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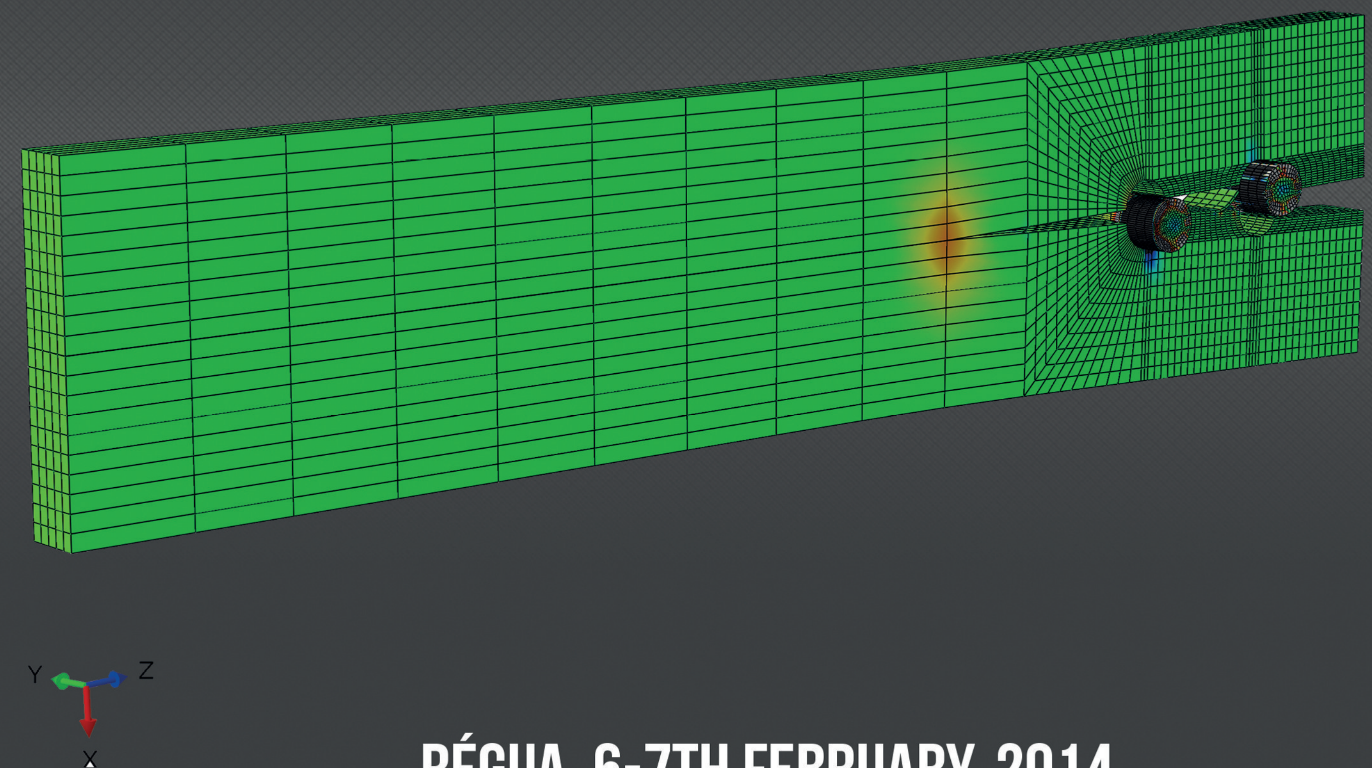

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Mixed-mode I+II fracture characterization of bovine bone tissue using the SLB test

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Abstract

Fracture of bone *in vivo* generally occurs as a result of multiaxial loaded conditions, which leads to complex mixed-mode stress-states involving the combination of tension, compression and shear. As a result of this the characterization of the mixed-mode crack propagation assumes a high level of importance.
In this work we analysed the adequacy of a miniaturized version of the single leg bending test (SLB) to characterize the mixed-mode I+II fracture behaviour of young bovine bone tissue. Hence, a new data reduction scheme based on specimen compliance and crack equivalent concept was used to overcome the difficulties inherent to crack monitoring during its growth. The method was applied to the experimental results in order to obtain the Resistance-curves in each mode. It was concluded that the developed version of SLB test is adequate for mixed-mode fracture characterization of bone, since it permits to obtain a complete Resistance-curve though revealing an almost constant mode ratio.

Keywords: Bone, Mixed-mode I+II, Fracture characterization, Single Leg Bending test.

1. INTRODUCTION

Bone fractures are common events as a result of accidental loading, fatigue and diseases. Hence, the evaluation of fracture properties of cortical bone is an important research topic with relevant impact on public health. However, this is a very challenging endeavour because bone tissue is a composite material with heterogeneous, anisotropic and hierarchical microstructure. It is essentially constituted by a mineral phase (mainly hydroxyapatite), an organic phase (mainly collagen) and water. The mineral phase is essentially responsible for stiffness and strength while the organic phase and water play an essential role on viscoelasticity and toughness. Structurally, bone tissue can be classified as trabecular and cortical. Cortical tissue plays an important role on the propensity of long bone to fracture.
The large majority of works dedicated to bone fracture characterization address the pure mode I loading. Several fracture tests have been used in this context: compact tension (CT)[1]; chevron notched beam [2]; compact sandwich tension [3]; single edge notched beam (SEN) [4]; and double cantilever beam (DCB) [5]. The CT and SEN tests are the most used. However, they present a limitation related to confinement of non-negligible fracture process zone due to compressive stresses induced by bending that develop ahead of the crack tip [6]. This is a spurious phenomenon that can artificially increase the measured toughness and leads to overestimation of bone fracture properties. Since cortical bone specimens have obvious limitations in size, this kind of difficulties arise naturally. Recently, a miniaturized version of traditional DCB test was proposed [5], owing to size restrictions imposed by bovine femur. In fact, DCB specimen propitiates a longer length for self-similar crack propagation without undertaking spurious effects. As a consequence, a *Resistance*-curve (*R*-curve) was obtained allowing an adequate characterization of cortical bone fracture under mode I loading.
Much less attention has been dedicated to fracture characterization under mode II loading, which is justified by the difficulty on the

definition of an adequate test. Mode II fracture can occur under pure shear loading, as is the case of twisting efforts during exercise. Norman et al. [7] proposed the compact shear test for mode II fracture characterization of human cortical bone. Subsequently, Brown et al. [8] used the same test to evaluate fracture toughness dependency on bone location and age. However, this test presents some disadvantages: small variation of compliance as a function of pre-crack length which turns difficult the establishment of compliance calibration; mixed-mode crack growth instead of pure-mode II; unstable propagation, which means that only crack initiation fracture toughness is available. Recently, miniaturized versions of the end-notched flexure (ENF) and end loaded split (ELS) were proposed [9,10]. It was verified that both tests can be used when a judicious selection of specimen dimensions is carried out. In fact, it must be assured that self-similar crack growth occurs for a given crack extent in order to provide a valuable measurement of fracture energy.

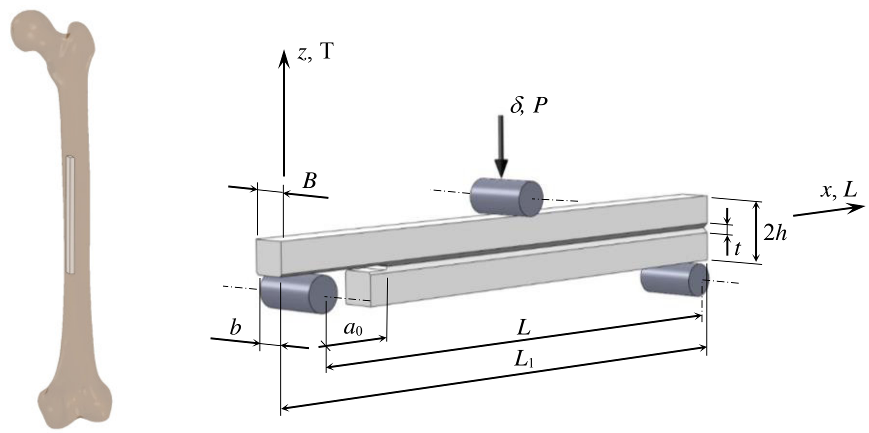
Fracture characterization under pure modes (I and II) is important for specific cases of loading. However, under general loading fracture conditions involving both mode I and mode II will prevail. Moreover, mixed-mode fracture conditions are also stimulated by bone anisotropy which defines directions prone to failure. Effectively, the marked anisotropy induced by the alignment of osteons along the long axis of bone delineates regions prone to crack propagation (i.e., paths). Consequently, cracks can initiate and propagate under mixed-mode conditions, since they are confined and obliged to grow in pre-established regions. Therefore, the definition of a cortical bone fracture criterion in the mode I *versus* mode II space is a fundamental task. Only few works including mixed-mode loading are available in the literature. George et al. [11] studied the combined effect of axial torsional fatigue loading on fracture. These authors concluded that uniaxial testing of materials subjected to multiaxial stresses provides a non-conservative estimate of fatigue life by a factor of twenty because multiaxial loading promotes mixed-mode failure, in which the microcracks form in mode I and propagate in mode II or in mode III. Zimmermann et al. [12] attempted to measure the *R*-curve of human cortical bone under physiologically relevant mixed-mode loading conditions. These authors used the asymmetric four-point bending test but some difficulties related to crack deflection and continuous rise of *R*-curve were pointed. This later phenomenon is probably motivated by a spurious effect related to confinement of non-negligible FPZ by means of compressive stresses developed ahead of crack tip induced by bending.

In the present work fracture characterization of bovine bone under mixed-mode I+II loading was performed using a miniaturized version of the single leg bending test (SLB). This test provides a constant mode-mixity thus defining a single point in the G_I-G_{II} space. However, the main advantage of the SLB test is its simplicity. In fact, it consists on a three-point-bending test on a beam specimen with a pre-crack. An equivalent crack length method based on beam theory and specimen compliance was used to overcome the evident limitations in crack monitoring during propagation. Using a partition mode methodology the equivalent crack length method permits achieving the *R*-curves for both components of strain energy release rate (i.e., mode I and mode II components).

2. EXPERIMENTS

Eight specimens were prepared from the mid-diaphysis (Figure 1a) of each femur of young bovine animals (aged about 8 months) within one day post-mortem. The specimen configuration was obtained using milling and cutting operations, with the average dimensions shown in Figure (1b). These dimensions were limited by the femur curvature and cortical bone thickness in the diaphysis region. During the machining process of specimens the endosteal and periosteal tissues were removed. Specimens were preserved with physiological saline at all steps of the machining process and frozen at −20 ◦C for storage.

Due to orthotropy, three different directions can be defined for cortical bone: the longitudinal (L) aligned with osteons (long-axis of femur), the radial (R) along thickness and the Tangential (T). The initial crack length a_0 was introduced in two steps. First, a notch (0,3 mm thick) was machined using a circular saw. Then, a pre-crack was created just before the fracture tests, by



(a) (b)

Figure 1. Schematic of a (a) femur segment showing the specimen position in femur and (b) the SLB testing setup (L = 60; $2h$ = 6; t = 1; B = 3.3; b = 2.3; a_0 = 20 mm).

tapping a sharp razor blade into the notch (Figure 2), using a test machine. This has been accomplished by moving the actuator 0.25 mm towards the specimen with a velocity of 100 mm/s.

The experimental practice has shown that crack moves away from the mid-specimen plane containing the pre-crack (i.e., z = 0 in Figure 1b). This fact leads to unwanted spurious phenomenon that impedes bone fracture characterization under the intended mode mixity. To overcome this drawback two longitudinal lateral grooves (V-shape) with 0.5 mm depth were machined (Figure 1b) in order to compel the crack to propagate along its initial plane.

Figure 2. Pre-crack operation.

An initial crack with a nominal length of a_0 = 20 mm was introduced. This value provides a distance of 10 mm to the central loading point, which was found acceptable to assure self-similar crack propagation for a given extent. This condition is fundamental to guarantee accurate measurements of fracture energy, and occurs when FPZ freely develops at the crack tip. This happens when FPZ is not affected by any spurious effects during the crack propagation process.

Experimental three-point-bending tests were executed in a servo-electrical testing system (MicroTester INSTRON 5848), using a constant displacement rate of 0.5 mm/min (Figure 3). The load-displacement curves (P-δ curves) were registered during the test and then used in the developed data reduction scheme to evaluate the R-curves in each loading mode.

Figure 3. Testing setup of the SLB test.

A detail of the fractured region, revealing the presence of relative shear and opening displacements (detail A) characteristic of mixed-mode I+II loading is presented in Figure 4. Detail B puts into evidence that it is not easy to identify the crack-tip position with the accuracy required for a truthful evaluation of its length, necessary to evaluate toughness using classical data reduction methods.

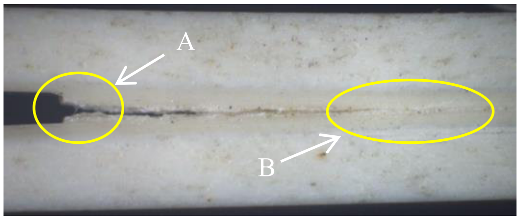


Figure 4. Opening and shear displacements at the notch tip (Detail A) and undefined crack tip position (Detail B).

Figure 5 shows different surfaces observed by SEM (Philips-FEI Quanta 400) in a tested SLB bone specimen. Region A shows the typical pre-crack surface initiated by a saw and adjusted by a sharp blade. Region B corresponds to the fractured surface under mixed-mode I+II loading and lateral grooves are identified by regions C. Figure 6 shows in more detail the fractured surface originated by mixed-mode I+II crack propagation (region B in Figure 5). It can be seen that the surface is in general rough and irregular which is explained by the internal bone microstructure. Cortical bone of young bovines is characterized by a plexiform microstructure, constituted by layers of woven and lamellar bone [13]. These layers contain a three-dimensional network of vascular canals that are also irregularly disposed with the associated primary osteons. This complex microstructure leads to material heterogeneity which explains the observed irregular fracture surface. Figures 6 clearly shows the combination of peel (mode I) and shear (mode II) effects, as a consequence of the mixed-mode I+II loading. Shear effects result in a preferential longitudinal alignment of the fractured micro-structures, although peel loading induces a lifting effect – the combination of these two effects are clearly visible in several locations in Figure 5 (e.g., detail A). This complex damaging process taking place ahead of the crack tip originates a pronounced FPZ, which is responsible for a non-negligible quantity of energy dissipation during fracture propagation. As a consequence, non-linear fracture mechanics based approaches should be used to deal with such phenomenon. Another concern is related to the difficulty to distinguish the FPZ from the clear crack, thus becoming problematic the crack length monitoring during the test. In the following section an alternative data reduction scheme based on crack equivalent concept, specimen compliance and beam theory is presented to solve this drawback.

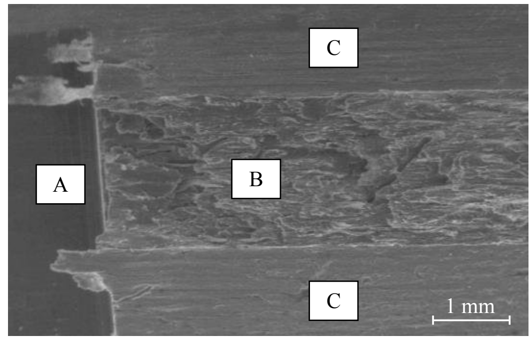


Figure 5. Fracture surface: A – Initial pre-crack; B – Mixed-mode I+II fracture surface; C – Lateral grooves.

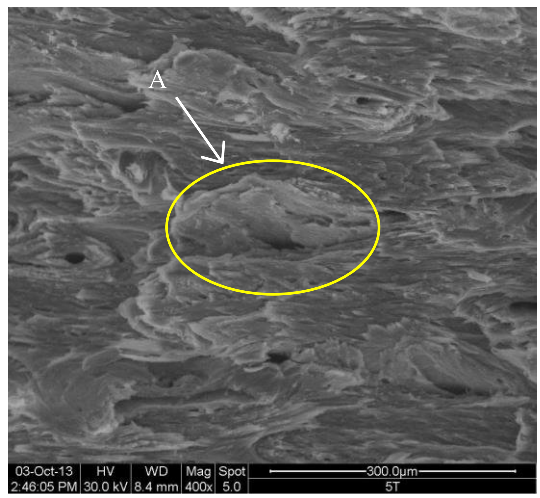


Figure 6. Microphotography of the fracture surface - detail A highlights shear and peel effects.

3. COMPLIANCE BASED BEAM METHOD (CBBM)

Considering the Timoshenko beam theory the specimen compliance C is obtained (Fig. 1b) from the elastic strain energy,

$$U = \int_0^L \frac{M_\mathrm{f}^2}{2E_\mathrm{L} I} dx + \int_0^L \int_{-h}^{h} \frac{\tau^2}{2G_\mathrm{LT}} B\, dz\, dx \qquad (1)$$

with M_f standing for the bending moment, I for the second moment of area, and

$$\tau = \frac{3}{2}\frac{V_i}{A_i}\left(1 - \frac{z^2}{c_i^2}\right) \qquad (2)$$

V_i is the shear-load of segment i ($0 \le x \le a$, $a \le x \le L/2$ or $L/2 \le x \le L$), A_i the cross-section area, c_i the half-thickness of the beam. Thus, based on the Castigliano theorem $\left(\text{i.e., } \delta = \partial U/\partial P\right)$, the specimen compliance is determined as follows,

$$C = \frac{28a^3 + L^3}{32Bh^3 E_\mathrm{L}} + \frac{3(a+L)}{20BhG_\mathrm{LT}} \tag{3}$$

where E_L and G_LT represent the elastic longitudinal and shear moduli, respectively. Due to scatter in the elastic properties of bone tissue, an effective flexural modulus E_f may be used instead of E_L which reveals a significant scatter among specimens. This is accomplished by considering in Eq. (3) the initial values of crack length a_0 and compliance C_0, to obtain

$$E_\mathrm{f} = \frac{28a_0^3 + L^3}{32Bh^3}\left(C_0 - \frac{3(a_0+L)}{20BhG_\mathrm{LT}}\right)^{-1} \tag{4}$$

This procedure allows accounting for material variability, thus eliminating the influence of scatter in elastic properties on the measured fracture energy. In addition, a previous test to evaluate the elastic modulus of each specimen is unnecessary. It should be referred that G_LT has a minor influence on the results [10], which means that a typical value can be used (Table 1).
During propagation, Eq. (3) can be used to evaluate an equivalent crack length (a_e) as a function of the current compliance (i.e., $C = \delta/P$). This requires the resolution of a cubic equation which can be performed by means of the Matlab® software [5]. Fracture energy under mixed-mode (G_T) can be computed using the Irwin-Kies equation

$$G_\mathrm{T} = \frac{P^2}{2b}\frac{dC}{da} \tag{5}$$

The width of the ligament section b is dictated by the presence of the longitudinal grooves (Fig. 1b), thus differing from the specimen width (B). Combining Eq. (5) with Eq. (3), where a was replaced by a_e, one can write

$$G_\mathrm{T} = \frac{21P^2a_\mathrm{e}^2}{16E_\mathrm{f}\,bBh^3} + \frac{3P^2}{40G_\mathrm{LT}\,bBh} \tag{6}$$

Considering the partition modes method proposed by Szekrényes and Uj [14], mode I and mode II strain energy release rate components yield

$$G_\mathrm{I} = \frac{12P^2a_\mathrm{e}^2}{16E_\mathrm{f}\,bBh^3} + \frac{3P^2}{40G_\mathrm{LT}\,bBh} \tag{7}$$

$$G_\mathrm{II} = \frac{9P^2a_\mathrm{e}^2}{16E_\mathrm{f}\,bBh^3} \tag{8}$$

Following this methodology crack length monitoring is unnecessary, which constitutes a valuable advantage since it is not easy to perform with the required accuracy. Moreover, bone is considered a quasi-brittle material characterized by the presence of a non-negligible fracture process zone (FPZ) at the crack tip, which influences the load-displacement curve. Since in the present formulation the current compliance is used to compute the equivalent crack length the influence of the FPZ is indirectly taken into account.

4. RESULTS

Figure 7 presents the experimental load-displacement curves corresponding to eight SLB tests. Some scatter is visible which is characteristic of a biological materials as bone. The equivalent crack based data reduction scheme presented in Section 3 was used to obtain the *R*-curves for total energy and corresponding mode I and mode II energy components (Fig. 8). It can be observed that after a certain crack extent, the energy release rate tends to a plateau, which means that crack advance occurs under self-similar way. This remark puts into evidence that the developed fracture process zone is fully developed ahead of the crack tip and grows freely for a given crack extent. These conditions allow accurate evaluation of total fracture energy as well as its mode I and II components. Table 1 summarizes the set of results corresponding to the eight valid tests. A scatter of approximately 15% was obtained which can be viewed as quite acceptable for a natural material as bone. The global mixed-mode ratio ($G_\mathrm{I}/G_\mathrm{II}$) using the average energy component values is equal to

1.35, which is in agreement with the values obtained in other materials using the SLB test [14,15].

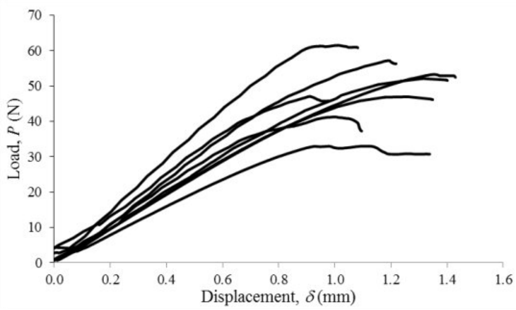


Figure 7. Experimental load-displacement curves.

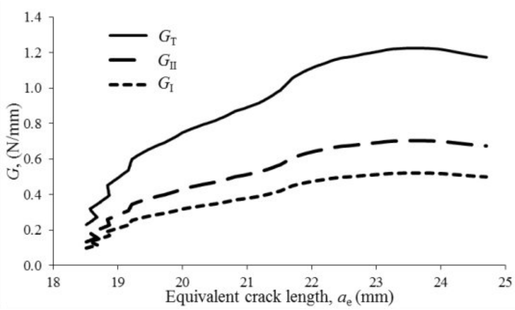


Figure 8. *R*-curves obtained in a SLB test (total energy, mode I and mode II components).

Table 1. Resume of experimental results.

Specimen	G_I (N/mm)	G_{II} (N/mm)	G_T (N/mm)
1	0.880	0.640	1.520
2	0.590	0.425	1.015
3	0.710	0.530	1.240
4	0.850	0.640	1.490
5	0.783	0.584	1.367
6	0.605	0.450	1.055
7	0.735	0.545	1.280
8	0.855	0.635	1.490
Average	0.751	0.556	1.307
CoV (%)	14.9	15.3	15.02

5. CONCLUSIONS

Fracture characterization of bovine cortical bone tissue under mixed-mode I+II loading was analysed in this work. A miniaturized version of the Single Leg Bending test (SLB) was developed owing to natural limitations on the specimen dimensions of bone. The SLB only permits fracture characterization under an almost constant mode ratio but consists in a very simple three-point bending test.

An equivalent crack length procedure was used to evaluate the *Resistance*-curves of the strain energy release rate components without requiring crack length monitoring during the test, which is not easy to accomplish rigorously.

The experimental results suggest that all the identification procedure and the miniaturized version of the SLB test is a valid solution concerning fracture characterization of bone under mixed-mode I+II loading.

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