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COMBINED ACOUSTIC EMISSION AND X-RAY MICRO-TOMOGRAPHY APPROACH FOR STRUCTURAL HEALTH MONITORING OF WOOD-BASED STRUCTURES

Seif Eddine Hamdi¹, Malick Diakhaté², Rostand Mouttou Pitti^{1,3,4}

ABSTRACT: Wood based-structures are very sensitive to the effects of climatic loadings such as temperature and hydric variations, during their service life. Therefore, mechanical properties modification due to these impacts leads to compromise the durability of timber structures. The present paper consists in investigating the cracks tip advance within tropical *Pterocarpus soyauxii* (Padouk) species, in order to improve their sustainability. This work gives a combination approach of the Acoustic Emission (AE) and X-ray Computed Tomography (X ray CT) techniques for their applications in wood structure health monitoring. The AE approaches of focus are the parametric and signal analysis which can be used to develop damage evaluation criteria. The X ray CT is used to internally investigate the damage opening and orientation at different lamella thicknesses to capture size effects.

KEYWORDS: Damage evaluation, Signal and Image analysis, Acoustic Emission, X-ray Computed Tomography, Wood material

1 INTRODUCTION

Optimizing the performance of wood based-structures often requires relating mechanical behaviour or morphological characteristics to microstructure. X-ray computed microtomography (X-ray CT), which provides 3D images with a high level of detail at both the micro- and macro-scales [1], may overcome these difficulties. When a damage mechanism occurs in wood material, a transient wave, resulting from the sudden release of stored energy during the damage process, propagates from the damage source through the medium. This phenomenon, known as the Acoustic Emission (AE) [2], is a very suitable technique for in situ health monitoring applications [3]. A key part of the analysis aims then to identify the most relevant descriptors of critical damage mechanisms occurring in these materials.

Various signal processing and pattern recognition techniques have been performed for damage feature extraction from AE signals [4]. As an example, the Hilbert–Huang Transform (HHT) [5], has recently been applied for analysing such non-stationary signals features analysis. A very promising 3D technic,

frequently used as a non-destructive technique is X-ray computed tomography (X ray CT) [6]. The reconstructed 2D consecutive slices provide a 3D volume visualization with high resolution, thereby enabling morphological measurements of microstructure parameters such as porosity, effective area or fibre diameter in a heterogeneous material [6].

In this paper, the HHT is used for the extraction of a damage mechanisms descriptor from AE signals in wood sample. A combined analysis of the potential of XCT (3D) and the AE technique for damage characterization is presented and discussed regarding the properties of the Padouk wood specie.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SETUP

The double cantilever beam geometry modified [11-12] in which the variable inertia allows a compatibility of the energy release rate behaviour is used in this work, Fig. 1(a). The DCB geometry is designed by calculating the energy release rate evolution for one unitary force using an elastic finite element approach, Fig. 1 (b). The calculation of G is performed by using the G-theta method implemented in the finite element software Castem developed by the French atomic energy commission [13].

The study was made from beech samples and linear friction welded or glued. Machining necessary to achieve timber samples adapted to Arcan assembly and testing were done in Institut de Recherche Dupuy de Lôme (IRDL). Preliminary tests combined with finite element

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modelling of the beech samples allowed to retain the geometries of specimens as depicted in Fig 1(a) [6-13]. The welded joint is less efficient than wood substrates, then, it is not necessary to make a reduction in the thickness of the study area. Some tests were used to compare the results for test samples with or without thickness reduction, it was not detected significant influence.

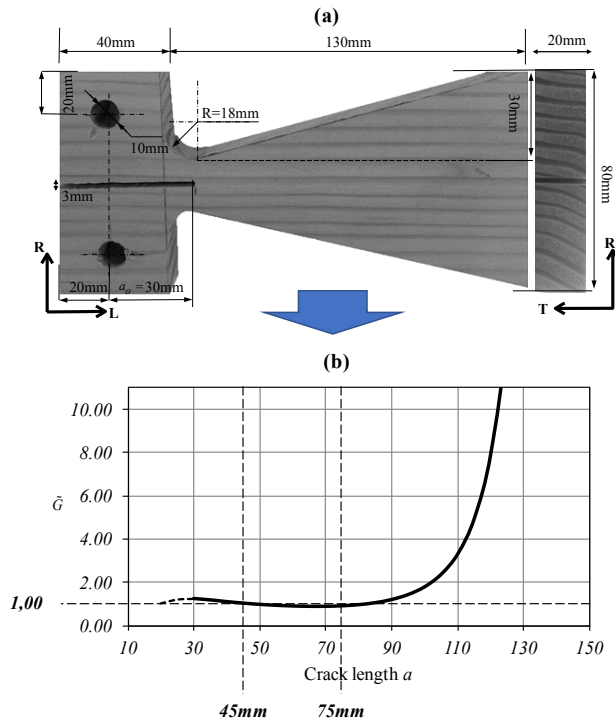


Figure 1: (a) DCB wood specimen – (b) Evolution of energy release rate versus crack length a (crack stability)

In order to introduce mixed mode configuration, the Mixed Mode Crack Growth (MMCG) specimen has been subject of several scientific studies [6-14], and allows 7 loading directions as shown in Fig. 2(a-b). MMCG is also applied to X-ray microtomograph tests. As the stress state is not homogeneous in the mean plane of the specimen, finite element simulations were performed to obtain the stress distribution in the useful part of the specimen. Thus, knowing the force applied by the testing machine on the specimen, it is possible to determine, in particular, stress at break as a function of the nature of the solicitation.

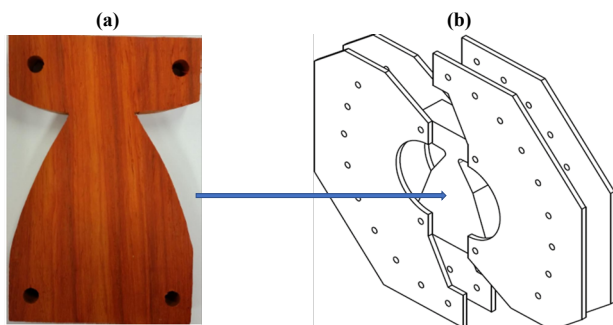


Figure 2: (a) wood specimen – (b) Modified Mixed Mode Crack Growth (MMCG) specimen

2.2 ACOUSTIC EMISSION

Fig. 3 provides a general overview of the experimental set-up with DCB specimen of Fig. 1 (a). An electromechanical MTS® press was used to apply the loading. The machine is equipped with a ± 500 N cell force, and a displacement sensor. Two linking parts made of aluminium were manufactured, and allow connecting the specimen to both the jack and the cell force of the testing machine. The tests were performed at a constant crosshead speed of 0.5 mm/min. This displacement control allows forcing stable crack growth during the fracture test. Both imposed displacement and resulting force values were recorded with a data acquisition system.

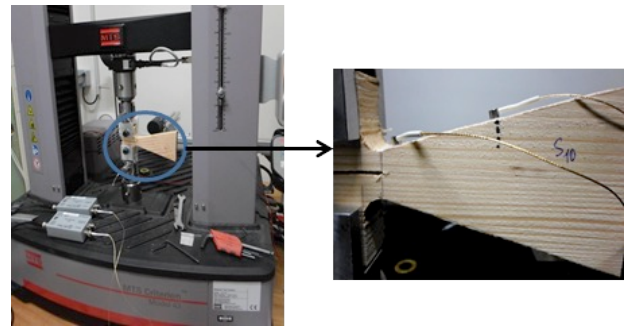


Figure 3: AE setup (Material, DCB specimen, AE sensors)

Under mechanical loading, the wood cracks generate transient elastic waves. The latter are referred to as AE waveforms. A Four-channel AE system designed by MISTRAS Group was used to record the AE waveforms generated during the laboratory tests. Since the crack path within the material is expected to follow the grain direction, two AE channels were enough to both record and perform a linear localization of the AE sources. Thus, two lightweight miniature piezoelectric sensors were connected to two preamplifiers. The latter were connected to the data acquisition card of the AE system. The AE sensors are coupled to the specimen with a double-face adhesive tape. This latter ensures a good acoustic coupling between the specimen and the sensors, and avoid the use of clamps to hold the sensors positions all along the test.

The acoustic signal acquisition threshold was set at 35 dB, which is slightly above the noise background amplitude. The AE waveforms were sampled at a rate of 40 MHz. Based on the literature review, which focussed on wave velocities within wood material, researchers reported that the anisotropic media of the wood material strongly affects the acoustic wave propagation velocity. Indeed, along the grain (longitudinal) direction, the measured wave velocity varies between 4000 and 6000 m/s (depending on the specie), whereas along the radial direction, the measured wave velocity varies between 1500 and 2500 m/s. In this study, the pencil lead breaking test was used to evaluate the AE wave propagation velocities within the wood material. The wave propagation velocity of 4000 m/s was used in the linear localization algorithm of the AE sources.

2.3 X-RAY COMPUTED MICROTOMOGRAPHY

A high-resolution Skyscan X-ray microtomograph with a closed X-ray micro-focus source, was used for non-destructive three-dimensional (3D) image acquisitions. A peak voltage of the X-ray source was set at 50 kV with a maximum power of 40 W. A 14-bit cooled CCD camera was used for pixel detection. The images were acquired with a minimum pixel size of 6 μm . The process is non-destructive and requires no special preparation of the specimen. The investigated cracked wood sample with dimensions around 10 x 10 x 10 mm^3 was withdrawn, and placed between the X-ray source and the detector, as shown in Fig. 3(a). Multiple 2D X-ray projections images were taken every 0.4° rotation step over 360°.

After reconstruction using image software, a 3D volume was obtained in consecutive slices from the 2D cross-sectional images of the investigated cracked wood, as shown in Fig. 4(a). Once the region of interest (ROI) was chosen, the crack path was then segmented and binary images were obtained. Three-dimensional rendering of the sample, as shown in Fig. 4(b), was used to obtain information regarding the orientation, porosity, density and size distribution using image analysis (Fig. 5), and thus about the crack growth process in dry and wet MMCG specimen (Fig. 2).

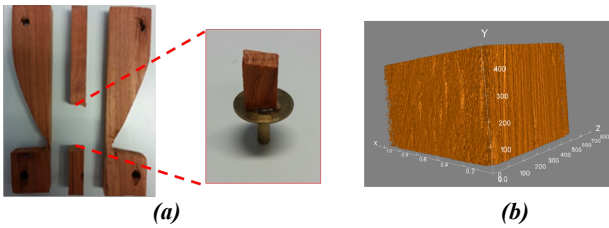


Figure 4: (a) Cracked wood sample – (b) Reconstructed 3D volume observation.

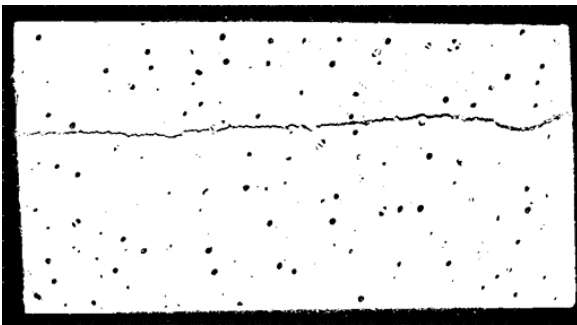


Figure 5: Crack properties extraction using image analysis.

2.4 PRINCIPLE OF THE HHT

The HHT [7, 8, 9] is a time–frequency method suited for splitting a multi-component non-stationary signal into a sum of elementary modes, or mono-component signals. The HHT uses two processing techniques, the Empirical Mode Decomposition (EMD) and the Hilbert spectral analysis (HSA). The EMD is based on the empirical estimation of the so-called Intrinsic Mode Functions (IMFs), each IMF, noted $ck(t)$ (for $k \in [1, N]$), corresponding to a given mono-component of the actual

signal. Due the HHT algorithm, the lowest IMF, $c1(t)$, corresponds to the highest frequency component of $x(t)$, and increasing IMFs, $ck(t)$, correspond to decreasing frequency components. Before explaining how to obtain the IMFs from $x(t)$, it is important to notice that each IMF exhibits the same number of extrema and of zero-crossings, and that only one extremum appears between two successive zero-crossings.

According to [5, 7, 8], each IMF fits the following properties: First, in the whole data set, the number of extrema and the number of zero-crossings must either equal or differ at most by one. Second, at any point, the mean value of the envelope defined by local maxima and the envelope defined by the local minima is zero.

3 RESULTS AND DISCUSSION

3.1 HHT BASED DAMAGE SIGNATURE IDENTIFICATION APPROACH

Improving the interpretation of the different mechanisms responsible for structural damage can be achieved by optimizing the classification of EA signals. This optimization takes into account the various phenomena present in the acoustic signal by the extraction of new damage descriptors. In this context, the HHT, applied to the analysis of EA signals in wood materials, will make it possible to extract and identify a time–frequency signature of the damage mechanisms.

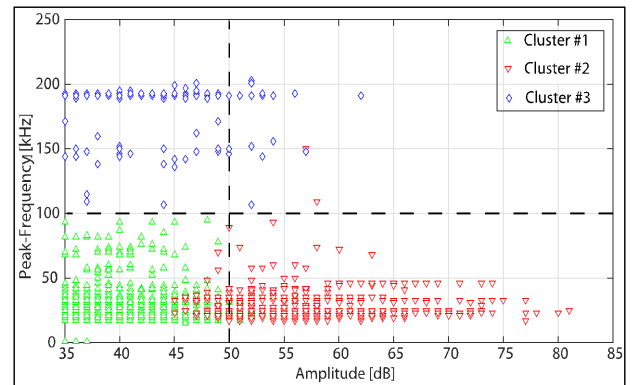


Figure 6: Clustering of AE events using two AE features

The collected AE signals were classified into three classes (Fig. 6) using the k-means method [10]. The HHT is applied to typical EA signals representative of three EA sources found in the wood and obtained by k-means method.

The HHT method is applied to the analysis of the classified signal waveforms. Respectively, Fig. 7(a), Fig. 8(a) and Fig. 9(a) present the classified AE waveforms obtained by the k-means method. The smoothed Hilbert spectrum of those AE waveforms, depicted in Fig. 7(b), Fig. 8(b) and Fig. 9(b), show the time–frequency representation of the AE signal. The colour in this figure corresponds to the instantaneous amplitude of each signal component.

The Smoothed Hilbert Spectrum (SHS) of these signals, shows energetic locations (high levels of the instantaneous amplitude) that correspond to the frequency signature of the wood damage mechanisms. The first class signal, depicted in Fig. 7(b), has a local energy distribution at the beginning of the signal, located at high frequencies (around 160 kHz). While second class signals, depicted in Fig 8(b), has a larger energy distribution over the entire signal, with a concentration around 140 kHz. However, the third class signal, presented in Fig 9(b), show a mix of energy signature related to the combination of multiple damage signature.

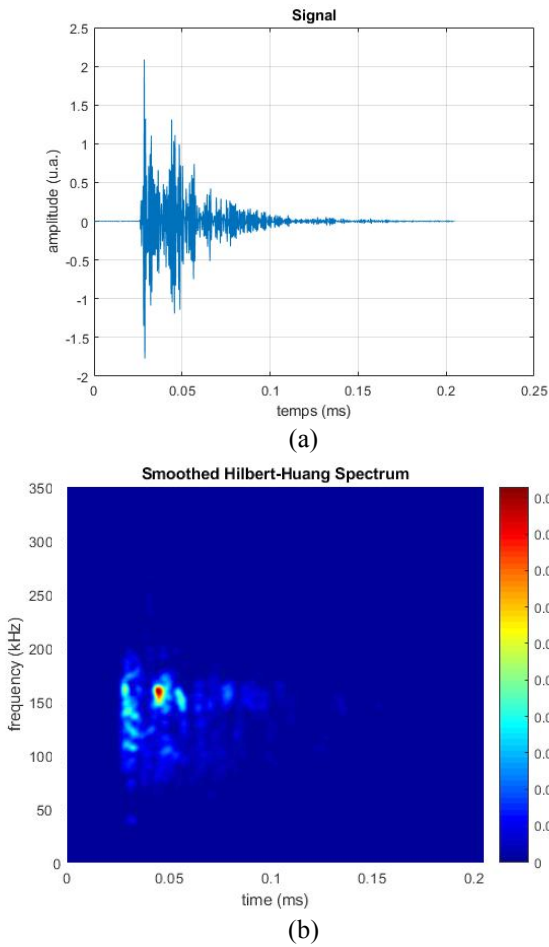


Figure 7: First Class signal waveform (a); AE signal analysis using HHT decomposition (b).

This first analysis shows that it is possible to discriminate the typical EA signals representative of HHT damage mechanisms as a function of their energy supply. A time-frequency descriptor, corresponding to the frequency peak of the Hilbert spectrum, is then proposed in the context of the discrimination of AE signals. The HHT then allows to associate the type and origin of the damage to a specific IMF. The great contribution of this technique lies in the fact that it is possible to go back to the time of occurrence of the damage in question, thus allowing a temporal location and, subsequently, a spatial location of the defect. Analysis of HHT based damage mechanisms identification can accurately track the kinetics of damage throughout the material's life cycle.

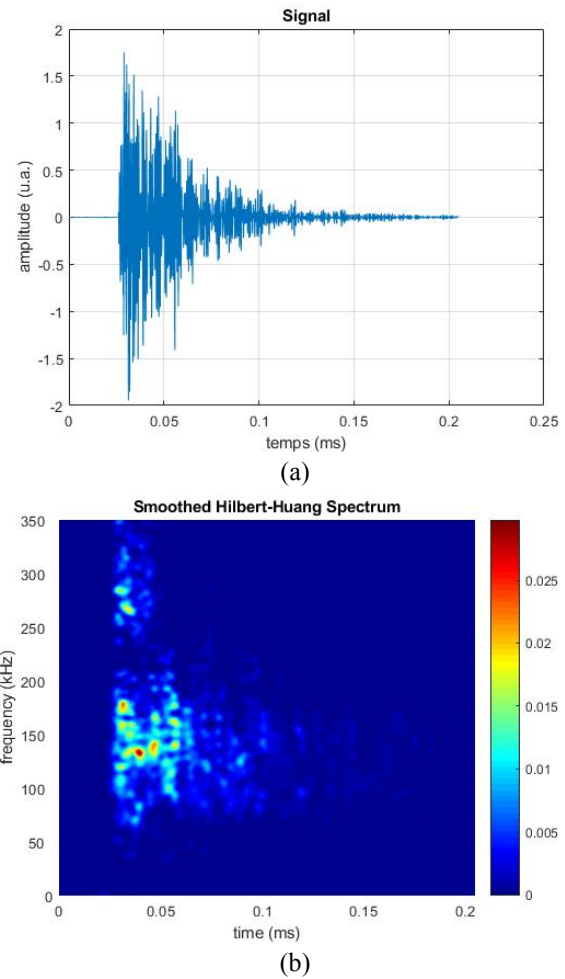
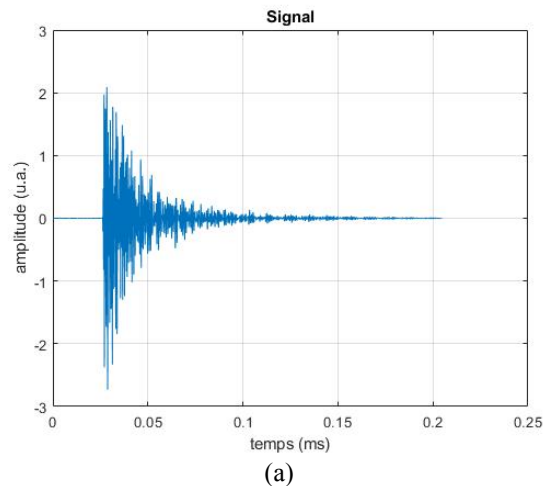


Figure 8: Second Class signal waveform (a); AE signal analysis using HHT decomposition (b).

However, The HHT analysis can pinpoint the frequencies changes evolution of the signal. Furthermore, it is to be noted the lack of precision of the HHT for instantaneous changes detection at high frequencies, and at each end of the signal (edge effects). In conclusion, the instantaneous frequency appears to have a good aptitude for the study of oscillatory parameters of a multi-components transient signal.



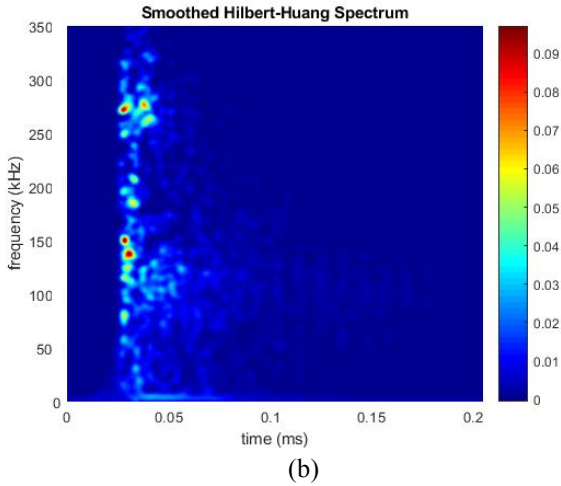
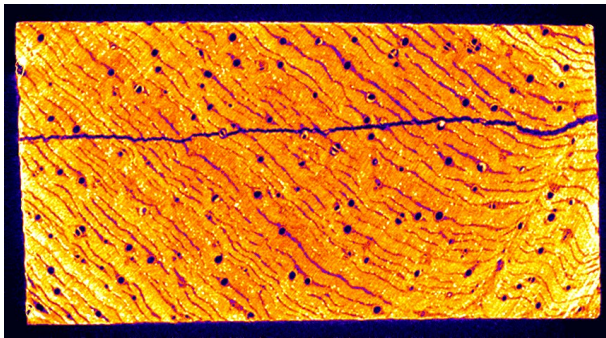


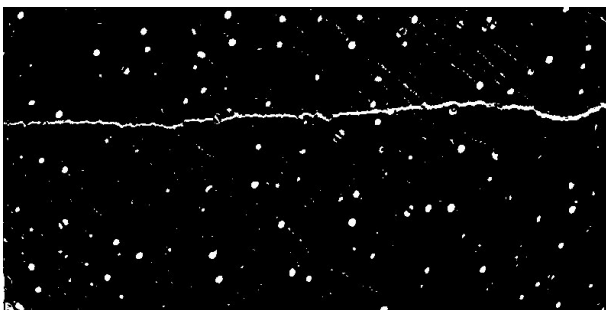
Figure 9: Third Class signal waveform (a); AE signal analysis using HHT decomposition (b).

3.2 3D IMAGE ANALYSIS OF CRACKED WOOD

Because the main purpose of this work was to assess the quality and reliability of the X-ray CT technique for observing the morphological characteristics of crack growth, the overall quality of the damage opening monitoring by 3D images analysis is discussed to highlight the strengths and weaknesses of the analysis method.



(a)



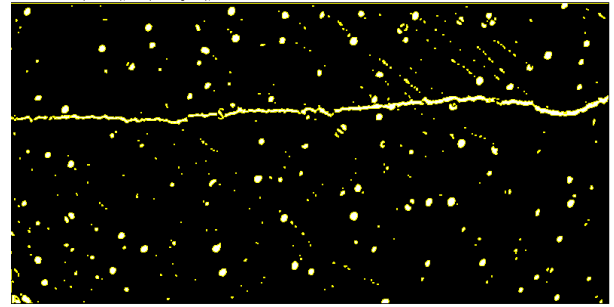
(b)

Figure 10: 2D cross sectional grey scale image of internal crack growth (a); Segmented crack opening by image analysis (b).

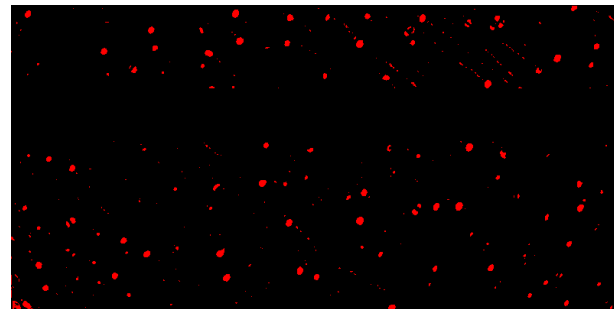
Fig. 10(a) presents the preliminary image processing step in order to extract information about the crack behaviour. The results of crack opening evolution by

means of X ray CT method is depicted in Fig 10(b). The surface-weighted hole distributions of wood fibres elements, calculated from 3D images is shown in Fig 11(a) and Fig 11(b), respectively. The surface-weighted diameter distribution showed that small particles and very short wood fibre do not occupy a large volume. However, the larger hole is responsible for crack bifurcation and advance due to the locally embrittlement of the wood strength. Nevertheless, the evolution of the crack opening is not similar for the both side of the wood sample, and the average damage area decreases when the crack length is decreased.

Thus, the surface-weighted pores, crack opening and orientation distributions calculated using the X ray CT method are suitable for the detection of small entities. Moreover, the maximum of the 3D volume analysed using the same method does not describe the entire length of the fibres. The X-ray CT resulted in slight overestimation of large heterogeneities based on the volume-weighted pores and crack opening distributions.



(a)



(b)

Figure 11: Crack length, orientation, and opening measure (a); Hole concentration and surface density estimation (b).

4 CONCLUSION

The analysis of the HHT-based classification leads to establish some conclusions. The first conclusion concerns that the HHT based descriptor, estimation from the mean frequency of the first IMF of AE signals, may be an accurate estimator for the AE classification. It can also be noticed that the mean frequency variation of the same class vectors is negligible compared to the boundaries variations of the damage frequency signatures in timbers materials. This can be explained due to the fact that these signals have as origin an energy release and their propagation within the structure alters

their amplitude, but does not impair their oscillation frequency. This shows the robustness of the HHT for non-stationary features extraction.

The HHT combined to X ray CT provide encouraging results for non-stationary AE signals features extraction. Moreover, instantaneous frequencies may provide relevant descriptors for in situ health monitoring applications. This paper opens new perspectives. Work on the instantaneous frequencies signals content can provide new relevant damage descriptors. In fact, once the acoustic signatures of the different damage mechanisms are recognized, a signals library is then available to help performing a supervised AE data sets clustering. Therefore, real time damage detection and its severity estimation may be possible. In this case, it is also conceivable to identify the diffuse damage by an embedded system, and to solve the problems of coupling pad structure. However, real-time implementation of the proposed method still needs a little works in the future.

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