# Acoustic Emission on Human Femur Tissue Fracture

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**Abstract.** This study describes the acoustic emission (AE) activity during fracture of human femur tissue under flexural load. The sample is fixed as a cantilever and two AE broadband sensors are placed in different points of the sample, one near the fixing end and the other near the head, where a pin load is applied. The aim is to investigate if AE procedures and indices well established in engineering materials characterization can also offer valuable insight to the fracture of a material as complex as the femur. Preliminary analysis shows that parameters like the number of acquired AE signals and their amplitude correlate well to the load history. Human bone tissues are known for their brittle nature, allowing nearly no visible signs of cracking until the final failure. However, AE detects the fracture of human tissue from the early micro-cracking events that occur at loads less than 20% of the ultimate, enabling monitoring of the whole fracture process. Additionally, source location correctly identifies the zone of fracture much earlier than the visual cracking appears. Frequency and waveform shape parameters are connected to the pattern of the bone fracture. Study of the samples by AE can increase the understanding of its fracture behavior providing information that is difficult to obtain with any other monitoring technique.

## Introduction

Acoustic emission (AE) is a technique used in several occasions for the monitoring of the fracture behavior 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 times, 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 either in the form of different stresses (normal vs. shear) or between cracking and pull out/delamination. 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. Nevertheless, 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. Some studies have used AE for characterization of bones behaviour. Ossi et al. [12] found that the transmission of the AE energy of bovine bones is based on the amount of saturation. Another study [13] claimed that during fatigue AE can indicate the onset of failure in human tibia cortical bone. However, there were some samples that failed without detection of significant crack activity. In addition, AE has been successfully applied for assessment of knee joint osteoarthritis [14].

Apart from the limited number of experimental works, another difficulty is the geometry of the specimens, which usually obtains curvatures and poses problems in the positioning and stability of the sensors. Another important factor is the interpretation of the results. Since the background is not strong in the field, it is not straightforward to explain the trends or numerical values of AE parameters as would be in other engineering materials. Despite the difficulties, the importance of such studies is high considering that bone fractures are very common (it is estimated that hip fractures are a significant cause of mortality and certainly loss of quality of life for millions of aged people [15]). Fractures are also common in the area of sports. In all cases, the understanding of the way that the tissue is fractured and the mechanical properties of the tissue are important for medical doctors who are occupied with the surgical repair. Apart from the AE studies, considerable effort is given in the ultrasonic assessment of properties, which can be applied for diagnosis purposes of fracture or healing of bones [15-18].

Another important reason for these tests is the scientific challenge (from the point of view of experimental mechanics) of using the experience gathered from other fields in order to interpret the results in such a complicated medium as human bone. In the present study preliminary results on fracture experiments in human femur specimens with concurrent monitoring of AE are reported. 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 [17].

## 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 and had been preserved using an injection of the vessels of a formol solution.

In order to perform the test, a large part of each bone was cast in concrete, as seen in Fig. 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 all specimens (point of minimum elevation) by a metal bolt in order to avoid the fracture at the fix point due to bending moments (Fig. 1a and b). 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.

Two AE broadband transducers were used. The first was placed near the fix point and the second at the bottom of the head (Fig. 1b). 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 vulnerable part in hip fracture. The sensors were of "pico" type of Mistras Holdings having a broadband response and peak frequency at 450 kHz. These sensors were selected due to their response but also their small size that enabled placement on the curved surfaces of the bones. The signals 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). The threshold was set at 30 dB. Acoustic coupling was improved by vaseline grease between the sensors and the surface of the femur, while tape was used to secure the sensors for the duration of the experiment. 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 [17].
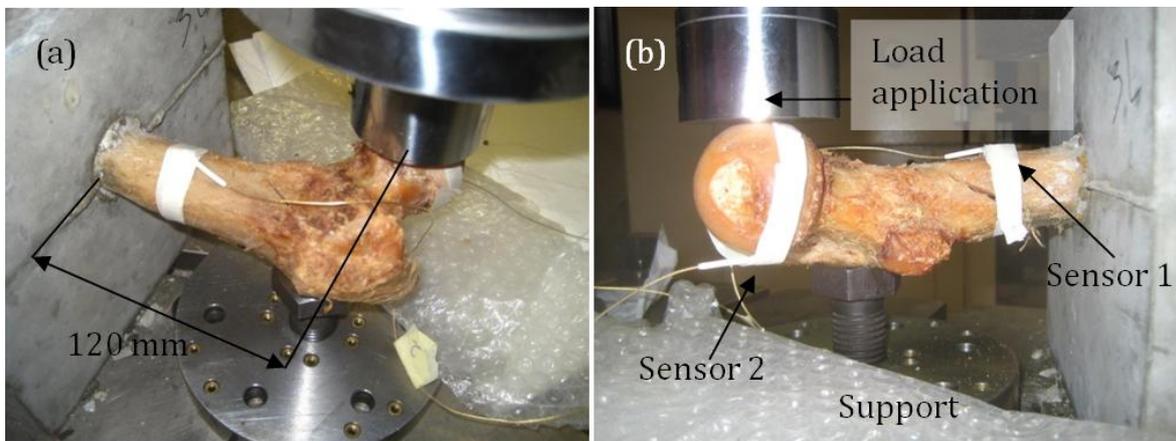


**Fig. 1.** Acoustic emission sensors placed on the femur diaphysis.

A typical AE waveform is seen in Fig. 2. Apart from the rise time (RT) which is the delay between the first threshold crossing (first count) and the peak, the RA value is also important, defined as RT over amplitude (A). Average frequency (AF) is the number of counts over the duration and it is a good approximation of the frequency content of the waveform.
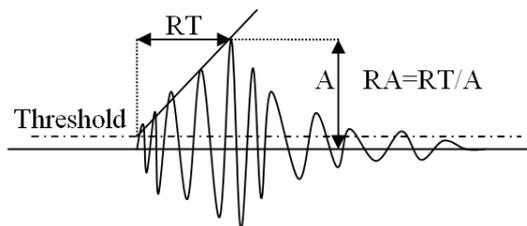


**Fig. 2**. Typical AE waveform

## 3. Results

### 3.1 General AE activity and parameters

The AE activity of specific bone specimens will be discussed in this section. First, the cumulative number of hits recorded from different sensors is depicted along with the load history in Fig. 3a. It is obvious that the activity started at very low load levels (0.5 kN which is 14% of the maximum load and is indicative of the activation of the preliminary cracking mechanisms. The rate was continuously increasing until a point when both sensors had a sharp increase, while a few seconds later, a macroscopic fracture was evident by a temporary load drop (from 3.38 to 3.29 kN, see the dash line). The specimen did not hold much longer, being macroscopically broken 3.6 kN. Apart from the information on the crack initiation, important trends are seen by AE waveform parameters. As an example, the RT values of all hits of sensor 1 (near the fixing point) are depicted in Fig. 3b. Most of them are up to 20 μs, with a few being up to 60 μs. At a certain point before the first strong fracture event, a group of points between 40 and 60 μs are exhibited, causing a strong fluctuation on the moving average line (see dash ellipse). Another strong fluctuation is noted at the moment of load drop. Apart from these, a smooth increase of the trend line is shown around time 2:30 symbolized by arrows in Fig. 3b. This increase may indicate a shift of the fracture mechanisms. In the engineering field, an increase of RT signifies stronger shearing in the form of fiber pull-out/layer debonding as opposed to matrix cracking or pure shear stresses as opposed to tensile ones acting on a matrix [1,9,19,20]. In this case due to the degree of heterogeneity of the medium and the limited experience, it would be premature to try to establish robust correlations between AE trends and fracture patterns. However, since both bending and torsional moments are active in the specimen, this kind of transition seems very likely and cannot be excluded.
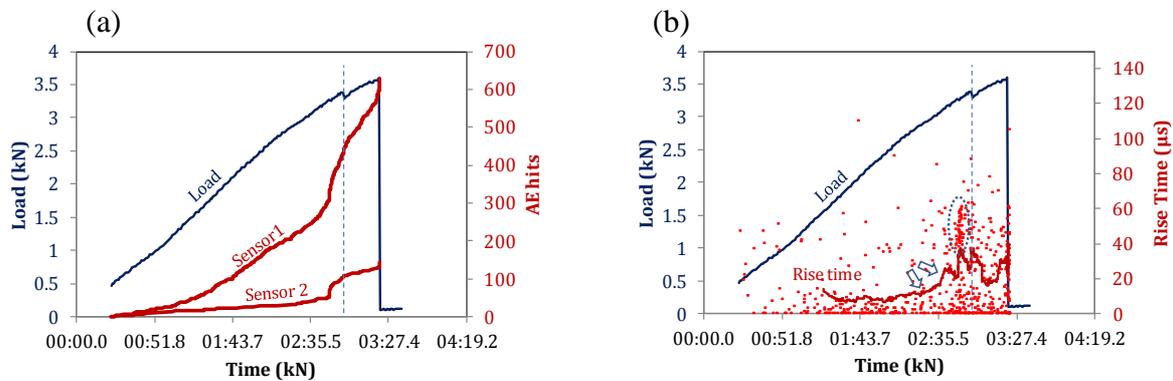


**Fig. 3.** Load history and (a) cumulative AE activity of different sensors, and (b) RT of sensor #1, for femur specimen #8

Another example is seen in Fig. 4. It concerns specimen #7. Again the AE started at 13% of the maximum load. The rate increased for sensor 1 (near the fix point) earlier than #2 indicating that more cracking activity was occurring near that point. However, sensor #2 started to register an increase at approximately 2:20 which was the precursor of the macroscopic fracture event at 2:52 s (again indicated by a dash line). This AE activity is in agreement with the visual observation of the specimen after the test. In the photograph of Fig. 5 a visible crack in the middle of the specimen near sensor #1 is clearly seen but obviously the specimen's ultimate fracture occurred near the head which was split from the main body and was responsible for the strong increase of sensor 2 data at the end. If we take a look at the AF of the hits of sensor 2 we notice again a strong shift earlier than the

macroscopic fracture event. Specifically at 2:22 (see arrow) the moving average line of AF drops by about 100 kHz, signifying possible changes in the fracture pattern. Strong fluctuations occur also at the macro-fracture moments as typical in these cases. The drop of frequency characteristics of AE is in general indicative of shear actions [1,19,20].
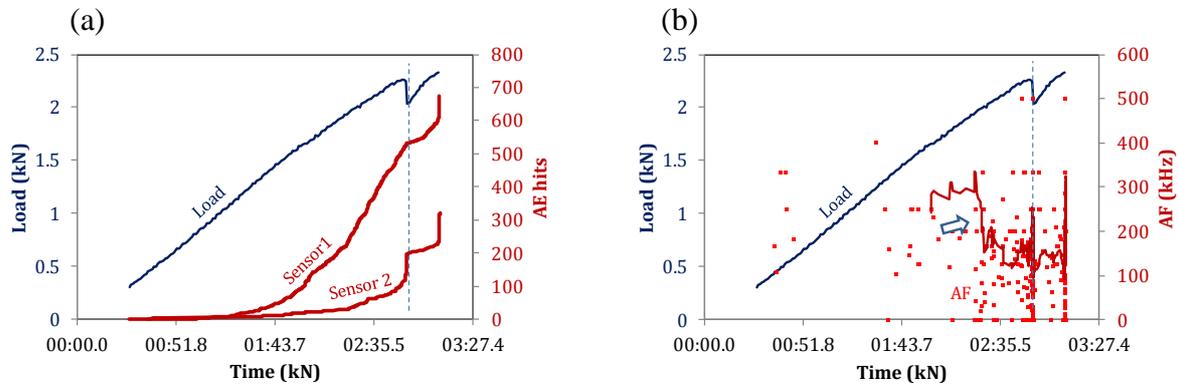


**Fig. 4.** Load history and (a) cumulative AE activity of different sensors, and (b) AF of sensor #2, for femur specimen #7.
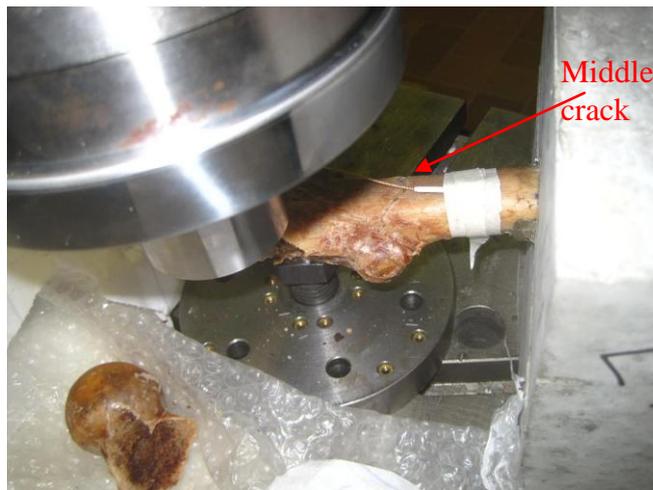


**Fig. 5**. Photograph of femur specimen #7, the AE behavior of which is shown in Fig. 4.

It is seen that the behavior of AE is case-specific and the effort to explain it requires serious considerations of the load, geometry and knowledge of the fracture behavior of the tissue. Though this is the next step of the study there were some parameters which yielded macroscopic correlations independent of the fracture pattern and area. Fig. 6 shows that a correlation exists between the average values of AF and RT of all specimens. Femur specimens that exhibited high RT values of 17-20 µs, exhibited frequency content of approximately 200 kHz, while when the average RT was less than 10 µs, the frequency was higher up to 260 kHz. These correlations (increase of frequency with simultaneous decrease of RT) have been observed in other engineering materials [19,20] and are therefore, encouraging in the sense that basic trends hold, and experience in other material fields may help in the interpretation of fracture in the bone tissue.
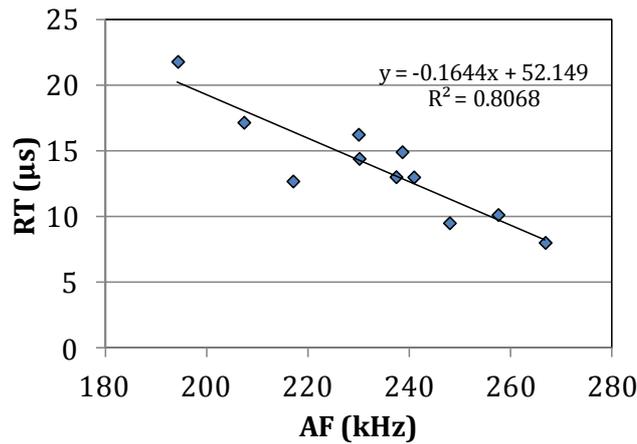
The chart shows RT (µs) on the y-axis (0 to 25) versus AF (kHz) on the x-axis (180 to 280), with data points and a fitted line. The equation is:

$$y = -0.1644x + 52.149$$
$$R^2 = 0.8068$$

**Fig. 6.** Correlation between average RT and AF for all specimens.

## 3.2 Correlation with thickness

Cortical bone is one of the three layers of the bone and it exhibits high heterogeneity. It is believed that cross-sections of cortical bone clearly show age-related differences in the thickness [21, 22]. The age range of the cadavers in the current study is between 73 to 95 years. This means that the cortical bone area is expected to be lower since the compact bone area decreases for older ages. Cross sections of five femur specimens where studied. In Fig. 7 the cross section of one femur specimen is shown. The thickness measurement is based on the cortical layer. The cortical thickness is derived by the magnified photographs of an optical microscope. The values have been measured at the cross-section surface (see indicative values in Fig. 7). The thickness values were measured as average of five measurements (6,8 mm in the current femur specimen). In any case, it is clear from the pictures that the thickness in the femur is not uniform (5,1 mm-8 mm). This is due to the inhomogeneous geometry of the femur tissue.
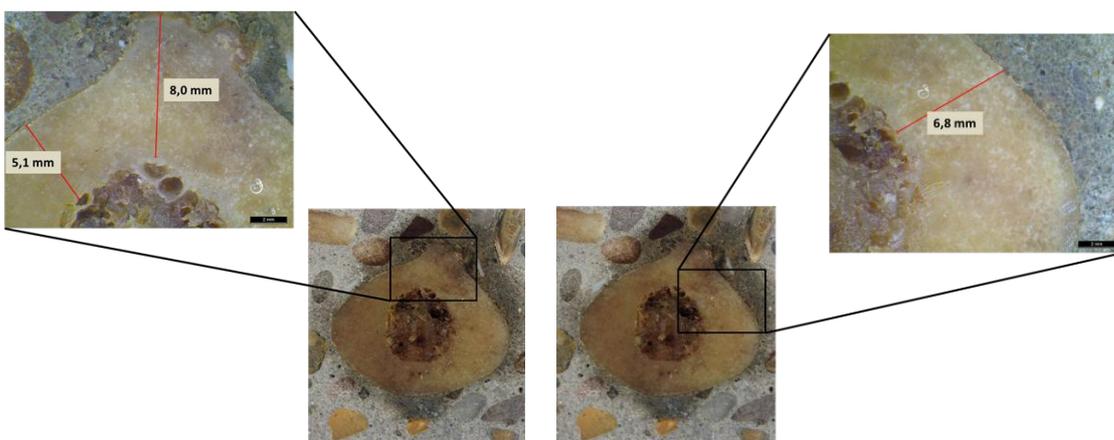


**Fig. 7.** Cross section of a femur specimen with different thickness measurements.

Considering the five specimens that were studied in cross section, some interesting correlations arise between AE frequency features and the thickness. Specifically Fig. 8 shows the partial power of 300-500 kHz in correlation to the thickness of the specimens. This partial power is the percentage of the energy of the specific band over the band of 0-500 kHz, as measured by the area under the FFT spectrum of each waveform. It is seen that

the specimens with the thicker layer of cortical bone exhibited AE with strong energy between the higher frequency range between 300 and 500 kHz (around 17% of the total energy). As the thickness decreases the energy of this band drops to 10%. These correlations are certainly preliminary and should be studied and validated in larger number of specimens. However, they are encouraging in the sense that parameters measured by a monitoring technique exhibit dependence on the physical properties of the tissue.
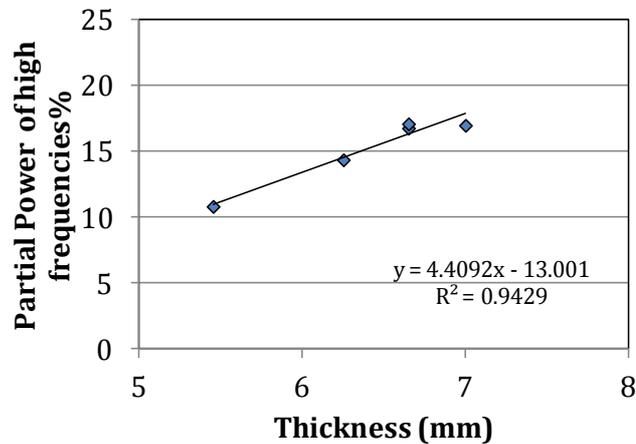


**Fig. 8.** Correlation between partial power of the band 300-500 kHz with the average thickness of the bones.

## 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). 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. Mechanical/physical properties and thickness are also taken into account in an effort to examine the possibility of applying AE indices to interpret the fracture behavior of bones based on the experience from other material fields.

## References

[1]     C.U. Grosse, M. Ohtsu. Acoustic emission testing. Heidelberg: Springer; 2008.
[2]     A. Shanyavskiy, M. Banov. (2010)  The twisting mechanism of subsurface fatigue cracking in Ti–6Al–2Sn–4Zr–2Mo–0.1Si alloy, Engineering Fracture Mechanics 77, 1896–1906.
[3]     Z. Han, H. Luo, J. Cao, H. Wang. (2011) Acoustic emission during fatigue crack propagation in a micro-alloyed steel and welds, Materials Science and Engineering A 528, 7751– 7756.
[4]     B. Zárate, J. Caicedo, J. Yu, P. Ziehl, (2012) Probabilistic Prognosis of Fatigue Crack Growth Using Acoustic Emission Data, J. Eng. Mech., 138(9), 1101–1111.
[5]     E. Maillet, N. Godin, M. R'Mili, P. Reynaud, G. Fantozzi, J. Lamon, (2014) Damage monitoring and identification in SiC/SiC minicomposites using combined acousto-ultrasonics and acoustic emission, Composites: Part A 57, 8–15.
[6]     M. Iwamoto, Q-Q. Ni, T. Fujiwara, K. Kurashiki. (1999) Intralaminar fracture mechanism in unidirectional CFRP composites Part I: Intralaminar toughness and AE characteristics, Engineering Fracture Mechanics 64, 721-745.
[7]     T. Shiotani, K. Fujii, T. Aoki, K. Amou. (1994) Evaluation of progressive failure using AE sources and improved b-Value on slope model tests. Progress in Acoustic Emission 7, 529– 534.

[8] J.H. Kurz, F. Finck, C.U. Grosse, H.W. Reinhardt. (2006) Stress drop and stress redistribution in concrete quantified over time by the b-value analysis. Structural Health Monitoring 5:69

[9] T. Shiotani, M. Ohtsu, K. Ikeda. (2001) Detection and evaluation of AE waves due to rock deformation. Construction and Building Materials 15:235–246.

[10] Browne M, Roques A, Taylor A. (2005) The acoustic emission technique in orthopaedics-a review. The Journal of Strain Analysis for Engineering Design 40:59–79.

[11] S. Shrivastava and R. Prakash. (2009) Assessment of bone condition by acoustic emission technique: A review, J. Biomedical Science and Engineering, 2, 144-154.

[12] Z. Ossi, W. Abdou, R. L. Reuben, and R. J. Ibbetson. (2013) Transmission of acoustic emission in bones, implants and dental materials.," Proc. Inst. Mech. Eng. H.,227(11), 1237–45.

[13] S. Agcaoglu and O. Akkus. (2013) Acoustic emission based monitoring of the microdamage evolution during fatigue of human cortical bone. J. Biomech. Eng., 135(8) 81005.

[14] Shark L-K, Chen H, Goodacre J (2011) "Acoustic emission: a potential biomarker for quantitative assessment of joint ageing and degeneration". Medical Engineering & Physics 33:534–545.

[15] http://www.ultrasonics.org/Proceedings_2007_UIA/Laugier_2007_UIA.pdf

[16] M.G. Vavva, V.C. Protopappas, L. N. Gergidis, A. Charalambopoulos, D.I. Fotiadis, D. Polyzos. (2009) Velocity dispersion of guided waves propagating in a free gradient elastic plate: Application to cortical bone, J. Acoust. Soc. Am. 125(5) 3414-3427.

[17] M. Strantza, O. Louis, D. Polyzos, F. Boulpaep, D. Van Hemelrijck, D. G. Aggelis, (2014) Elastic wave propagation on human femur tissue, Proc. SPIE 9062, Smart Sensor Phenomena, Technology, Networks, and Systems Integration 2014, 90620T doi: 10.1117/12.2048393 ISBN 9780819499882

[18] M. Määttä. (2012) Assessment of osteoporosis and fracture risk, Axial transmission ultrasound and lifestyle-related risk factors, PhD Thesis, University of Oulu, Finland.

[19] D. G. Aggelis. (2011) Classification of cracking mode in concrete by acoustic emission parameters, Mechanics Research Communications 38, 153–157.

[20] K. Ohno, M. Ohtsu. (2010) Crack classification in concrete based on acoustic emission, Construction and Building Materials 24, 2339–2346.

[21] S.A. Feik, C.D.L. Thomas, J.G. Clement. (2002) Age-related changes in cortical porosity of the midshaft of the human femur, Journal of Anatomy 191, 407–416.

[22] M.S. Stein, C.D.L. Thomas, S.A. Feik, J.D. Wark, J.G. Clement. (1998) Bone size and mechanics at the femoral diaphysis across age and sex, Journal of Biomechanics, 1998, 31(12), 1101-1110.