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Abstract

Purpose – Fracture characterization of human cortical bone under pure mode I loading was performed in this work. The purpose of this paper is to validate the proposed test and procedure concerning fracture characterization of human cortical bone under pure mode I loading.
Design/methodology/approach – A miniaturized version of the double cantilever beam (DCB) test was used for the experimental tests. A data reduction scheme based on crack equivalent concept and Timoshenko beam theory is proposed to overcome difficulties inherent to crack length monitoring during the test. The application of the method propitiates an easy determination of the Resistance-curves (*R*-curves) that allow to define the fracture energy under mode I loading from the plateau region. The average value of fracture energy was subsequently used in a numerical analysis with element method involving cohesive zone modelling.
Findings – The excellent agreement obtained reveals that the proposed test and associated methodology is quite effective concerning fracture characterization of human cortical bone under pure mode I loading.

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Originality/value – A miniaturized version of traditional DCB test was proposed for cortical human bone fracture characterization under mode I loading owing to size restrictions imposed by human femur. In fact, DCB specimen propitiates a longer length for self-similar crack propagation without undertaking spurious effects. As a consequence, a *R*-curve was obtained allowing an adequate characterization of cortical bone fracture under mode I loading.

Keywords DCB test, Human bone, Mode I toughness

Paper type Research paper

1. Introduction

Nowadays, bone fracture characterization is a very important topic of research. In fact, the increase of aged population leads to a rising number of accidental fractures with obvious social, economic and human health impact. Fractures can result from accidents, fatigue loading, diseases and as a result of administration of drugs for a long time. However, these type of studies are not easy since 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. Cortical bone defines the propensity of long bone to fracture and justifies the study of its fracture properties. In humans, the cortical bone microstructure consists of Haversian systems also known as osteons. Osteons are predominantly circular and run parallel to the long axis of the bone. They contain central blood vessels, in a cylindrical canal known as a Haversian canal, which join to perpendicular Volkmann canals. The blood vessels are surrounded by concentrically arranged and differently orientated lamellae along which collagen fibres are disposed. The cement line is the region that surrounds the exterior lamellae and is the weakest constituent of bone where micro-cracks nucleate. The longitudinal orientation of the osteons embedded in the cement line provides a material behaviour similar to a fibre reinforced composite. As a consequence of this complex microstructure, bone presents some variability on its mechanical properties (Norman *et al.*, 1995).

There are several works concerning fracture characterization of bone under mode I loading. Several fracture tests have been used in this context: compact tension (CT) (Norman *et al.*, 1995; Yang *et al.*, 2006); chevron notched beam (Yan *et al.*, 2006); compact sandwich tension (Wang and Agrawal, 1996); single edge notched beam (SEN) (Phelps *et al.*, 2000; Zimmermann *et al.*, 2014); and double cantilever beam (DCB) (Morais *et al.*, 2010). The CT and SEN tests are the most used. However, they present a limitation related to confinement of non-negligible fracture process zone (FPZ) due to compressive stresses induced by bending that develop ahead of the crack tip (de Moura *et al.*, 2010). This is a spurious phenomenon that can artificially increase the measured toughness and lead 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 for cortical bovine bone fracture (de Moura *et al.*, 2010), 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.

An interesting issue is that although bovine bones are longer than human's, the last ones propitiate longer specimen due to a less pronounced curvature effects on the diaphysis. This is an important aspect since the most critical feature related with fracture tests in bovine bone is related to the limited specimen lengths available from bovine femurs.

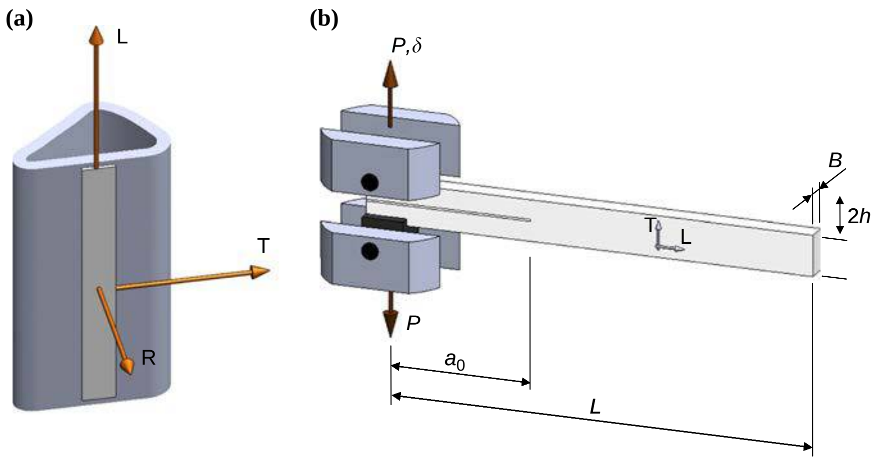
In this work, fracture characterization of human bone under mode I loading was performed using a miniaturized version of the DCB. This test is very simple to execute and provides a large extent of self-similar crack growth which is a fundamental aspect concerning accurate measurement of fracture energy. An equivalent crack length method based on Timoshenko beam theory and specimen compliance was used to avoid crack length monitoring during propagation. This task is particularly difficult to execute with the required accuracy in bone. The procedure was validated numerically by means of the finite element analysis including cohesive zone modelling. The excellent agreement obtained reveals that the DCB test and the proposed procedure is a valuable method concerning fracture characterization of human bone under mode I loading.

2. Experiments

Five specimens were prepared from the diaphysis (Figure 1(a)) of tibia of a young male human donor (21 years old). Tibia was stored in a container at −196°C (in liquid nitrogen) in the Hospital of University of Coimbra (HUC), Portugal. Due to orthotropy, three different directions can be defined (Figure 1(b)) for cortical bone: the longitudinal (L) aligned with osteons (long-axis of tibia), the radial (R) across thickness and the tangential (T). This setup allows the crack growth to occur in the so-called TL crack propagation system (the first letter identifies the normal to the crack plane and the second one the direction of propagation) where fractures are common.

The specimen configuration was obtained using milling and cutting operations (Plate 1), leading to the average dimensions shown in Figure 1(b). These dimensions were limited by the tibia curvature and cortical bone thickness in the diaphysis region.

During the specimens machining process the endosteal (the layer of cells on the inside of the bone) and periosteal (the layer of cells on the outside of the bone) tissues were removed. Specimens were preserved with physiological saline at all steps of the



Notes: (a) L, longitudinal; R, radial; T, tangential; (b) $L = 70$, $2h = 6$, $B = 2$, $a_0 = 22$ mm

Figure 1. (a) Orthotropic directions of tibia; (b) schematic representation of the DCB test

Plate 1.
Milling and cutting operations performed to get the final specimens

machining process and frozen at −20°C for storage. Tibia is initially cut in three main parts: interior, exterior and posterior (Plate 2).
Subsequently, five DCB specimens were produced in order to perform the fracture characterization tests (Plate 3).

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 precrack was created just before the fracture tests, by tapping a sharp razor blade into the notch (Plate 4), 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.

An initial crack with a nominal length of $a_0 = 22$ mm was introduced. This value provides a ratio L/a_0 approximately equal to 7, which is acceptable for application of Timoshenko beam theory (Timoshenko and Gere, 1972). Experimental tests were executed in a servo-electrical testing system (MicroTester INSTRON 5848), using a constant displacement rate of 0.5 mm/min (Plate 5). 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 pure mode I loading.

A detail of the crack region obtained by magnified lens (50×) reveals that is very difficult to identify the crack tip position with the required accuracy for a correct evaluation of its length (Plate 6). The classical data reduction methods are based

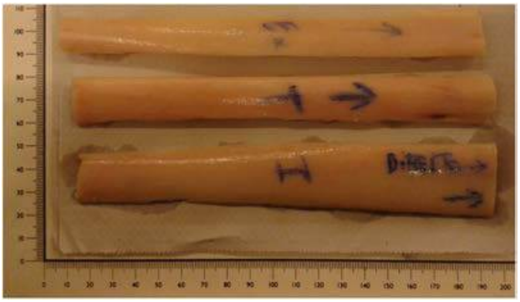


Plate 2.
Three main parts of tibia after a pre-cut operation

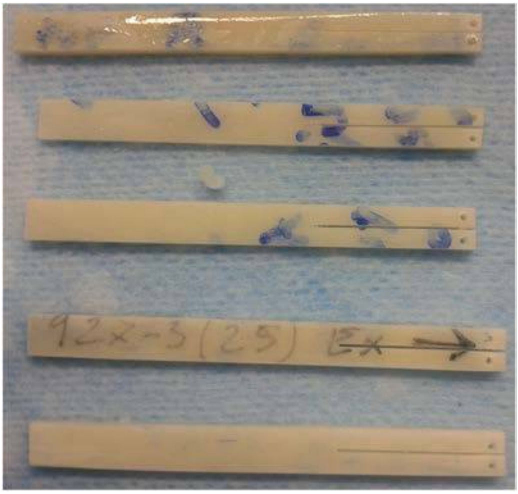


Plate 3.
Five DCB specimens obtained from the young male tibia

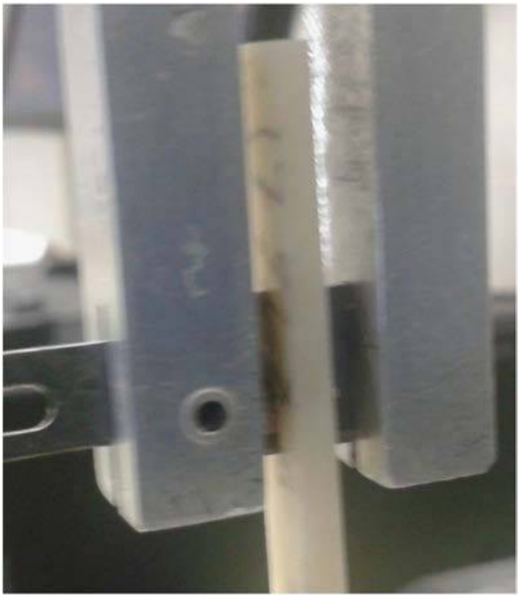


Plate 4.
Pre-crack execution using a blade in a testing machine

Plate 5.
Testing setup of the DCB test

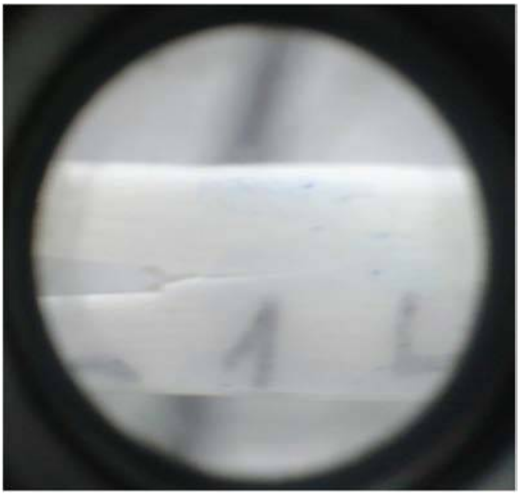


Plate 6.
Detail of the crack region revelling the undefined crack tip position

on crack length parameter to estimate the fracture energy. Surely they should not be used in such circumstances since the measure values will be probably influenced by remarkable reading errors.
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.

3. Compliance-based beam method

Considering the Timoshenko beam theory (Timoshenko and Gere, 1972) the compliance ($C = \delta/P$) as a function of crack length ($C = f(a)$) relationship can be written as:

$$C = \frac{8a^3}{E_L B h^3} + \frac{12a}{5BhG_{LT}} \tag{1}$$

being E_L and G_{LT} the longitudinal and shear moduli, respectively, in the LT plane (Figure 1(b)). The other parameters refer to specimen dimensions and are represented in Figure 1(b). This equation was obtained assuming a perfect clamping at the crack tip (de Moura *et al.*, 2008), which does not comply with the physical reality.

In order to include the effect of root rotation at the crack tip, a correction to the crack length can be incorporated (Hashemi *et al.*, 1990):

$$\Delta = h\sqrt{\frac{E_{\mathrm{f}}}{11G_{LT}}\left[3-2\left(\frac{\Gamma}{1+\Gamma}\right)^2\right]} \tag{2}$$

where:

$$\Gamma = 1.18\frac{\sqrt{E_f E_T}}{G_{LT}} \tag{3}$$

where E_T is the tangential elastic modulus. Bone is a natural material presenting some variability of its elastic properties, which means that the longitudinal modulus E_L can vary from specimen to specimen. In this context, an effective elastic modulus (E_f) can be evaluated considering the initial values of compliance (C_0) and crack length (a_0) as follows:

$$E_f = \left(C_0 - \frac{12(a_0 + |\Delta|)}{5BhG_{LT}}\right)^{-1} \frac{8(a_0 + |\Delta|)^3}{Bh^3} \tag{4}$$

An iterative procedure involving Equations (2-4) should be used till a converged value of E_f is reached. During crack growth an equivalent crack length (a_e) can be estimated to account for the damaging processes occurring ahead of the crack tip. Effectively, since a non-negligible FPZ develops, the energy dissipated in this region should be accounted for, which does not occur if the real crack length is used. In this context, Equation (1) can be solved to yield a_e as a function of the current compliance during the test ($a_e = f(C)$), using Matlab® software (de Moura *et al.*, 2008).

The R-curve ($G_I = f(a_e)$) can be obtained combining the Irwin-Kies equation:

$$G_I = \frac{P^2}{2B}\frac{dC}{da} \tag{5}$$

with Equation (1), which leads to:

$$G_I = \frac{6P^2}{B^2h}\left(\frac{2a_e^2}{h^2E_f} + \frac{1}{5G_{LT}}\right) \tag{6}$$

Following this methodology crack length monitoring is unnecessary, which constitutes a valuable advantage since it is not easy to measure it with the required accuracy. Indeed, the crack length monitoring during its growth is not necessary since the equivalent crack is a calculated parameter as a function of the current specimen compliance (data captured from the P-δ curve). This is a very important aspect, since crack length monitoring in bone fracture is not easy to perform (Plate 6). Moreover, bone is considered a quasi-brittle material characterized by the presence of a non-negligible FPZ at the crack tip, which influences the P-δ 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. Furthermore, this method accounts for scattering of elastic properties, since the used elastic modulus (E_f) is a computed parameter using the initial values of a_0 and C_0. From Equation (6) it can be observed that the shear modulus G_{LT} has a small influence on the results and a typical value can be used (de Moura *et al.*, 2008).

4. Numerical validation

Finite element analysis including cohesive zone modelling was used to validate the DCB test and the proposed data reduction scheme applied to human bone fracture characterization under mode I loading. Figure 2 illustrates the FE mesh used in the numerical simulations presenting 3,840 two-dimensional plane stress solid elements, with 240 interface finite elements positioned in the crack path (i.e. ligament section).

Small increments (0.005 of the applied displacement) were used to ensure smooth damage propagation during the loading process, using the elastic properties presented in Table I.

The bilinear softening cohesive law (Figure 3) was used to simulate damage initiation and propagation in human bone. The bilinear law intends to simulate two different damaging processes that develop ahead of the crack tip: micro-cracking corresponding to the initial softening branch and fibre bridging represented by the final branch of the cohesive law.

The area circumscribed by the cohesive law corresponds to the mode I fracture energy G_{Ic}. The remaining cohesive parameters defining the softening law (local strength and coordinates of the inflection point) were determined by an inverse procedure involving the agreement between the experimental and numerical P-δ curves. A trial and error procedure by adjusting the referred cohesive parameters till a good agreement between the numerical and experimental P-δ curves was performed. The cohesive parameters providing good agreement are the ones selected as being representative of the material fracture behaviour.

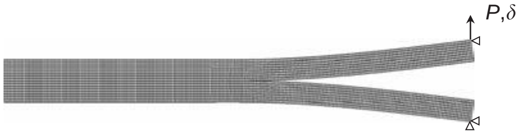


Figure 2.
Finite element mesh showing the used loading and boundary conditions

Table I.
Nominal elastic properties of human cortical bone

E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ν_{LT}
13.6	9.6	4.74	0.37

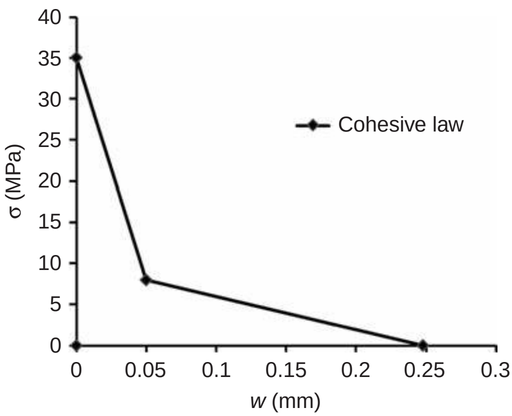


Figure 3.
Bilinear cohesive law used

5. Results

Although five DCB tests were performed, only three valid results were collected. In fact, in two tests the crack deviated prematurely (i.e. from the beginning of its propagation) from the mid-specimen plane (Plate 7). This circumstance does not provide a valid toughness measurement since a pronounced mixed-mode I+II loading takes places instead of the intended pure mode I loading.

The remaining three tests revealed self-similar crack growth without crack deviation from its initial mid specimen plane (Plate 8). These tests were considered valid and used to assess fracture energy of human bone under mode I loading and to validate the proposed procedure.

Figure 4 presents the experimental P-δ curves corresponding to three valid DCB tests. The three P-δ curves revealed to be very consistent showing similar initial

Plate 7.
Crack deviation at initiation in a DCB test of human bone

Plate 8.
Self-similar crack propagation without deviation from its initial plane

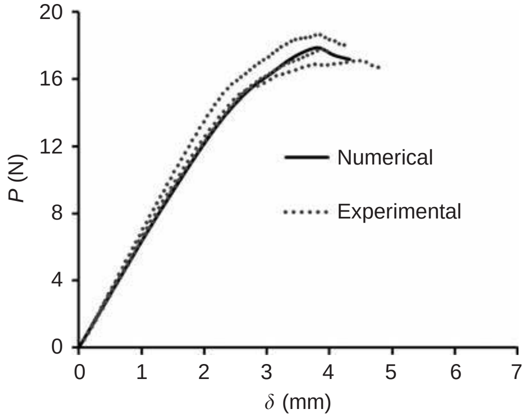


Figure 4. Experimental and numerical load-displacement curves of the DCB test of human bone

stiffness, maximum load and also the post-peak behaviour. This can be viewed as a remarkable result since bone is a natural material with important scatter on its elastic and fracture properties.

The equivalent crack-based data reduction scheme presented previously was used to obtain the mode I *R*-curves (Figure 5). 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 conditions. This reveals that the FPZ is completely developed ahead of the crack tip and grows with constant size for a given crack extent. These conditions allow accurate evaluation of mode I fracture energy.

An average experimental value of $G_{Ic} = 1.86$ N/mm with a coefficient of variation (CoV) equal to 2.5 per cent was found. This value is higher than the one of Zioupos and Currey (1998) who obtained 1.34 N/mm with a CoV equal to 6.7 per cent. The measured average value was used in the numerical simulations of the DCB test in order to determine the remaining cohesive parameters.

After some iterations it was verified that the cohesive law presented in Figure 3 provide excellent agreement between the numerical and experimental *P*-δ (Figure 4)

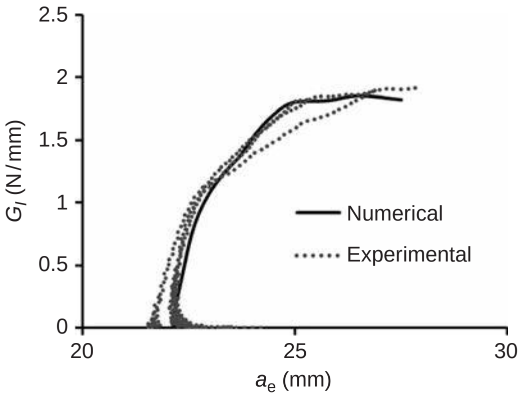


Figure 5. Experimental and numerical *R*-curves obtained in DCB tests

and *R*-curves (Figure 5). The found cohesive parameters point to a local strength of 35 MPa and 0.05 mm and 8 MPa as the coordinates of the inflection point (Figure 3). The ultimate relative displacement corresponding to total failure points to 0.25 mm. This law mimics with excellent accuracy the fracture behaviour of human bone under mode I loading.

It can be concluded that the proposed test and associated procedure is quite effective concerning fracture characterization of human bone under mode I loading.

6. Conclusions

Fracture characterization of human cortical bone tissue under mode I loading was performed in this work. A miniaturized version of the DCB was used due to its simplicity. The DCB test provides self-similar crack growth for a reasonable crack extent which is crucial for an accurate fracture characterization.

An equivalent crack length procedure based on Timoshenko beam theory was used to evaluate the *R*-curves without monitoring crack length during the test which is difficult to perform due to failure mechanisms in bone that include micro-cracking and fibre bridging. Very consistent experimental results were obtained in the three valid tests.

A numerical analysis based on finite element method including cohesive zone modelling was performed to validate all the procedure. A bilinear softening law was used to mimic the observed failure modes. The experimental fracture energy was used as an input in the numerical model. The remaining cohesive parameters were determined by an inverse method involving a fitting procedure between the numerical and experimental P-δ curves.

Excellent agreement was obtained between the numerical and experimental P-δ and *R*-curves, which validates the use of the DCB test as well as the proposed data reduction scheme and the determined cohesive law.

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