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Damage characterization on human femur bone by means of ultrasonics and acoustic emission

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Abstract. Human bone tissue is characterized as a material with high brittleness. Due to this nature, visible signs of cracking are not easy to be detected before final failure. The main objective of this work is to investigate if the acoustic emission (AE) technique can offer valuable insight to the fracture process of human femur specimens as in other engineering materials characterization. This study describes the AE activity during fracture of whole femur bones under flexural load. Before fracture, broadband AE sensors were used in order to measure parameters like wave velocity dispersion and attenuation. Waveform parameters like the duration, rise time and average frequency, were also examined relatively to the propagation distance as a preparation for the AE monitoring during fracture. After the ultrasonic study, the samples were partly cast in concrete and fixed as cantilevers. A point load was applied on the femur head, which due to the test geometry resulted in a combination of two different patterns of fracture, bending and torsion. Two AE broadband sensors were placed in different points of the sample, one near the fixing end and the other near the femur head. Preliminary analysis shows that parameters like the number of acquired AE signals and their amplitude are well correlated with the load history. Furthermore, the parameters of rise time and frequency can differentiate the two fracture patterns. Additionally, AE allows the detection of the load at the onset of fracture from the micro-cracking events that occur at the early loading stages, allowing monitoring of the whole fracture process. Parameters that have been used extensively for monitoring and characterization of fracture modes of engineering materials seem to poses characterization power in the case of bone tissue monitoring as well.

1. Introduction

Acoustic emission (AE) is a technique used in several occasions for the monitoring of the fracture behaviour of materials. Usually piezoelectric sensors are attached on the surface of the material to record the elastic waves generated by cracking incidents in the material. This provides valuable input on the failure process from early stages, certainly before fracture is apparent by visible macro-cracks [1]. Study of the rate and amount of recorded activity is correlated to the applied load and the damage

condition of the material [2-6]. Additionally, indices based on the energy or amplitude of the recorded waveforms are used to characterize the intensity of fracture and possibly make projections for the future life [7,8]. In different types of engineering materials AE has demonstrated the capability to characterize the damage mode. This has been demonstrated in different materials like rock, concrete, metal, ceramics and composites [2-9]. The application of AE in human tissue studies though, reveals specific difficulties. A basic one is that due to the nature of specimens (excised from cadavers), limited number of experiments can be conducted. However, there is an extensive literature study by Browne et al. [10] and Shrivastava et al. [11] regarding the use of AE technique in the general biomedical field.

Apart from the limited number of experimental works, another difficulty is the geometry of the specimens and the interpretation of the results. It should me mentioned that considerable effort is given in the ultrasonic assessment of properties, which can be applied for diagnosis purposes of fracture or healing of bones [12-16]. Cortical bone is one of the most complex materials. Due to the microstructure, the properties of porosity and stiffness are varying from the periosteum to endosteum. It appears that the thin and curved geometry of cortical bone endows additional plate wave dispersion. In that kind of heterogeneous media, the elastic waves have the tendency to separate into different modes due to the different velocities of the several frequency components. This complexity and dispersive nature may lead to false AE characterization during fracture. There are extensive studies in AE monitoring on structural materials with respect to the crack characterization with sufficient results [17,18]. Nevertheless, this is not the case for bone tissue where the AE waveform character cannot linked with a fracture mode under a certain load level. Due to the aforementioned irregularities, it is essential to make an ultrasonic study on the same specimens as a preparation for the AE characterization during fracture experiments. Crucial parameters of the AE waveforms can provide information which will exhibit differences due to the propagation distance through the volume of the bone.

In the present study results on fracture experiments in human femur specimens with concurrent monitoring of AE are reported. Waveform parameters like the duration, rise time and average frequency, are also examined relatively to the propagation distance as a preparation for the AE monitoring. The setup applies a mixed bending-torsion monotonic loading on the head until fracture. The AE activity shows the point of micro-cracking onset as well as its development. AE parameters like frequency and rise time exhibit strong shifts with the increase of load, showing that the fracture mechanisms are not stable throughout loading. Discussion is made on the possible correlations between AE parameters and maximum load, thickness and ultrasonic parameters that have been investigated prior to failure [19].

2. Experimental details

This study was performed on eleven femur specimens excised from cadavers. The specimens were supplied by the Anatomy Department of the School of Medicine of the Vrije Universiteit Brussel.

Initially, a preliminary study was conducted on five specimens with the purpose to study the separating burst of the waveforms. In order to obtain these results, four sensors were recording the changes during wave propagating. The sensors were placed in a way to capture the propagation in axial transmission and not through the thickness of the bone. The distance between the sensors was set on 10 mm and the pulse was excited by fractures of mechanical pencil leads in a distance of 5 mm in front of the first sensor. The sensors were of Pico type with a broadband response and maximum sensitivity at 450 kHz. The electric waveforms were pre-amplified by 40 dB and recorded to the acquisition board with sampling rate of 10 MHz in the acquisition board (PAC micro-II, 8 channels). Vaseline grease was used as acoustic coupling and the sensors were located on flat areas of the femur specimens in order to avoid contact problems.

After the ultrasonic study, the samples were partly cast in concrete and fixed as cantilevers (see Figure 1). The “head” of the femur was 120 mm away from the fix point in all specimens. A support was provided in the main body of the specimens (point of minimum elevation) by a metal bolt in order to avoid the fracture at the fix point due to bending moments. The load was applied by a piston

resulting in a vertical (nearly) point force. The geometry of the setup resulted in a combination of bending and torsion and different fracture patterns as will be mentioned in the results section.

During AE monitoring two AE broadband sensors (of the same specifications) were used. The first was placed near the fix point and the second at the bottom of the head as it is depicted from Figure 1. While the general placement was similar, their exact position could not be identical in all specimens due to local differences in geometry and curvature. The sensor position was such that AE signals could be potentially captured from the fix point of maximum bending moment as well as from the head which is usually the most exposed part in hip fracture. The threshold was set at 30 dB and acoustic coupling was improved by vaseline grease between the sensors and the surface of the femur, while the sensors were secured by means of tape. Despite the geometry and heterogeneity of the medium, event location was enabled and it resulted in satisfactory localization since pencil lead breaks could correctly be identified in three areas (head, middle of the specimen and close to the fix point). The pulse velocity was measured in an earlier study on the level of 3500 m/s [19].

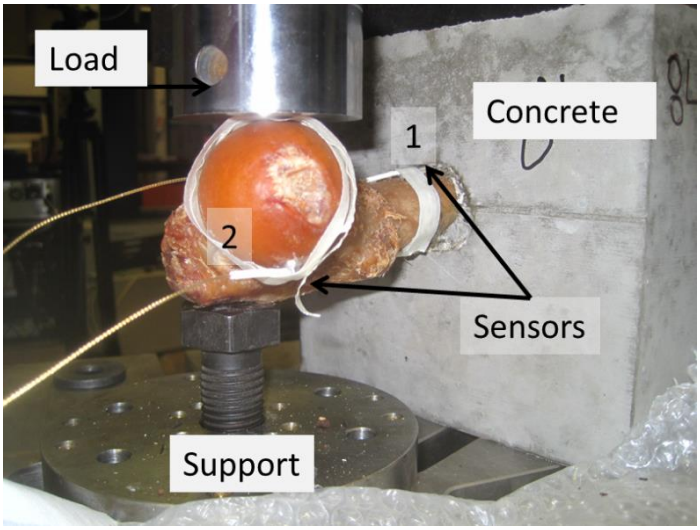
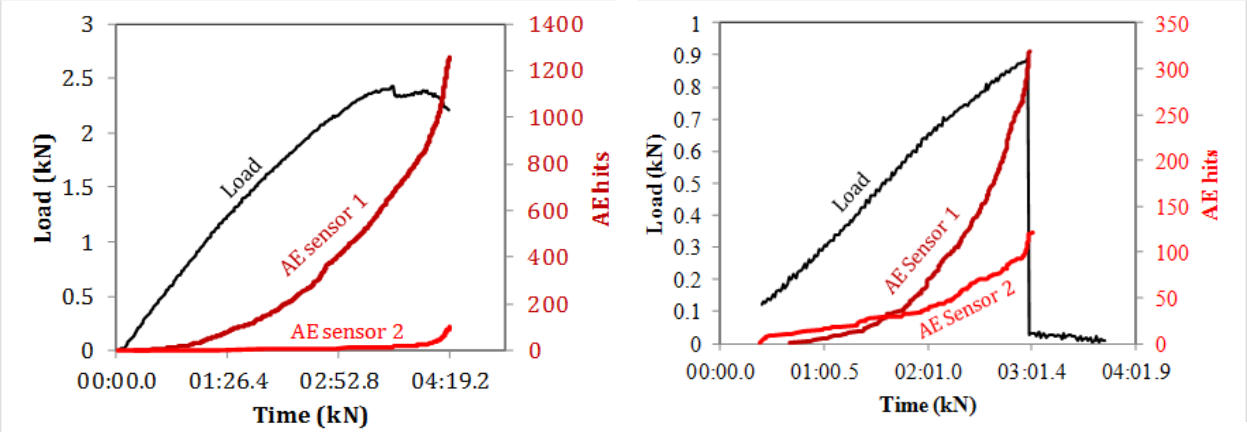


Figure 1. Acoustic emission sensors placed on the femur diaphysis**.**

3. Results

3.1 General AE activity

Figure 2 shows two typical cases of AE activity history. The load is also depicted in both graphs. In Figure 2a, it is seen that AE starts to accumulate shortly after application of load. Specifically it started at around 15% of the maximum load indicating that this load level was necessary to activate microcracking. The load at the onset of AE was very repeatable for all tested specimens. The activity of sensor 1 (placed near the fixing end) was almost ten times higher than sensor 2 something justified by the fact that fracture took place near the fix point, while the area of the femur head of this specimen was seemingly undamaged (see Figure 4a). On the other hand Figure 2b shows the activity of a specimen fractured at the head (photograph in Figure 4b). Although sensor 1 still recorded the highest amount of activity at the end, sensor 2 accumulated a much higher proportion of AE activity (close to 1/3) showing that significant fracture mechanisms were taking place in the head as well. It is indicative that sensor 2 recorded the first hits and up to 50% of the load it had received most of the activity before fracture was widely spread to the whole specimen. It is worth to mention that the AE activity from concrete is considered minor. The modulus of elasticity of the bone is lower than the corresponded of the concrete. Due to this reason, the damage was concentrated either on the diaphysis or on the head of the femur bone.



(a) (b)

Figure 2. Load history and cumulative AE activity of different sensors for (a) specimen 1, and (b) specimen 6

The maximum load ranged from less than 1 kN up to 3.6 kN depending on the geometry and thickness of the specimens. Although the number of specimens cannot be considered sufficient for establishing robust correlations, some trends between AE parameters and mechanical data seem promising and are worth discussing in this text.

Figure 3 shows the correlation plot between the maximum load and the accumulated energy received by both sensors. A general increasing trend is seen. The two specimens with the lowest load exhibited also the lowest amount of AE energy, while as the maximum load increased, so did the AE accumulated energy. The coefficient R is of the order of 0.8 while in the expense of a single point (that of the higher energy) the coefficient R rises higher than 0.9, as shown by the blue dash line in Figure 3. These correlations cannot be regarded as global with the limited amount of points, but still they are encouraging in the sense that parameters from acoustic monitoring techniques show some trend with the mechanical results and specifically the load, something that has not been examined thoroughly so far.

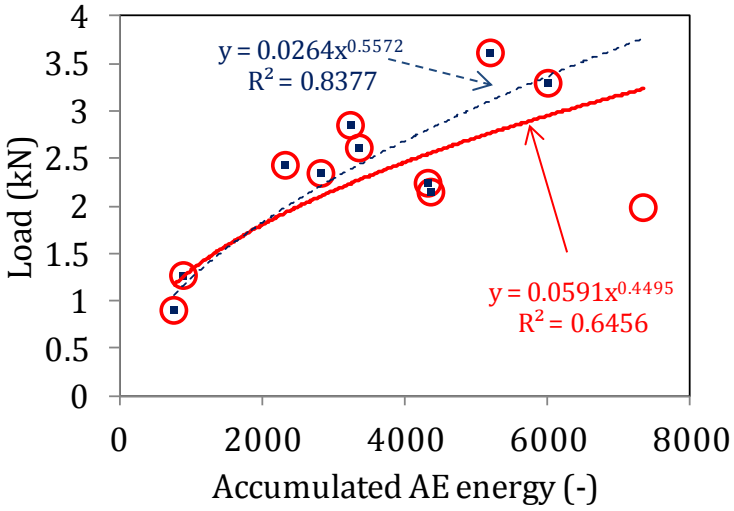
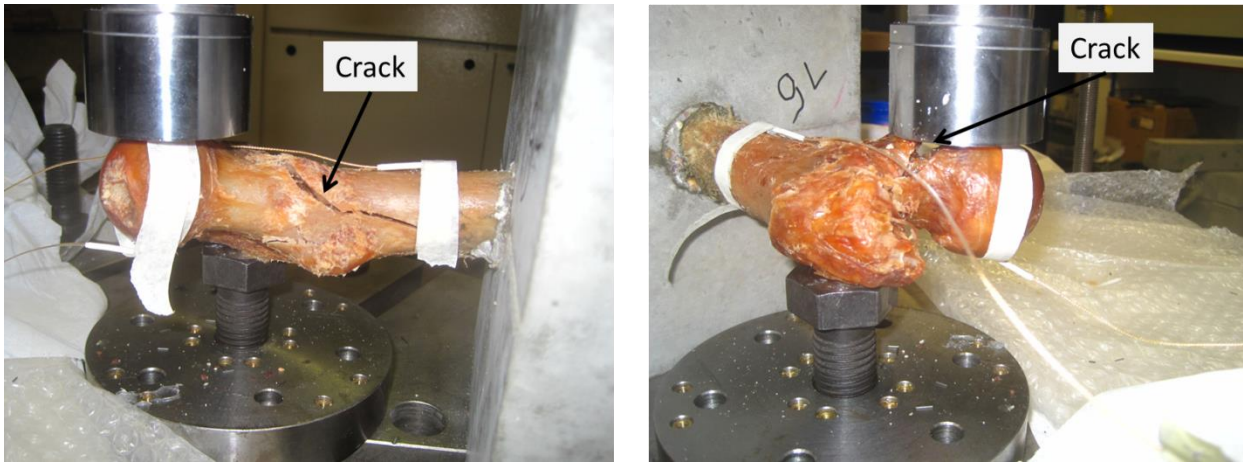


Figure 3. Maximum load and accumulated AE energy for both sensors



(a) (b)

Figure 4. Photograph of femur specimen after the fracture (a) fracture on the diaphysis of the femur bone and (b) on the head of the femur bone

3.2 Ultrasonic assessment

The ultrasonic investigation, offers some other correlations. Specifically, pulse velocity was calculated by the first threshold crossing of the waves. It is mentioned that the pulse velocity corresponds to the fastest mode (which has been identified as S0, symmetric), while a few μs later another burst is identified as A0 (antisymmetric) [20]. An indicative waveform of the last sensor (approx. 40 mm from the excitation) is seen in Figure 5. There, a fast small burst can be identified followed by a larger wave packet. In the same graph the wavelet transformation of the waveform is depicted based on the "Gabor" wavelet [21].

Most of the energy is included in the time window between 120 and 160 μs that corresponds to the second high amplitude mode. By following the maxima of each frequency component of this mode it becomes evident that the wave packet is dispersive. The higher frequencies arrive earlier something typical of plate wave propagation. This behavior may be further highlighted by the microstructure of the tissue that imposes further dispersion (frequency dependence of velocity). It is mentioned that the maxima of the wavelet intensity shown by cross symbols coincide with the theoretical dispersion curves validating the correspondence to the S0 and A0 modes. The curves were developed for material with longitudinal wave velocity 3800 m/s and shear wave velocity of 1800 m/s, close to the velocities of the two modes of this study [20].

Attenuation coefficient was calculated by the exponential decay of the maximum amplitude of the four successive sensors after each excitation meaning that it corresponds to the 2nd burst (A0) which was the strongest packet. In total 5 specimens were ultrasonically investigated and later they were cut for microscopy assessment of the cross sections at the area of ultrasonic measurements.

Pulse velocity, as measured by the propagation distance the first threshold crossing ranged from 3100 m/s to 3700 m/s indicating a quite high stiffness (this value is close to concrete longitudinal wave velocity). The velocity of the second mode measured by a characteristic peak was always between 1000 m/s to 1300 m/s, values that coincide with values in literature. The velocity values showed weak correlation to the maximum sustained load. However, the attenuation exhibited a much better correlation as shown in Figure 6.

The specimens with the highest measured attenuation (between 75 dB/m to 80 dB/m), exhibited the lowest mechanical capacity, below 2.5 kN while as the attenuation coefficient decreased to 50 dB/m maximum load reached 3.6 kN. This correlation between an ultrasonic parameter and strength should first be further validated by more specimens and then investigated as to its origin. However, higher attenuation is connected to lower stiffness and higher amount of heterogeneity in engineering materials [22, 23].

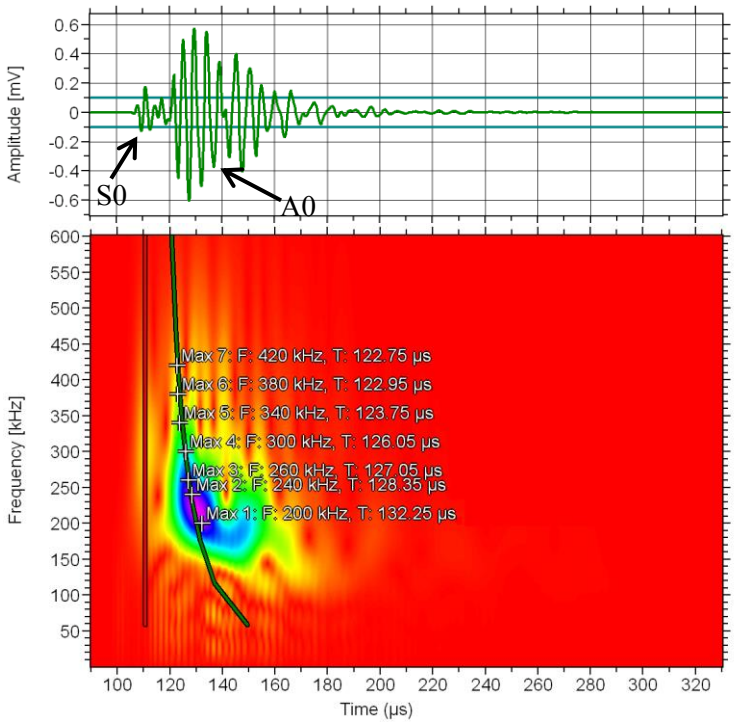


Figure 5. Typical waveform of the 4th sensor (top) and its wavelet transformation

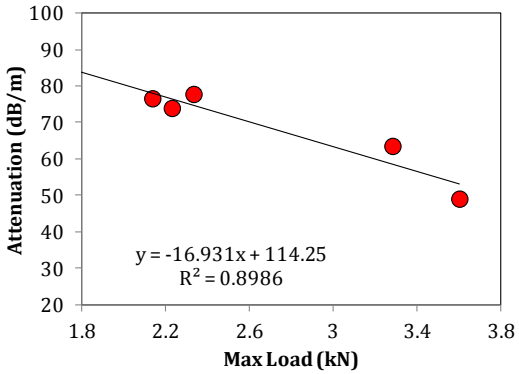


Figure 6. Attenuation coefficient vs. maximum load for five femur specimens.

4. Conclusions

In the present paper, the AE activity during fracture of human bone tissue is discussed. The specimens were femurs the fracture of which is very common especially in aged people (hip fracture) [24-25]. Results show that AE activity can be used for identification of the onset of cracking which occurs much earlier than macroscopic fracture or visible cracks. Additionally, the increase of rate of incoming signals is a precursor of serious fracture phenomena, while the parameters of the obtained waveforms reveal more information as to the shift between fracture mechanisms. During ultrasonic investigations, strong dispersive and attenuative trends are observed with high frequencies propagating faster for the band up to about 420 kHz. Also, it is highlighted from the results that the specimens with the highest measured attenuation exhibited the lowest mechanical capacity. Mechanical properties are also taken into account in an effort to examine the possibility of applying AE indices to interpret the fracture behaviour of bones based on the experience from other material fields.

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