MODE I FRACTURE OF CORTICAL BONE TISSUE

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ABSTRACT

The objective of this work is to analyse the adequacy of the Double Cantilever Beam (DCB) test to determine the fracture toughness under pure mode I loading of cortical bone tissue. A data reduction scheme based on specimen compliance and crack equivalent concept is used to overcome the difficulties inherent to crack monitoring during its growth. The data reduction scheme provides a complete resistance curve, which is fundamental to estimate the fracture energy. The obtained results demonstrate the efficacy of the DCB test and the proposed data reduction scheme on the bone fracture characterization under mode I loading.

KEY WORDS: bone, fracture, mode I loading, DCB test

1. INTRODUCTION

The development of accurate testing methods to evaluate bone toughness is fundamental, since it provides an essential tool to predict the age-related bone fracture risks and associated bone diseases [1-3]. The compact tension test [1] and the single-edge notched specimen under three point bending [4] are frequently used in bone fracture characterization under mode I loading. The difficulties associated to get specimens with the required size lead to the employment of the single-layer compact sandwich specimen [3]. In this specimen a bone coupon was sandwiched between two holders of polymethylmethacrylate.

In order to overcome the difficulties associated to the definition of a suitable test, the objective of this work is to analyze the adequacy of the Double Cantilever Beam (DCB) test to determine the fracture toughness under pure mode I loading of cortical bovine bone tissue (Figures 1 and 2). This test is particularly adequate for mode I fracture characterization due to its simplicity and the possibility to use the beam theory to measure the fracture energy. However, the classical data reduction schemes used for the DCB, are usually based on crack length (a) monitoring during its growth, which was observed to be very difficult to perform with accuracy in this quasi-britlle material (Figure 3). To overcome this drawback, a data reduction scheme [5] based on specimen compliance (C) and crack equivalent concept was used. The method is based on the beam theory to establish the C = f(a) relationship. The equivalent crack length (a_e) is estimated from the current compliance measured during the experimental test. The Irwin-Kies equation is used to compute the toughness (G_{Ic}) as a function of a_e. This procedure provides the complete R-curve estimate, which is fundamental to get the fracture energy.

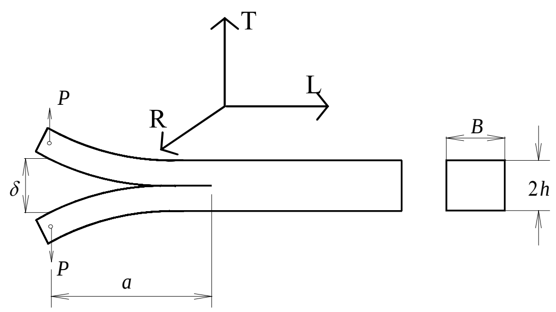

Figure 1. DCB test (a = 20, B=2 and h=3.5 mm).

2. DATA REDUCTION SCHEME

The developed data reduction scheme is known as Compliance Based Beam Method (CBBM) since it uses the Timoshenko beam theory to establish the relationship [5]

$$C = \frac{8a^3}{E_{\mathrm{L}} B h^3} + \frac{12a}{5BhG_{\mathrm{LT}}} \qquad (1)$$

where E_{L} is the longitudinal elastic modulus and G_{LT} the shear modulus in the TL plane (Figure 1). This equation can be used to estimate the equivalent crack length as a function of the current compliance C computed directly from the measured load-displacement (P-δ) curve, i.e. a_{e} = f(C)). The solution of this equation is obtained using the Matlab® software. Following this procedure the effect of the FPZ is taken into account, since its presence affects the current compliance. The combination of Eqs. (1) and Irwin-Kies's

$$G_{\mathrm{I}} = \frac{P^2}{2B}\frac{dC}{da} \qquad (2)$$

leads to

$$G_{\mathrm{I}} = \frac{6P^2}{B^2 h}\left(\frac{2a_{\mathrm{e}}^2}{E_{\mathrm{L}} h^2} + \frac{1}{5G_{\mathrm{LT}}}\right) \qquad (3)$$

Using this method a complete R-curve is determined without the direct measurement of a_{e}.

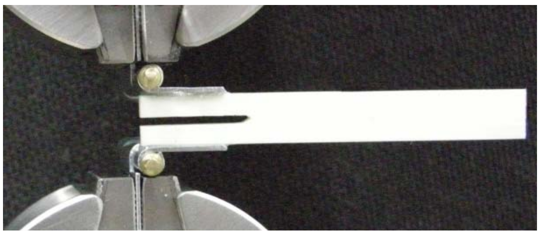

Figure 2. DCB test setup.

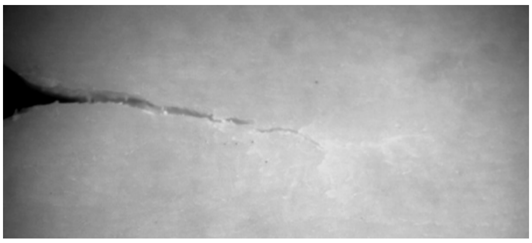

Figure 3. Crack-tip detail in bone under loading.

3. EXPERIMENTAL TESTS

A total number of nine DCB specimens with a length of 60 mm were machined using a milling machine to get the nominal dimensions (Figure 1): $B = 2$, $h = 3.5$ and $a_0 = 20$ (dimensions in mm). The initial crack length a_0 was introduced in two steps. First, a notch (1 mm thick) was machined using a circular saw. Then, a pre-crack (depth: 0.5 – 1.0 mm) was created just before the fracture tests, by tapping a sharp razor blade into the notch. The specimens were orientated with the initial crack in the TL propagation system (where T is the normal to the crack plane and L is the crack propagation direction, Figure 1) and the nominal crack-growth direction along the proximal–distal direction of the femur. The specimens were kept moist at all steps of the machining process with physiological saline. Moreover, they were wrapped in gauze soaked in physiological saline, and frozen at -20ºC for storage.

A servo-electrical material testing system (MicroTester INSTRON 5848) was used to undergo fracture tests under displacement control and normal environmental conditions (65% RH at 20°C). A 2 kN load-cell was installed and the displacement rate of the actuator was set to 0.5 mm/min. The acquisition frequency was set to 5Hz . The loading was applied to the specimen through a couple of piano hinges (Figure 2), thus inducing a pure mode I loading. Piano hinges were bonded to the specimen using a fast curing epoxy adhesive. Figure 3 shows the difficulty associated to the direct crack-length (a) measurement during damage progression.

4. EXPERIMENTAL RESULTS

Figures 4 and 5 present the typical P-δ and the corresponding R-curve, obtained using the proposed data reduction scheme. The P-δ curve shows a pronounced non-linear behaviour near the peak load. This trend is explained by the existence of a pronounced fracture process zone (FPZ) constituted by micro-cracking and crack-branching (Figure 3).

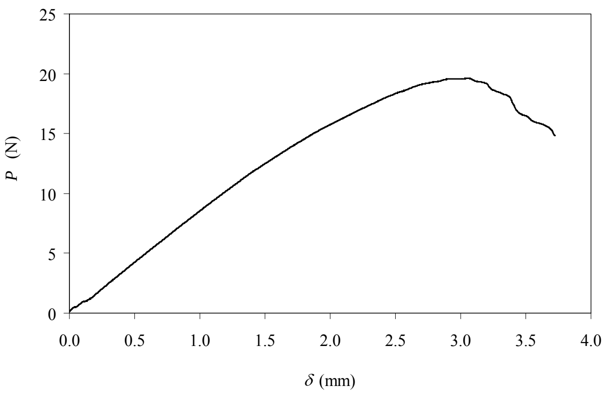

Figure 4. Typical P-δ curve of bone (mode I).

The consequence of this softening process is a ductile behaviour which is reflected on the referred non-linear profile of the P-δ curve. Consequently, the respective R-curve (Figure 5) shows a large ascending branch (approximately 3 mm of a_e) till the plateau value defining the material fracture energy (G_{Ic}) is attained (i.e., approximately 2.0 N/mm in Figure 5). The extensive ascending branch corresponds to the FPZ development up to its critical size, from which the self-similar crack growth takes place, leading to conditions for an appropriate measurement of the material fracture energy. Table 1 presents a summary of the elastic modulus and fracture energy obtained for nine tested specimens. The coefficient of variation is acceptable for this type of material. Effectively, bone is a natural material exhibiting a high variability in its properties.

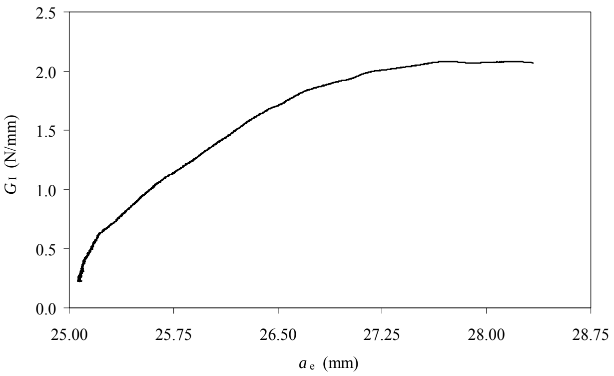

Figure 5. R-curve of bone under mode I.

Table 1. Fracture test results of cortical bone.

	Experimental	
Specimen	E_L (GPa)	G_{Ic} (N/mm)
1	19.498	1.606
2	16.659	1.690
3	17.323	2.224
4	17.984	2.133
5	22.375	1.524
6	19.857	2.050
7	21.098	1.715
8	21.364	2.367
9	23.311	1.893
Average	19.94	1.91
Cov (%)	11.53%	15.53%

5. CONCLUSIONS

In this work fracture of cortical bone tissue from young bovine femur under mode I loading was analysed. The double cantilever beam test was used with success, which constitutes an important result owing to significant advantages that this test presents relatively to other fracture tests for mode I fracture characterization. In addition, a new data reduction scheme based on the specimen compliance and crack equivalent concept was applied. The compliance based beam model does not depend on crack measurements during its growth and allows the attainment of the entire *Resistance*-curve (*R*-curve), thus leading to the clear identification of fracture energy. The experimental tests were performed on bone specimens, considering the TL propagation system. The *R*-curves obtained using the proposed data reduction scheme, clearly show that a plateau value defining the fracture energy of cortical bone under mode I loading is easily obtained.

The principal achievements of this work put into evidence the applicability of the double cantilever beam test applying the described data reduction method to determine the fracture energy of bone under mode I loading.

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