Acoustic Emission Technique (AET) for Failure Analysis in wood materials

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Abstract Understanding failure mechanisms of construction materials as well as their damage evolution are two key factors to improve design tools of structures. Depending on failure modes to be highlighted, and studied, several tests methods, and analysis tools have been developed, in particular AET. This latter is an experimental tool well suited for characterizing material behavior by monitoring fracture process. Despite the wide use of AET to characterize and monitor damage evolution of composite materials, few research studies focused on using AET to characterize the mechanical behavior of wood materials.
In this work, the failure process in wood material under monotonic loading is studied by confronting three experimental methods; by analyzing stress-strain curves, AE measurements, and digital image acquisition. First, results show good correlation and complementarity between the used methods. Second, simple approach in analysis of AE signals (cumulative event and energy) gives important information about crack initiation and growth without the material. Moreover, advanced analysis of AE data (determination of source locations and the study of mechanism of individual events; study of amplitude distributions; investigation of frequency characteristics of emission events) will allows us to understand some key damage mechanisms such as the fracture process zone.

Keywords Acoustic Emission, Cracking, Wood, Fracture Energy

1. Introduction

Knowledge of the failure mechanisms of construction material as well as their damage evolution are two key factors to improve design tools of structures. In this context, Seismic **N**on-**D**estructive **T**echniques **(NDT)** which are based on stress wave propagation are interesting techniques for monitor structural integrity and characterize the behavior of materials when they undergo deformation, fracture, or both. These techniques can be divided into two methods: passive and active. This paper focuses on the **A**coustic **E**mission **T**echnique (**AET**) which is a passive method. Acoustic emission may be defined as transient elastic waves generated by the rapid release of strain energy in a material. A number of micro and macro processes contribute to both the deformation and the deterioration of a material under strain, resulting to a series of acoustic events. Thus, the events released by the material contain information regarding the general deformation process.
Kawamoto and Williams [1] reported literature review on the feasibility of AET for monitoring defects in wood. The advantages and the disadvantages of this technique were also described. It was noted that the AE investigations for wood products can be classified into five fields: (i) monitoring and control during drying; (ii) prediction of deformation; (iii) estimation of strength properties; (iv) fracture analysis, and (v) machine control.

This introduction focuses on fracture analysis by AET. Ansell [2] related the AE-strain characteristic from three softwoods tested in tension to mechanisms of deformations observed by scanning electron microscopy. The authors also reported correlation of EA total count with fracture toughness. Similar relationship was obtained by Suzuki and Schniewind [3] during cleavage failure in adhesive joints. Landis and Whittaker [4] compared the energy released by a mode I crack propagation in wood with the resulting acoustic emission energy. Results of the energy comparison indicated a good correlation. Reiterer et al., [5] investigated the mode I fracture behavior of softwoods and hardwoods under the splitting test associated to acoustic emission measurements. The measured AE parameters included cumulative counts, amplitude and frequency spectra. The results showed that the AE counts until the maximum force was reached are much higher for the softwoods supporting the interpretation that the softwoods behave more ductile and therefore build a process zone containing much more microcracks. It was also shown that the differences in macrocrack formation and propagation can be visible in the shape of the cumulated AE counts and the AE amplitudes. More recently, Ando et al., [6] used AET to examine the microscopic process of shearing fracture of old wood.

In conclusion, the potential of laboratory AET to examine the fracture process in wood has been clearly demonstrated in the literature review. Simple AE approaches were used, for example: recording the events by expressing them in the form of event rate or cumulative events; study of amplitude distributions; investigation of frequency characteristics of emission events. All these approaches were performed by considering AE events without determination of source locations. The purpose of this study is to investigate mode I fracture of wood using determination of the position of developing cracks with AE measurements. The AE source is determined from the time differential of AE signals among two piezoelectric transducers (linear location). The determination of source locations associated to the attenuation curve in the tested sample allows correction of the output signal amplitude of the AE transducer. In this study, AE measurements were associated to digital image acquisition during the tensile test.

2. Experimental Procedure

For the present study specimens were cut from softwood (Douglas) and conditioned, in climate-controlled room, to constant moisture content for about 10%. The temperature and relative humidity were regulated at 20 °C and 40% RH, respectively. The specimens had the following dimensions: W = 80 mm; L = 170 mm; T = 15 mm (Fig. 1). Next, a 50 mm notch was cut along the grain to create a mode I double cantilever configuration. The starter notch was introduced with a band saw (3mm) and the notch orientation was chosen such that crack propagation took place in longitudinal direction.

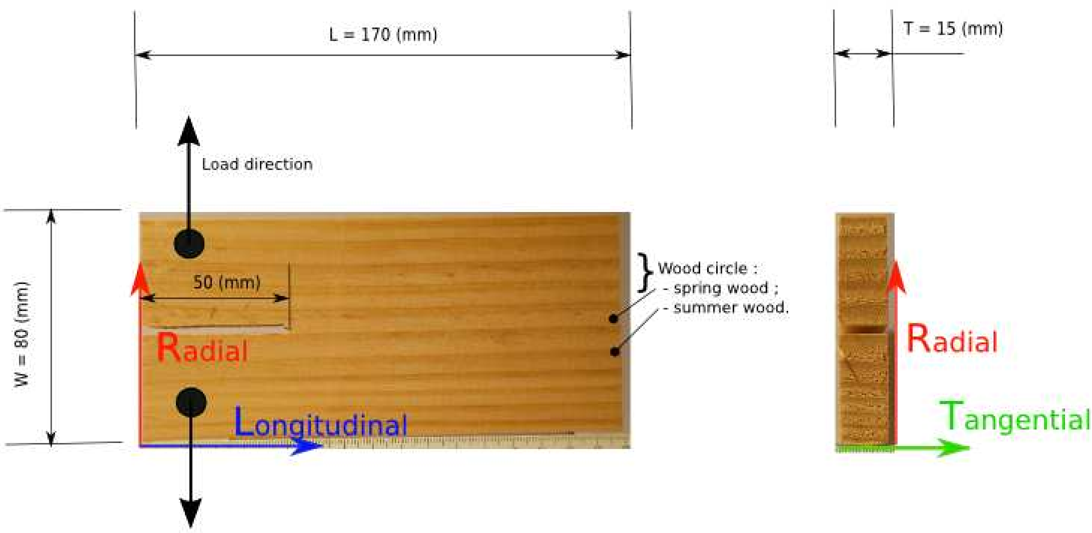


Figure 1. Photography of mode I fracture specimen.

The specimens were loaded under displacement control in an universal testing machine with a 50 kN load capacity. Load was applied to the specimen through the use of shafts that are pushed into holes drilled through the top and bottom cantilevers. A total of 4 specimens were tested at constant displacement-rate of 0.5 mm/min. Synchronized with the testing machine, an 8-bit Charge-Coupled Device camera measured the displacement fields. Thanks to this full-field optical method, the displacement evolution on the specimen surface could be recorded throughout the test. Also note that the image rate of the camera was set at 2 frames/s.

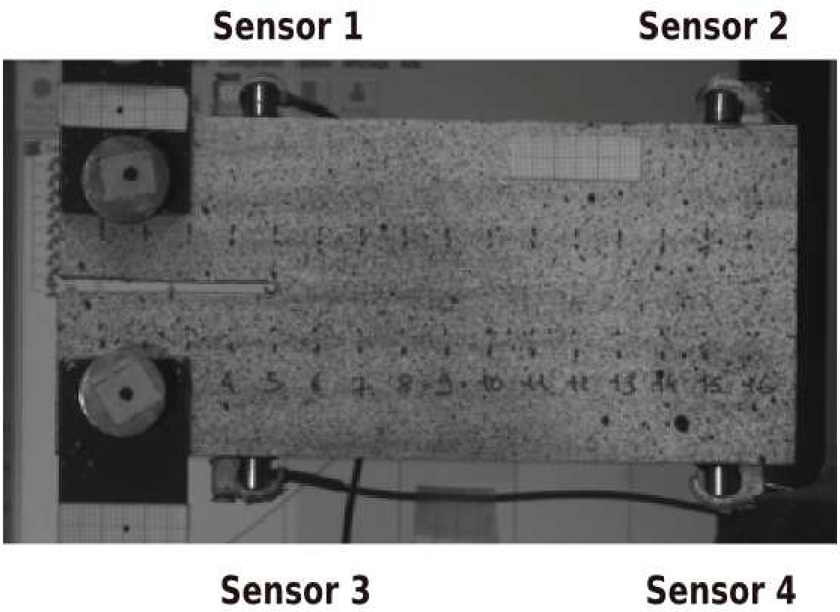


Figure 2. Photography of a specimen instrumented with AE sensors

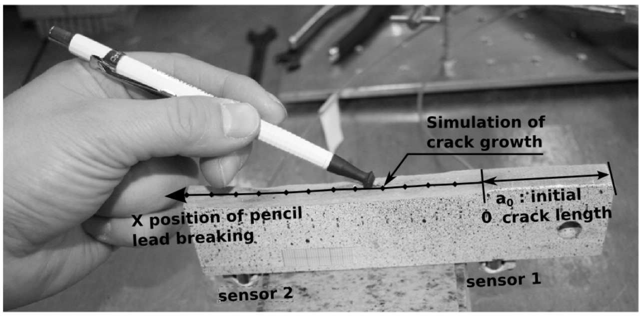
During the test, AE event signals were monitored and recorded using a Euro Physical Acoustics (EPA) system:

- Four piezoelectric transducers (Nano30), with a band characteristic from 125 to 750 kHz, and 140 (and 300) kHz resonant frequency, were mounted on the specimen (Fig. 2). The transducers were coupled to the specimen with a silicon grease to avoid loss of acoustic signal at the transducer-sample interface;
- Pre-amplification of the AE signals was provided by four preamplifiers (IL40S model) with a gain set for 40 dB;
- AE signals were sampled at 20 MHz and filtered with amplitude threshold about 40 dB. It is clear that the detected events depend on the value of this threshold. Before the loading test, the effective propagation velocity of the longitudinal waves was determined by generating an elastic wave using the conventional pencil lead breaking.
- A signal conditioner and software that allow recording the AE features in a computer for further analysis.

3. Data Analysis and Discussion

3.1. Calibration of Acoustic Emission Measurements

For wood, the wave velocities are very dependent on propagation direction. Consequently, conventional AE source location techniques such as 2D planer location mode, which assume isotropic velocity, cannot easily be used for wood. Thus, AE source location, the most identifiable and beneficial factor of the AE technique for homogenous materials, is difficult to use on wood. In order to overcome these difficulties, we adopted in this study a liner location mode combined with a specific calibration procedure. The value of effective AE wave velocity (5350 m/s) was evaluated by the conventional pencil lead breaking.



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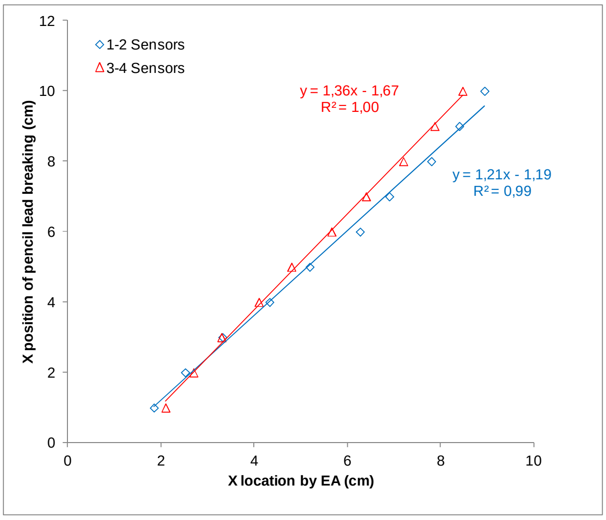

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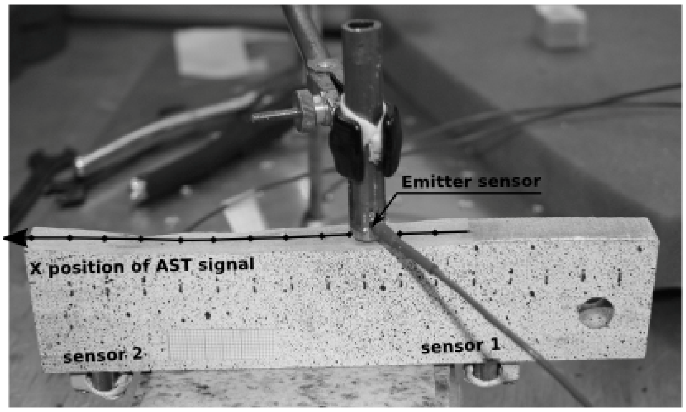

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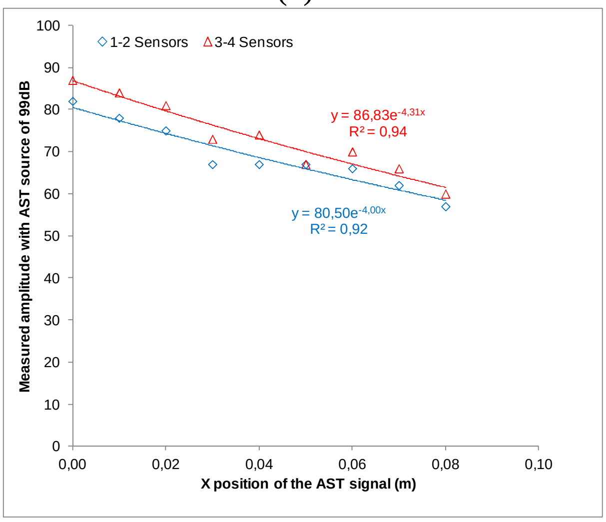


(d)

Figure 3. Calibration of Acoustic Emission Measurements. a) Photography of the pencil lead break method. b) calibration curve of the acoustic emission location. c) Photography of the AST method for attenuation measurements. d) Attenuation profile of the AE response on the wood sample.

All specimens were tested, after the fracture loading, using pencil lead break to simulate the burst signal propagation. The device (pencil lead break) is an aid to simulate an acoustic emission event using the fracture of a brittle graphite lead in a suitable fitting. This generates an intense acoustic signal, quit similar to a natural AE source, which the sensors detect as a strong burst. Figure 3 presents the principle of the pencil lead break method preformed on the fractured sample (Fig. 3.a) and the calibration curve of the acoustic emission location (Fig. 3.b).

The amount of AE wave attenuation depends on the proprieties on the material. For the tested samples, attenuation curve (Fig. 3.d) is performed by using the AST procedure (Auto Sensor Test, Fig. 3.c). AST provides an automated means of pulsing and receiving of simulated AE burst that is coupled to the structure. Similar results of attenuation curve can be also obtained by using the pencil lead break method. The attenuation curve plotted in figure 3.b is the consequence of several phenomena taking place as AE waves propagate along the sample: dispersion, scattering and eventually dissipation. The results presented in these figures highlight the importance of the AE calibration procedure in the analysis of AE data.

3.2. Analysis of Energy Balance

The energy approach states that crack extension occurs when the energy available for crack growth is sufficient to overcome the resistance of the material. The material resistance may include the surface energy, plastic work, or other type of energy dissipation associated with a crack propagation. Figure 4.a illustrates the load-displacement behavior of tested wood specimens with a growing crack. Consider point A on the presented curve. The crack has grown with Δa length from initial length a_0. The crosshatched area represents energy that would be stored in the material where considering linear elastic behavior; the remainder is the energy dissipation associated with a propagation crack.

Examination of the plot of figures 4.c&d illustrates a number of things. First, crack growth initiation detected by image analysis occurs closely after the end of the linear elastic behavior. The progression of the crack front propagation according to the displacement loading is quasi-linear showing stable crack growth in the tested specimens. A second point to observe is the over shape similarity when we compare the fracture energy curve and the crack front propagation curve. Thus we can assume validity of the initial hypothesis, linear release of stored elastic energy, used in the energy balance analysis.

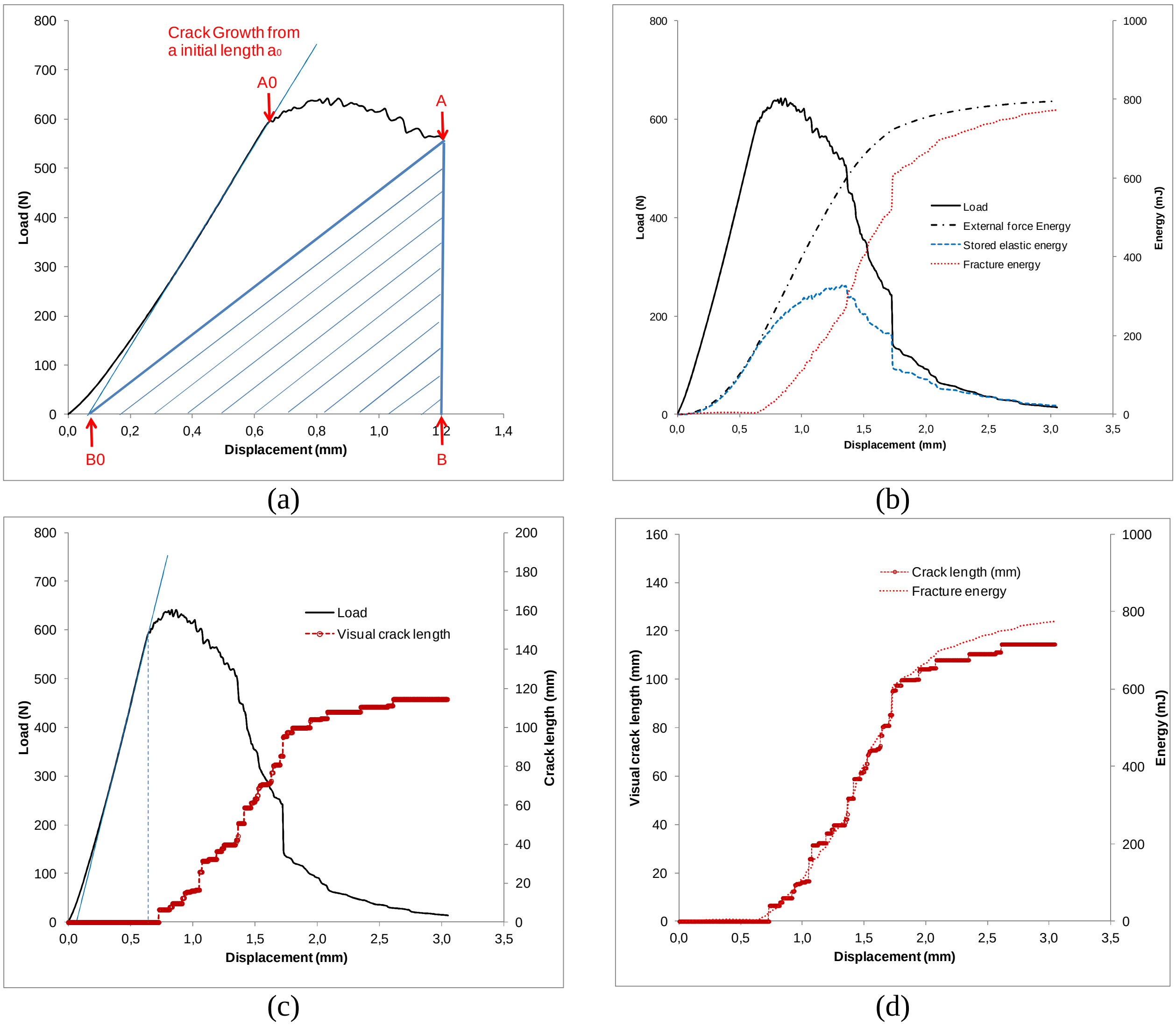
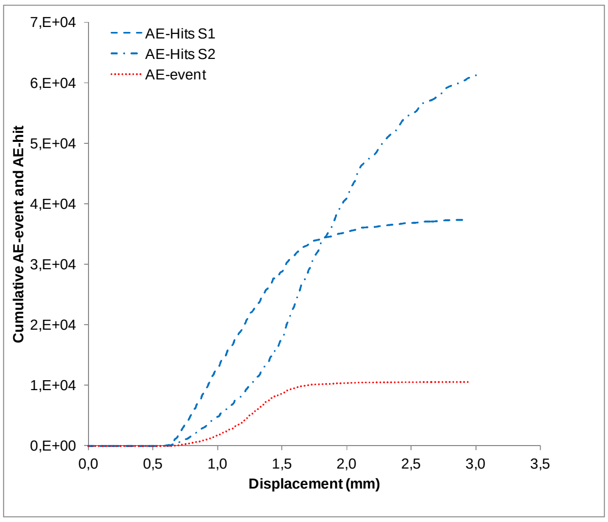


Figure 4. a) load-displacement curve for a specimen with a crack that grows with Δa length from initial length a_0: A_0ABB_0 (External force energy); ABB_0 (Stored Elastic Energy) and B_0A_0A (Fracture energy). b) Energy balance according to the displacement loading. c) Plot of load-displacement curve and crack front propagation measured by image analysis. d) Plot of fracture energy curve and crack front propagation.

3.3. Acoustic Emission Analysis

The recorded AE data are presented with respect to both AE-event (located material change giving rise to acoustic emission) and AE-hit (detected and measured signal for each cannel). To perform comparison with the mechanical results (energy balance) we consider one of the most important characteristic parameter of the AE in the amplitude-time domain, namely AE energy. With conventional AE energy analysis, the AE waveforms are squared and integrated over time. Although that analysis produces an energy measure, the resulting units do not lend themselves to direct comparisons with other energy analyses.



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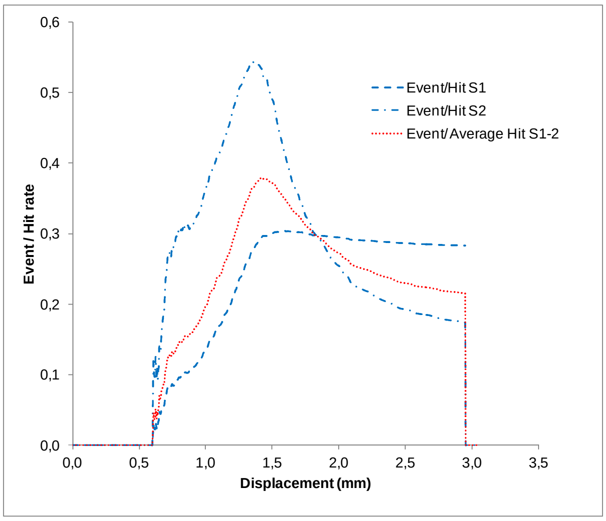

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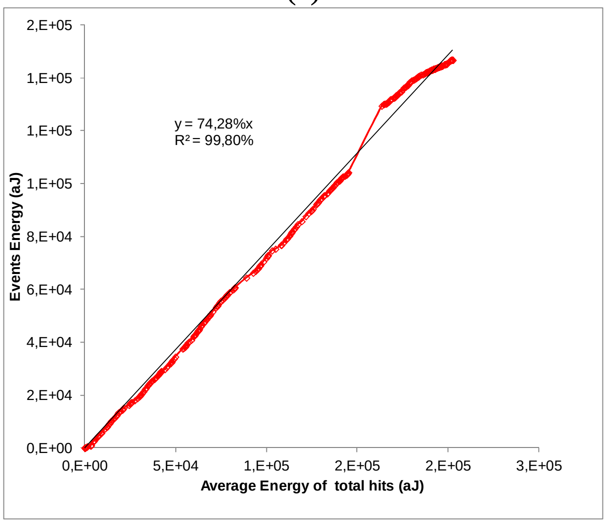

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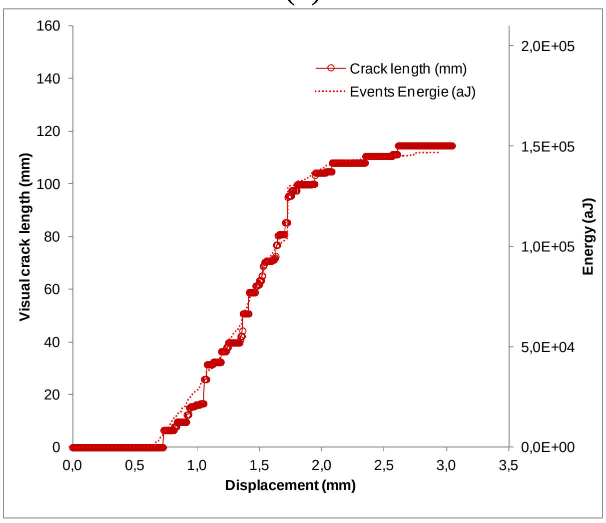

(d)

Figure 5. AE data. a) Cumulative AE-event and AE-hit for 1-2 sensor's group location. b) ratio between cumulative AE-event and cumulative AE-hit. d) Comparison of AE-event energy and AE-hit energy. d) Plot of AE-event energy curve and crack front propagation.

Plotted in figure 5 is, for each AE sensor, the cumulative AE-event along with the cumulative AE-hit. Similar results was observed between 1-2 sensor's group location and 3-4 sensor's group location, and only data from the first group are plotted. For linear location mode of AE source, calculation of x-position of each event is based on the measurement of the differences in first wave arrival times between two recorded AE-waveforms (Hits). The first wave arrival time is detected as the first threshold crossing by AE signal. Another parameter necessary for time difference location method is effective velocity. It can be established experimentally with or without considering different wave propagation modes (longitudinal, shear and Rayleigh waves). In this study, the value of effective AE wave velocity was evaluated by the conventional pencil lead breaking, and the obtained value is 5350m/s. The propagation modes were not separated inducing AE-hits which cannot be located. Indeed, figures 5.a&b show that approximately 30% of the average recorded hits from the 1-2 sensor's group location are located. However, figure 5.c shows a good correlation between AE-event energy and AE-hit energy. It should be noted that AE-hit energy is not corrected according to the attenuation curve. Some part of the no-located events can be caused by external noise such that caused by the loading system. Finally, if we compare figures 4.d and 5.d it can be shown that greater correlation between the energy release and the crack front propagation is obtained from the AE measurements.

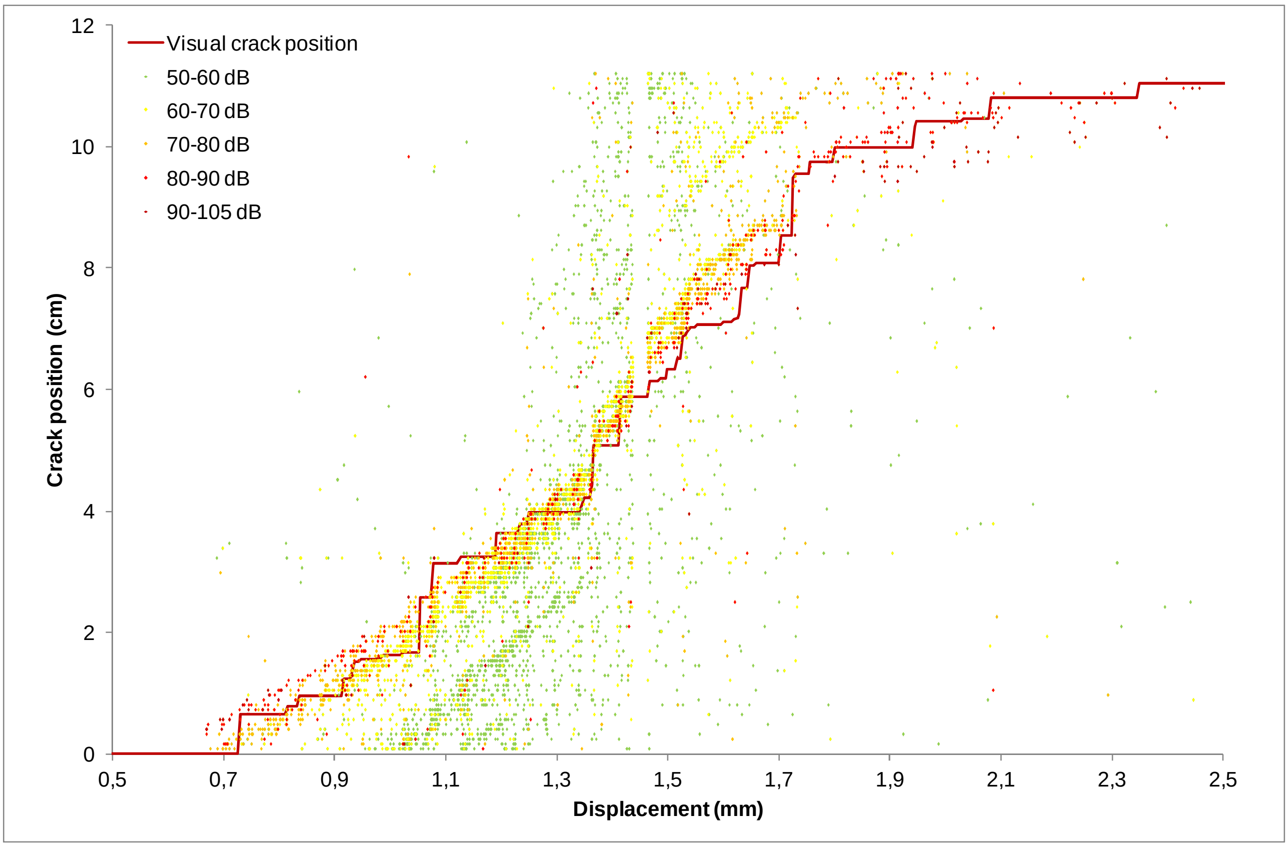

Figure 6. AE-events location and visual crack position vs. displacement loading.

In figure 6 is presented the crack front propagation curve obtained from the AE location process. The dynamic of the crack propagation is in good agreement with the results obtained with the image analysis. In addition, it was observed that the crack front appears to be associated with a Fracture Process Zone. Future works, based on AE waveform analysis using moment tensor components, will allow the crack classification and understand the mechanisms of this localized area.

4. Conclusion

In this study, we observed that the AE technique is an efficient tool for characterizing the failure process in wood materials. First, the experiment showed that crack initiation and crack growth detected by the AE activities is in a good agreement with the image analysis results. A second point to observe is that progress in AE-energy, during the test, is very similar to changes in fracture energy calculated from the load-displacement curve. These results were obtained for the both approaches used in the analysis of acoustic data: global approach with considering AE-hit signals and localization approach by using AE-event signals. For future works, this experimental investigation shows that the use of the localization approach seems to be a very promising method to investigate the cracks mechanisms such as the process zone.

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