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XIV Portuguese Conference on Fracture

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Alfredo Ribeiro
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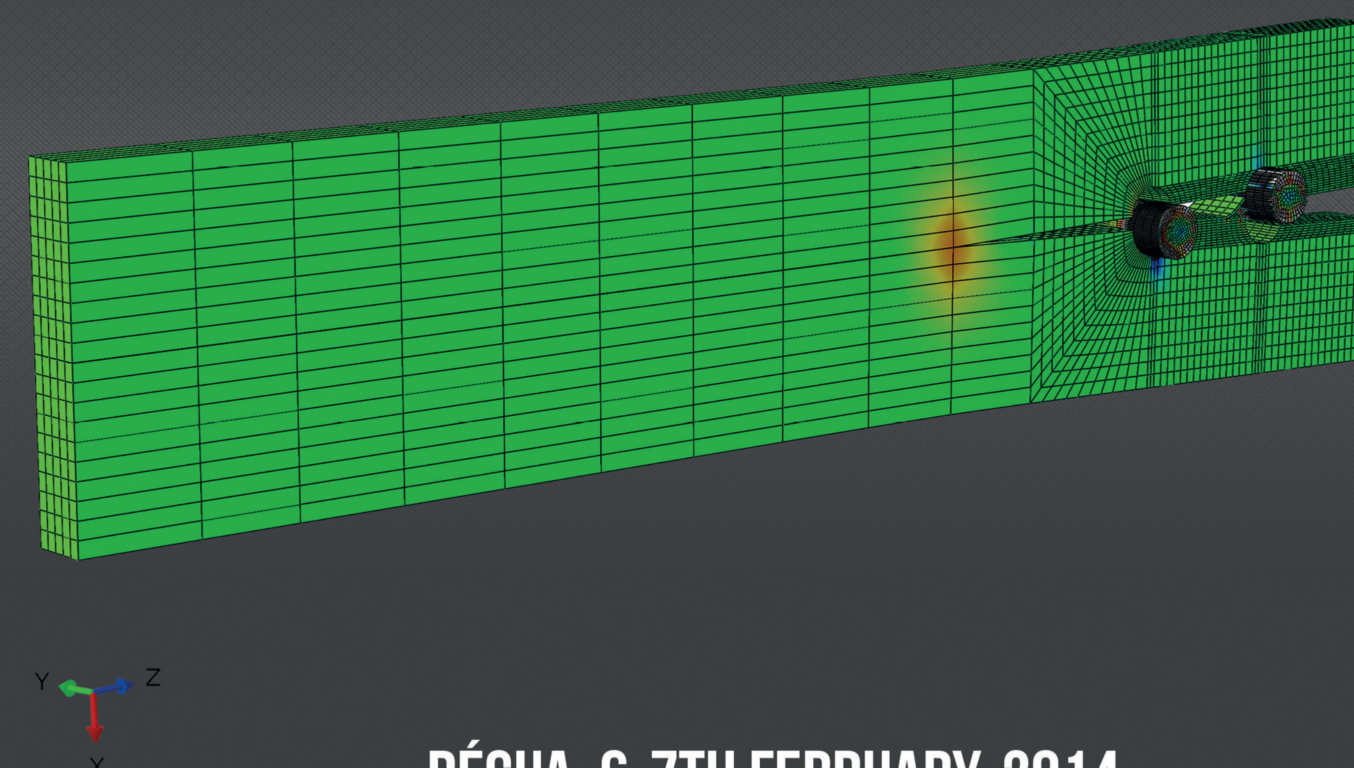
José Xavier
Nuno Dourado



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MODE I FRACTURE CHARACTERIZATION OF HUMAN BONE USING THE DCB TEST

F. Silva[1], M.F.S.F. de Moura[2], N. Dourado[3], F.A.M. Pereira[2,3], J.J.L. Morais[1], M.I.R. Dias[4], P.J. Lourenço[5], F.M. Judas[5]

[1]INEGI - Instituto de Engenharia Mecânica e Gestão Industrial, Rua Dr. Roberto Frias, 400 4200-465 Porto, Portugal

[2] Faculdade de Engenharia da Universidade do Porto, Departamento de Engenharia Mecânica, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

[3] Universidade de Trás-os-Montes e Alto Douro, UTAD, CITAB, Departamento de Engenharias, Quinta de Prados, 5000-801 Vila Real, Portugal

[4] Universidade de Trás-os-Montes e Alto Douro, UTAD, CITAB, Departamento de Ciências Veterinárias, Quinta de Prados, 5000-801 Vila Real, Portugal

[5] Faculdade de Medicina da Universidade de Coimbra, Banco de Tecidos Ósseos do Centro Hospitalar e Universitário de Coimbra - CHUC, EPE, Praceta Prof. Mota Pinto 3030-396 Coimbra, Portugal

Abstract

Fracture characterization of human cortical bone under pure mode I loading is performed in this work. A miniaturized version of the double cantilever test (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 that allow defining 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. The aim is to validate the proposed test and procedure concerning fracture characterization of human cortical bone under pure mode I loading. A bilinear cohesive zone model was used to simulate damage initiation and growth. The cohesive parameters were determined by an inverse procedure involving the fitting of numerical and experimental load-displacement curves. 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.

Keywords: Human bone, Mode I, Fracture characterization, Double cantilever test.

1. INTRODUCTION

Nowadays, bone fracture characterization is a very important topic of research. In fact, the increase of aged population leads to an increase of accidental fractures with obvious social, economic impacts and human health. 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 cells, an extracellular matrix (ECM) with a mineral phase (mainly hydroxyapatite) and an organic phase (mainly collagen) and water. The ECM 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 plays an important role on the propensity of long bone to fracture and justifies the study of its fracture properties.

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)[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 ones. 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 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 [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.

An interesting issue is that although bovine bones are longer than humans', the latter propitiate longer specimens due to a less pronounced curvature of the diaphysis segments. 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 in bovine femurs.

In this work fracture characterization of human bone under mode II loading was performed using a miniaturized version of the double cantilever test (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 DCB test and proposed procedure is a valuable procedure concerning fracture characterization of human bone under mode I loading.

2. EXPERIMENTS

Five specimens were prepared from the diaphysis region (Figure 1a) of a tibia of a young human male (21 years old). Due to material orthotropy, three different directions can be identified (Figure 1b) in cortical bone: the longitudinal (L) aligned with osteons (long-axis of tibia), the radial (R) along thickness and the Tangential (T) one.

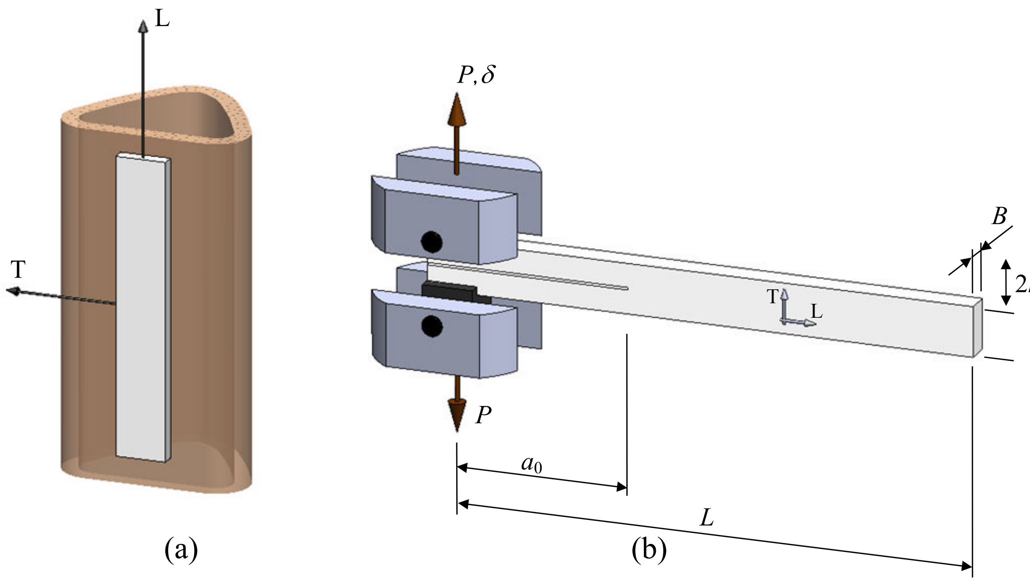

Figure 1. Schematic representation of the DCB test (L: longitudinal direction; R: radial direction, and T: tangential direction of a tibia) (L = 70; $2h$ = 6; B = 2; a_0 = 22 mm).

The specimen configuration was obtained using grinding and cutting operations (Figure 2), with the average dimensions shown in Figure (1b). These dimensions were limited by the tibia curvature and cortical bone thickness in the diaphysis region.

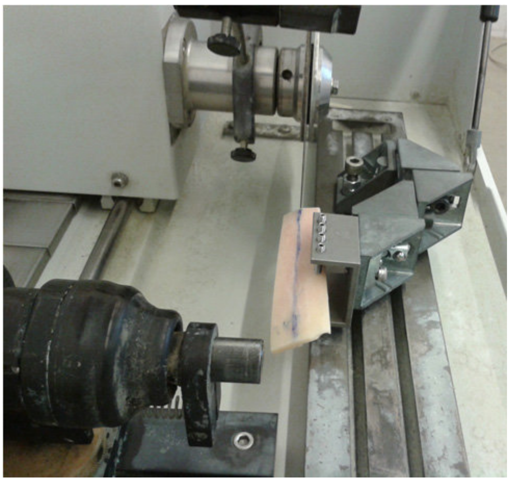

Figure 2. Cutting operations performed to get the final specimens.

During the specimens machining process the endosteal and periosteal tissues were removed. Specimens were preserved with physiological saline solution at all steps of the machining process and frozen at -20° C for storage.

Tibia is initially cut in three main parts: interior (medial face), exterior (lateral face) and posterior face (Figure 3).

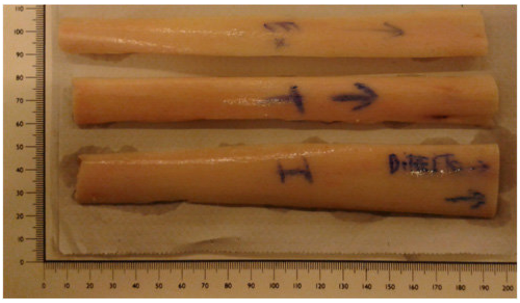

Figure 3. Three main parts of tibia after a pre-cut operation.

Subsequently, five DCB specimens were produced in order to perform the fracture characterization tests.

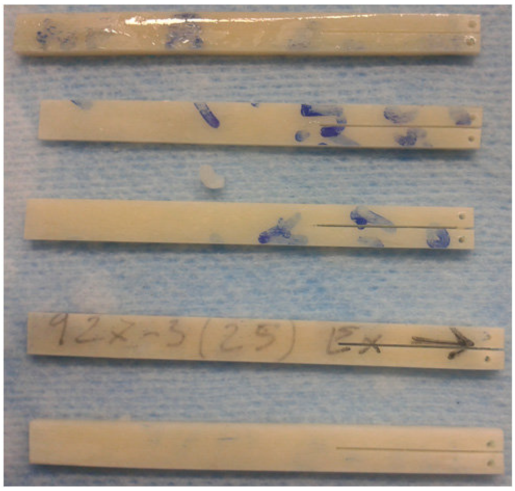

Figure 4. Five DCB specimens obtained from the young male tibia.

The initial crack length a_0 was introduced in two steps. First, a notch (0.3 mm thick and 21.75 mm length) was machined using a circular saw. Then, a pre-crack was created just before the fracture tests, by tapping a sharp razor blade into the notch (Figure 5), using the test machine. This has been accomplished by moving the actuator 0.25 mm towards the specimen with a velocity of 100 mm/s.

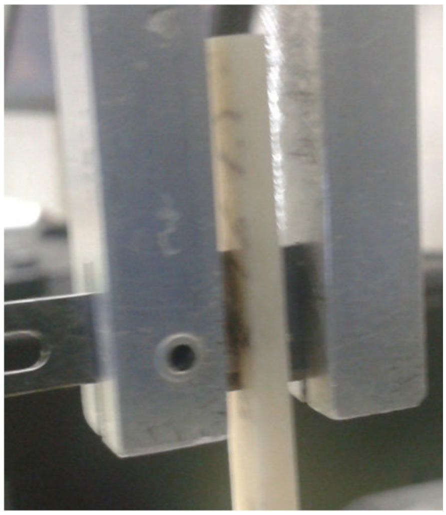

Figure 5. Pre-crack operation.

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. Experimental tests were then executed in a servo-electrical testing system (MicroTester INSTRON 5848), using a constant displacement rate of 0.5 mm/min (Figure 6). 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.

Figure 6. Testing setup of the SLB test.

A detail showing the crack region obtained by magnified lens reveals that it is very difficult to identify the crack tip position with the required accuracy for a correct evaluation of its length (Figure 7). The classical data reduction methods are based on crack length parameter to estimate the fracture energy. Surely they should not be used in such circumstances since the measure values would be probably influenced by remarkable reading errors.

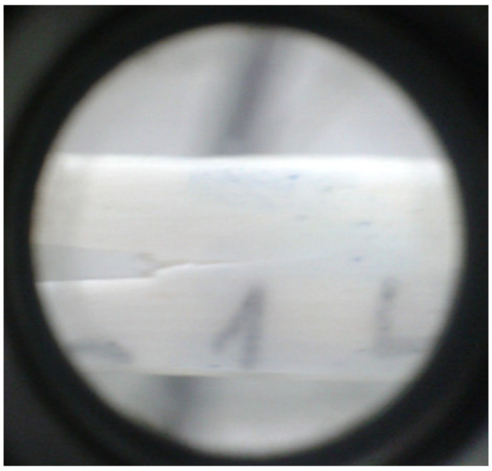

Figure 7. Detail of the crack region reveling the undefined crack tip position.

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 (CBBM)

Considering the Timoshenko beam theory the $C = \mathrm{f}(a)$ relationship can be written as

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

being G_LT the shear modulus in the LT plane (Figure 1). This equation was obtained assuming a perfect clamping at the crack tip [8], which does not comply with the physical reality.

In order to include the effect of root rotation at the crack tip, a correction of the crack length can be incorporated [9],

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

where

$$\Gamma = 1.18\frac{\sqrt{E_\mathrm{f} E_\mathrm{T}}}{G_\mathrm{LT}} \tag{3}$$

Bone is a natural material presenting some variability in 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

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

An iterative procedure involving Eqs. (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 fracture process zone (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, Eq. (1) can be solved to yield a_e as a function of the current compliance in the course of the test (a_e=f(C)), using Matlab® software [8].

The R-curve (G_{I} = f(a_e)) can be obtained combining the Irwin-Kies equation

$$G_{\mathrm{I}} = \frac{P^2}{2B}\frac{dC}{da} \tag{5}$$

with equation (1), which leads to

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

Following this methodology crack length monitoring is unnecessary, which constitutes a valuable advantage since it is not easy to perform with the required accuracy. 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 load-displacement curve). This is a very important aspect, since crack length monitoring in bone fracture is not easy to perform (Figure 7). 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. Furthermore, this method accounts for scattering of elastic properties, since the elastic modulus is a computed parameter using the initial values of a_0 and C_0. From Eq. (6) it can be observed that the shear modulus G_{LT} has a negligible influence on the results and a typical value can be used [10].

3. NUMERICAL VALIDATION

Finite element analysis including cohesive zone modelling was used to validate the DCB test and data reduction scheme applied to human bone fracture characterization under mode I loading. Figure 8 illustrates the FE mesh used in the numerical simulations presenting 3840 two-dimensional plane stress solid elements, with 240 interface finite elements positioned in the crack path (i.e., ligament section).

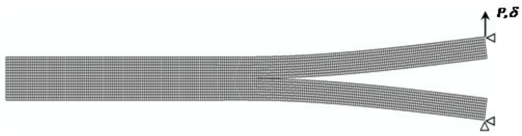

Figure 8. Finite element mesh showing the used loading and boundary conditions.

Small increments (0.005 of the applied displacement) were used to ensure smooth damage propagation in the course of the loading process, using the elastic properties presented in Table 1.

Table 1. Nominal elastic properties of human cortical bone.

E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ν_{LT}
13600	9.0	4.74	0.37

The bilinear softening cohesive law (Figure 9) 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 fiber 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 aiming the agreement between the experimental and numerical load-displacement curves. More details about this model can be found in reference [8].

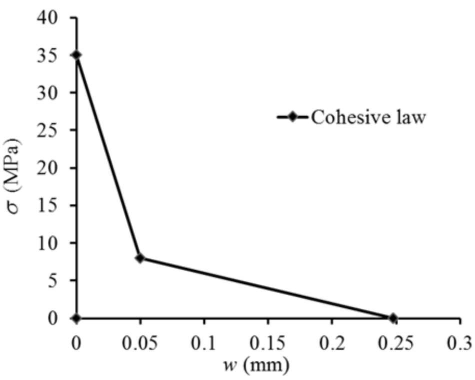

Figure 9. Bilinear cohesive law.

4. 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 (Figure 10). This circumstance invalidates the measured toughness since a pronounced mixed-mode I+II loading takes places instead of the intended pure mode I loading.

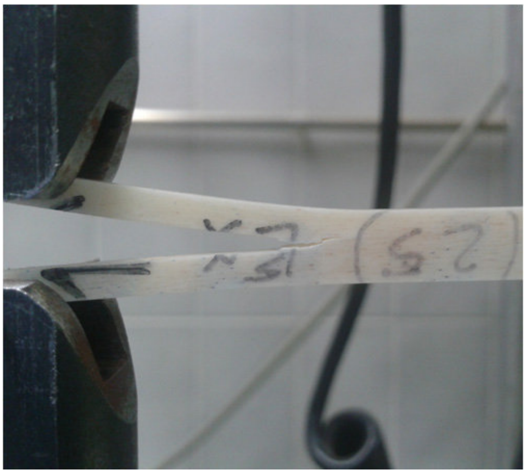

Figure 10. Crack deviation at initiation in a DCB test of human bone.

The remaining three tests revealed self-similar crack growth without crack deviation from its initial mid specimen plane (Figure 11). 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 12 presents the experimental load-displacement curves corresponding to three valid DCB tests. The three load-displacement curves revealed to be very consistent showing similar initial stiffness, maximum load and also the post-peak behavior. This can be viewed as a remarkable result since bone is a natural material with important scatter in its elastic and fracture properties.

Figure 11. Self-similar crack propagation without deviation from its initial plane.

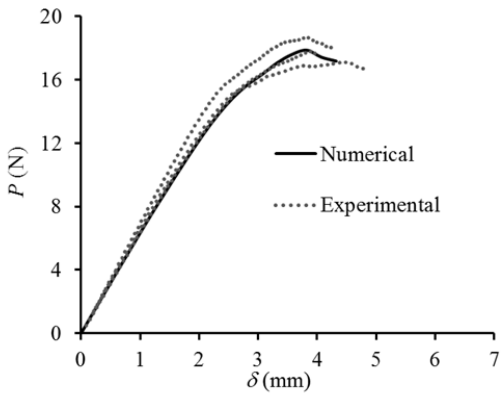

Figure 12. Experimental and numerical load-displacement curves of the DCB test of human bone.

The equivalent crack based data reduction scheme presented previously was used to obtain the mode I *R*-curves (Figure 13). 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 fracture process zone 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.

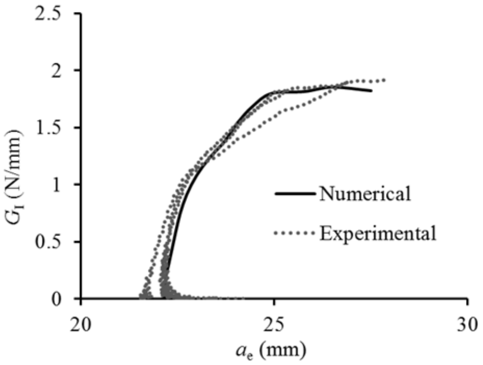

Figure 13. Experimental and numerical *R*-curves obtained in DCB tests.

An average experimental value of G_{Ic}=1.86 N/mm with a coefficient of variation equal to 2.5% was found. This 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 9 provide excellent agreement between the numerical and experimental load-displacement (Figure 12) and *R*-curves (Figure 13). 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 9). This law mimics with excellent accuracy the fracture behavior 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.

5. CONCLUSIONS

Fracture characterization of human cortical bone tissue under mode I loading was performed in this work. A miniaturized version of the double cantilever beam (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 *Resistance*-curves without monitoring crack length in the course of 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. 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 load-displacement curves.

Excellent agreement was obtained between the numerical and experimental load-displacement and *R*-curves, which validates the use of the DCB test as well as the proposed data reduction scheme.

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