening

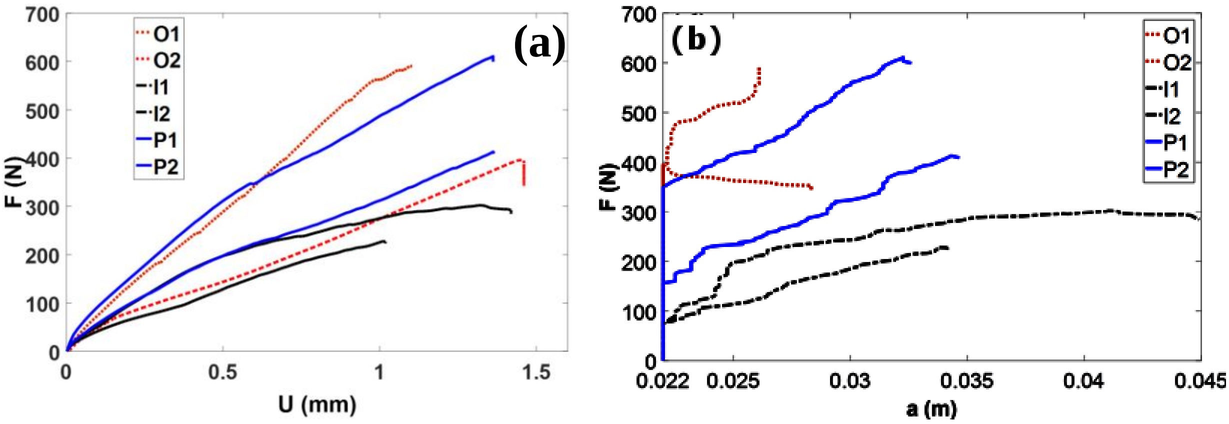
An example of typical displacement and strain fields obtained by DIC [8] are presented in Fig. 3. The crack pattern can be clearly distinguished from these maps. The aim here is to use these maps to determine the opening and the crack length for each loading step according to a Matlab algorithm.



(a) *(b)*

Fig. 3: Experimental set up (a); Displacement maps (b); Strain maps (c)

Fig.4 (a) and (b) illustrate the force (F) versus crack opening and the force (F) versus crack length curves respectively. The tests were performed only until the crack initiation in order to be able to scan it after the test using the X-ray microtomography technique (XMT). From these curves, it can be seen that the fracture toughness of the Okume specie is the most important.



(a) *(b)*

Fig. 4: Load versus crack opening curves (a); load versus crack length curves (b). O: Okumé, I:Iroko and P: Padouk

3.2 Crack growth monitoring using XMT

Because the main purpose of this work was to assess the quality and reliability of both X-ray tomography and 2D scanning method for crack progress monitoring in tropical wood samples, the overall quality of the damage growth assessment is discussed to highlight the strengths and weaknesses of these analysis methods.

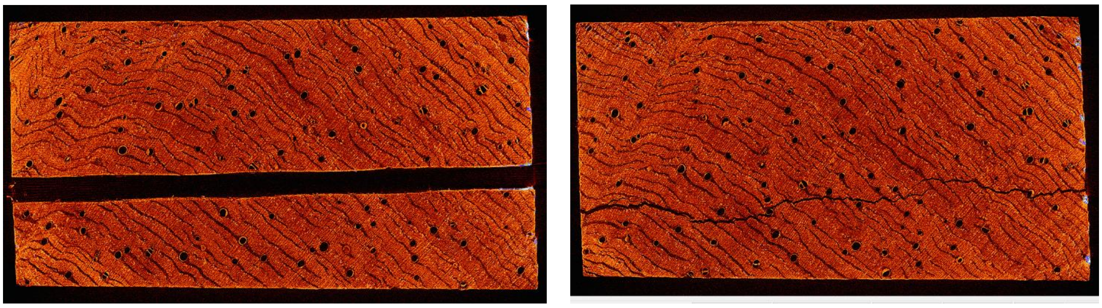
The use of weighted dimensions eliminates the effect of small-scale elements on average. This strategy may be relevant for assessment of the crack opening and direction estimation within 3D volume rendering.

Although crack length comparison performed on 2D and 3D images cannot be directly related to the specific features of the applied methods with regard to the analyzed crack length distribution, it provides some useful information. In fact, the mean length of the crack evolution is a good indicator of the damage level on MMCG wood samples, which is suitable for comparing the values obtained using different methods. Comparison of individual crack-based measurements is possible by relying on segmented images.

The volume-weighted crack length distribution of the analyzed tropical wood samples is calculated from 2D cross images (see Fig. 5). The volume-weighted crack length distribution presented in Table 1, showed that crack progress continues inside the MMCG wood samples most likely after this progress ends in the surface of the specimens. In addition, as the DIC method, the XMT technique showed that Iroko wood presents the lowest mechanical proprieties unlike the Okoumé sample, which showed the most resistance to rupture. This can be explained by, the fact that Padouk wood fibers and particles diameters, estimated using the XMT method (Fig 5b), showed a dispersion smaller than 60 µm and larger than 800 µm. Indeed, the conditions of fiber repartition inside the wood material affects the crack growth speed and direction as depicted in Fig. 5 b. The observation using the 3D scanning method showed that the crack tip progress tends to move towards larger fibers porosity all along crack path.

Table.1: Volume-weighted crack length distribution along the crack path

Wood samples	Padouk	Iroko	Okoumé
Volume-weighted crack length (cm)	2.46	3.72	1.67



(a) ***(b)***

Fig. 5: 2D Cross sectional images extracted from 3D volume of wet Padouk: sample with initial crack of 22 mm (a); progress of the crack under mechanical loadings (b).

4 Conclusion

This study compared X-ray MT, as a recently developed non-destructive technique, and DIC method for crack growth monitoring in tropical wood samples. 2D scanning technique is often used in the literature as a reference technique for surface tracking of crack growth in mechanical and civil engineering structures. This study confirmed that damage progress estimation of heterogeneous material such as wood is difficult. The results revealed that wood porosity distribution only available from 3D images may affect the crack tip orientation and the fracture toughness. Volume-weighted analysis based on the X-ray CT can provide a large range of different parameters that may be useful for crack advance monitoring, and then need to be interpreted. Additionally, it appears necessary to use an adaptive and complimentary analysis strategy to take advantage of the strengths of both X-ray micro tomography and DIC method.

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