Numerical analysis of the ENF and ELS tests applied to mode II fracture characterization of cortical bone tissue

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ABSTRACT The objective of this work is to verify numerically the adequacy of the ENF and the ELS tests to determine the fracture toughness under mode II loading of cortical bovine bone tissue. A data-reduction scheme based on the specimen compliance and the equivalent crack concept is proposed to overcome the difficulties inherent to crack monitoring during its growth. A cohesive damage model was used to simulate damage initiation and growth, thus assessing the efficacy of the proposed data-reduction scheme. The influences of the initial crack length, local strength and toughness on the measured fracture energy were analysed, taking into account the specimen length restriction. Some limitations related to spurious influence on the fracture process zone of the central loading in the ENF test, and clamping conditions in the ELS test were identified. However, it was verified that a judicious selection of the geometry allows, in both cases, a rigorous estimation of bone toughness in mode II.

Keywords bone; cohesive zone modelling; fracture characterization; mode II.

NOMENCLATURE

\(a\) = crack length
\(a_0\) = initial crack length
\(a_e\) = equivalent crack length
\(B\) = specimen width
\(C\) = specimen compliance
\(C_0\) = initial specimen compliance
\(E_f\) = corrected flexural modulus
\(E_L\) = longitudinal modulus
\(E_T\) = transverse modulus
\(G_{I}\) = strain energy release rate in mode I
\(G_{Ic}\) = fracture toughness in mode I
\(G_{II}\) = strain energy release rate in mode II
\(G_{IIc}\) = fracture toughness in mode II
\(G_{LT}\) = shear modulus
\(h\) = specimen height
\(L\) = specimen characteristic length
\(L_{ef}\) = effective length in the ELS test
\(P\) = applied load
\(\delta\) = applied displacement
\(\Delta t\) = crack length correction
\(\sigma_{i}\) = stresses in each mode \((i = I, II)\)
\(\sigma_{u,i}\) = local strengths \((i = I, II)\)

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INTRODUCTION

Fracture behaviour of cortical bone has attracted the attention of many researchers.\textsuperscript{1–7} Effectively, the fracture of healthy bone tissue needs to be understood in order to predict and reduce fractures due to aging, exercise, over-use and disease. The key issue is to determine the toughness which represents the mechanical property that describes the bone resistance to crack initiation and propagation. Two parameters can be used to identify the toughness: the critical stress intensity factor ($K_c$) and the critical strain energy release rate ($G_c$). The $K_c$ is a scaling factor that describes the alteration of stress state in the vicinity of the crack tip, whereas $G_c$ measures the energy required to extend a pre-existing crack. One important difference between both is that $K_c$ is a local parameter, whereas $G_c$ represents a global variation of the structure energy when the pre-existing crack grows. Cortical bone is a heterogeneous composite material, with an anisotropic and complex hierarchical microstructure, comprising mineral (mainly hydroxyapatite), organic (mostly type I collagen) and water phases. Consequently, being a global parameter, $G_c$ is more appropriate than $K_c$ to measure toughness because $K_c$ can be drastically affected by local variations of the internal material constitution. Alternatively, Yan et al.\textsuperscript{8} proposed the $J$-integral to account for the plastic deformation of bone induced by several toughening mechanisms, e.g. microcracking, osteon pullout, fibre bridging and crack deflection. The authors concluded that the toughness of bone estimated using the $J$-integral is much greater than the toughness measured using the critical stress intensity factor. Yang et al.\textsuperscript{9} proposed a cohesive model as a nonlinear fracture model in order to account for the damage zone developed in bone. They argue that linear elastic fracture mechanics is unable to account for the load-displacement curves shape but the nonlinear model overcomes this deficiency. Ural et al.\textsuperscript{10} used cohesive finite element modelling to analyse the age-related toughness loss in human cortical bone. The authors concluded that cohesive models are able to capture and predict the parameters related to bone fracture by representing the physical processes occurring in the vicinity of a propagating crack. The majority of the works about fracture characterization of bone tissue are dedicated to mode I loading. The compact tension test\textsuperscript{1} and the single-edge notched specimen under three-point bending\textsuperscript{11} are commonly used. The difficulties associated in getting specimens with the required size lead to the employment of the single-layer compact sandwich specimen.\textsuperscript{12} In this specimen a bone coupon was sandwiched between two holders of polymethylmethacrylate. Much less attention has been dedicated to fracture characterization under mode II loading which is justified by the difficulty of defining an adequate test. Norman et al.\textsuperscript{13} proposed the compact shear test for mode II fracture characterization of human bone. Subsequently, Brown et al.\textsuperscript{14} used the same test to evaluate fracture toughness dependency on bone location and age. However, this test presents three disadvantages: (1) small variation of compliance as a function of pre-crack length which turns difficult the establishment of compliance calibration; (2) mixed-mode crack growth instead of pure-mode II and (3) unstable propagation, which means that only crack initiation fracture toughness is available. Fracture tests using bovine bone are frequently performed because it provides longer specimens relative to the human's. Norman et al.\textsuperscript{3} reported that fracture toughness of human bone was lower than that of bovine. However, when normalized by their respective strengths, the two types of bone were equally tough, implying that the mechanisms which give higher strength may also be responsible for higher toughness. Although the fracture properties of bovine and human cortical bone are not equal,\textsuperscript{14,15} the same kind of experimental test can be applied to determine those properties. This particularity can be used to identify new test methods using bovine cortical bone.

The objective of this work is to perform a numerical study on the mode II fracture characterization of bone. This work acquires special relevancy in the context of shear and mixed-mode (I + II) fractures. In reality, it is known that the majority of the bone fracture \textit{in vivo} occurs under mixed-mode (e.g. I + II), which emphasizes the necessity to define adequate fracture criteria in the $G_1 - G_II$ space. In this context, it is important to determine the fracture toughness under mode II loading. Thus, the applicability of the ENF and the ELS tests to mode II fracture characterization of bovine bone in the tangential-longitudinal (TL) fracture system (Figs 1 & 2) was numerically assessed. These tests are particularly suitable for mode II fracture characterization because of their simplicity and the possibility to use the beam theory to measure the fracture energy. They are frequently used.
to evaluate the fracture properties of different materials, e.g. wood\textsuperscript{16,17}, composites\textsuperscript{18} or bonded joints\textsuperscript{19,20}. However, these fracture tests have never been applied to bone. Hence, the applicability of these tests in the context of bone fracture characterization requires a careful analysis owing to the limitations of producing adequate specimen sizes. Bone fracture in mode II exhibits a pronounced FPZ ahead of the crack tip due to several toughening mechanisms, which must not interact with the external loading or boundary conditions to assure self-similar crack propagation. This issue is fundamental to achieving truthful fracture toughness ($G_{\text{IIc}}$) from the plateau of the resistance curve ($R$-curve). In this work, a numerical analysis was performed using a CZM on the ENF and ELS specimen geometries. This approach allows the simulation of damage initiation and growth, thus providing an appropriate method to assess the influence of the specimen dimensions and material properties on the measured $G_{\text{IIc}}$. The simulations focus on the assessment of the effect of initial crack length, fracture toughness and local strength on the fracture toughness measurements.

**DATA-REDUCTION SCHEME**

**Classical methods**

The classical data-reduction schemes used to determine the fracture energy in mode II are usually based on the specimen compliance calibration or on the beam theory. The CCM is based on the Irwin–Kies equation:

\[
G_{\text{II}} = \frac{P^2}{2B} \frac{dC}{da}
\]

which depends on the compliance ($C = \frac{\delta}{P}$) calibration as a function of the crack length $a$. The most used
data-reduction scheme is the CBT,

$$G_{II} = \begin{cases} 
9 P^2 (a + |\Delta|)^2 & (\text{ENF}) \\
16 B^2 b^3 E_L & (\text{ELS}) 
\end{cases}$$

(2)

where $B$ is the specimen width, $E_L$ is the longitudinal elastic modulus and $\Delta$ is the specimen compliance for the ENF and $\Delta$ is the specimen compliance for the ELS, being

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

(3)

with,

$$\Gamma = 1.18 \sqrt{\frac{E_L E_T}{G_{LT}}}$$

(4)

where $E_T$ and $G_{LT}$ are the transverse and shear modulus, respectively (Fig. 2). Using these methods (CCM and CBT), the crack length measurement is a fundamental task to be performed during the fracture test. However, this procedure is very difficult to execute with the required accuracy. Effectively, in mode II fracture characterization tests the crack tends to close during propagation hindering a clear identification of its tip. Additionally, quasi-brittle materials develop a non-negligible FPZ in the vicinity of the crack tip, characterized by the development of toughening mechanisms leading to a softening nonlinear region. This phenomenon is responsible for energy dissipation during crack propagation and should be considered in the selected data-reduction scheme. Thus, when $a$ is used in the calculations, the FPZ effect is not accounted for in the evaluation of $G_{IC}$. Here, the equivalent crack concept is used to define a data-reduction scheme based on the specimen compliance. This method does not require crack length monitoring during its growth and accounts for the energy dissipated in the FPZ.

Compliance-based beam method

**ENF**

Using the Timoshenko beam theory, the specimen compliance is given by

$$C = \frac{3 a^3 + 2 L^3}{8 B b^3 E_L} + \frac{3 L}{10 B b G_{LT}}$$

(5)

In the early stages of loading, the initial values of compliance $C_0$ and crack length $a_0$ can be used to estimate a corrected flexural modulus $E_t$,

$$E_t = \frac{3 a_0^3 + 2 L^3}{8 B b^3} \left( C_0 - \frac{3 L}{10 B b G_{LT}} \right)^{-1}$$

(6)

**ELS**

The compliance equation for the ELS is given by

$$C = \frac{3 a^3 + L^3}{2 B b^3 E_L} + \frac{3 L}{5 B b G_{LT}}$$

(10)

This procedure is quite effective because material variability among different specimens leads to non-negligible scatter on the elastic modulus. The beam theory (Eq. 5) does not include root rotation effects and stress concentrations at the crack tip. Following this approach, the longitudinal modulus is not a measured property but a parameter estimated from $C_0$ and $a_0$, thus accounting for the above referred effects. During crack growth the current compliance $C$ is used to estimate an equivalent crack length $a_e$ through Eqs (5) and (6),

$$a_e = \left[ \frac{C_c}{C_{0c}} a_0^3 + \frac{2}{3} \left( \frac{C_c}{C_{0c}} - 1 \right) L^3 \right]^{1/3}$$

(7)

where

$$C_c = C - \frac{3 L}{10 B b G_{LT}}; \quad C_{0c} = C_0 - \frac{3 L}{10 B b G_{LT}}$$

(8)

Using Eqs (1) and (5), $G_{II}$ can be obtained as

$$G_{II} = \frac{9 P^2 a_0^2}{16 B^2 b^3 E_t}$$

(9)

The $R$-curve can now be determined without monitoring $a$ during propagation, which is difficult to perform accurately in this test. The only material property required is $G_{LT}$. However, previous studies using a wide range of values of $G_{LT}$ revealed that it does not influence the measured $G_{IC}$. Consequently, a typical value (Table 1) can be used.

Table 1 Nominal elastic properties of bovine cortical bone

<table>
<thead>
<tr>
<th>$E_L$ (GPa)</th>
<th>$E_T$ (GPa)</th>
<th>$G_{LT}$ (GPa)</th>
<th>$v_{LT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.4</td>
<td>11.7</td>
<td>4.1</td>
<td>0.36</td>
</tr>
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NUMERICAL ANALYSIS

A cohesive mixed-mode model developed in de Moura et al.\(^2\) was used to simulate damage initiation and growth. This formulation allows simulating pure-mode loading cases because they correspond to particular conditions of a more general mixed-mode loading. The model assumes a linear relationship between stresses and relative displacements in the softening region (Fig. 3). This linear softening law has proved to be adequate to simulate microcracking phenomenon ahead of the crack tip observed in mode II fracture characterization tests in wood.\(^2\) A similar damage mechanism is referred to occur in mode II fracture characterization of bone,\(^1\) which supports the choice of this law. Damage initiation is simulated by quadratic stress criterion

\[
\left( \frac{\sigma_I}{\sigma_{u,I}} \right)^2 + \left( \frac{\sigma_{II}}{\sigma_{u,II}} \right)^2 = 1 \quad \text{if } \sigma_I \geq 0
\]

\[
\sigma_{II} = \sigma_{u,II} \quad \text{if } \sigma_I \leq 0
\]

where \(\sigma_i, (i = I, II)\) represent the stresses in each mode and \(\sigma_{u,i}\) the respective local strengths. Crack propagation was simulated by linear energetic criterion

\[
\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} = 1
\]

From Fig. 3 it is shown that the small triangle area corresponds to the energy dissipated in each mode \((G_i)\) and the biggest one to the respective toughness \((G_{ic})\). More details are given in de Moura et al.\(^2\)

A two-dimensional analysis was implemented in ABAQUS® software using 7680 isoparametric plane stress 8-node solid elements. Two hundred forty 6-node cohesive elements were disposed at the specimens half-height along direction \(x\) (Fig. 4), allowing the simulation of damage initiation and growth. These elements are
Table 2 Range of the cohesive properties used in the simulations

<table>
<thead>
<tr>
<th>$G_{IIc}$ (N mm$^{-1}$)</th>
<th>$\sigma_{u,II}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3–7</td>
<td>30–50</td>
</tr>
</tbody>
</table>

compatible with the 8-node isoparametric solid elements and were implemented through the user subroutine option available in ABAQUS®. Along the pre-crack the cohesive elements were considered 'opened', which means that they were only able to transmit normal compressive stresses, avoiding spurious interpenetrations. The friction effects at the pre-crack were neglected, because it was observed in previous studies that contact is confined to the loading regions. Moreover, in the experiments the use of two Teflon® films with a pellicle of lubricator between them will drastically diminish this effect. Refined meshes (Fig. 4) were used to provide several points undergoing softening, thus contributing to smooth damage growth and mesh independent results. Loading and supporting devices (Fig. 2) were simulated as rigid bodies and contact conditions assumed to prevent interpenetration. Clamping in the ELS (Fig. 4b) was simulated by two rigid blocks that tighten the specimen. Different amounts of tightening were considered (step 1 in Fig. 4b) to verify their influence on the measured $G_{IIc}$. Friction coefficient of 0.25 for the contact pair bone/steel was considered in this support. Fracture simulations (material elastic properties in Table 1) were performed imposing the displacement $u_y$ (step 2 in Fig. 4b) to the loading pin considering the TL fracture system (Figs 1 & 2). Small displacement increments ($0.1\% \times \delta$) were considered to provide stable crack growth and a nonlinear geometrical analysis was carried out.

RESULTS

The objective of this work is to verify which conditions must be fulfilled to provide accurate measurements of $G_{IIc}$ using the ENF and ELS tests. Consequently, typical $G_{IIc}$ and $\sigma_{u,II}$ limiting values were assumed in the simulations (Table 2). The maximum specimen length that can be obtained from the bovine femur (Fig. 1) is in the order of 60–70 mm. Because the ENF test is more susceptible to the specimen length than the ELS (see discussion below), it was decided to use 70 mm for the ENF and 60 mm for the ELS test. The specimens’ height ($2b$) and width ($B$) were set equal to 8 and 3 mm, respectively.

ENF

The ENF test can lead to unstable crack growth, namely for shorter crack lengths. Consequently, in the ENF test

the available region for unconstrained damage growth is quite limited. In fact, during self-similar crack propagation the FPZ developed ahead of the crack tip must be maintained far from the central loading point (Fig. 2a), for a correct $G_{IIc}$ measurement, because the compressive effects lead to a spurious toughness enhancement. This problem is aggravated for higher values of $G_{IIc}$, which means that a parametric study is fundamental to define
the application limits of the ENF test. The local strength \( \sigma_{u,II} \) in Fig. 3) also plays an important role in this context. Effectively, lower values of \( \sigma_{u,II} \) increase the tail of the softening region for a given toughness (i.e. area of the biggest triangle in Fig. 3) thus contributing to increase the FPZ size. A similar effect occurs when, for a given \( \sigma_{u,II} \), higher values of toughness are considered.

The first parameter to be analysed is the pre-crack length, \( a_0 \), considering a useful specimen length \( 2L = 65 \text{ mm} \) (Fig. 2a). Figure 5 presents the \( R \)-curves (Eq. 9) and the corresponding FPZ length \( l_{FPZ} \) as a function of \( a_e \) (Eq. 7), for three different values of \( a_0 \). The strain energy release rate was normalized by its toughness value \( (G_{IIc} = 4 \text{ N mm}^{-1}) \) which means that the inputted value is well captured if the obtained ratio points to the unity. From Fig. 5a it can be verified that unstable propagation occurs for the lowest pre-crack length, \( a_0 = 15 \text{ mm} \). For the other crack lengths, stable propagation took place although the plateau corresponding to self-similar crack growth has become shorter, and practically does not exist for \( a_0 = 20 \text{ mm} \) (Fig. 5c). The explanation for this occurrence is related to compression effects near the central loading point affecting the FPZ development. Effectively, those effects come out earlier as \( a_0 \) increases. This consequence can be clearly verified by the pronounced decrease of the FPZ length \( l_{FPZ} \) after a quite short plateau, thus showing the spurious effect induced by the central loading.

The influence of the local strength which defines the maximum stress that the material can attain at the crack tip \( (\sigma_{u,II} \text{ in Fig. 3}) \) was also assessed. From Fig. 6 it can be observed that the size of the plateau region of the \( R \)-curves increases with the enhancement of \( \sigma_{u,II} \), considering the same toughness \( (G_{IIc} = 4 \text{ N mm}^{-1}) \), i.e. the same triangular area (Fig. 3). This is a consistent result owing to the decrease of the critical displacement corresponding to the complete failure observed on the triangular cohesive law, \( \mu_{IIc} \). For \( \sigma_{u,II} = 50 \text{ MPa} \) (Fig. 6c), the plotting of \( l_{FPZ} \) as a function of \( a_e \) shows an important plateau, thus revealing self-similar crack growth conditions for a remarkable length. The used values (35–50 MPa) represent a rather conservative range because in Turner et al.,\(^{28}\) values ranging between 50.4 and 51.6 MPa are measured for human bone which has inferior properties than bovine. This means that more favourable conditions (i.e. higher local strengths) are expected to exist in the experiments.

The performance of the ENF test for different values of toughness was also analysed. Feng\(^{2} \) evaluated the \( G_{IIc} \) of bovine bone as being equal to \( 2.43 \pm 0.836 \text{ N mm}^{-1} \). In order to have a conservative analysis it was decided to consider values of \( G_{IIc} \) ranging from 4 to 7 N mm\(^{-1} \), because the described spurious effects become more important with increasing values of \( G_{IIc} \). This means that the selected range of \( G_{IIc} \) (i.e. 4–7 N mm\(^{-1} \)) is more demanding in defining the specimen geometry, than the value pointed by Feng.\(^{2} \) Figure 7 presents the \( R \)-curves for three different values of \( G_{IIc} \) (5, 6 and 7 N mm\(^{-1} \)) considering \( \sigma_{u,II} = 50 \text{ MPa} \) and \( a_0 = 20 \text{ mm} \), which were also used in Fig. 6c with \( G_{IIc} = 4 \text{ N mm}^{-1} \). Thus, from Figs 6c and 7a–c, it can be verified that the plateau length of the \( R \)-curves diminishes as the \( G_{IIc} \) increases, which is a logical trend. In reality, the toughness enhancement
leads to an increase of the tail corresponding to the softening region of the triangular law when $\sigma_{u,II}$ is kept constant (Fig. 3), which reflects on higher values of $l_{FPZ}$.

Consequently, the FPZ is affected prematurely by the central loading $P$, thus leading to shorter plateaus, both on the $R$-curves and on the $l_{FPZ} = f(a_e)$ (Figs 6c & 7a–c).

In conclusion, it can be affirmed that a specimen with a total and useful lengths ($2L_1$ and $2L_2$) of 70 and 65 mm, respectively, with a pre-crack ($a_0$) of 20 mm

(Fig. 2a) provides satisfactory conditions to perform the mode II toughness ($G_{IIc}$) measurements in cortical bovine bone using the ENF test. This conclusion is based on a parametric analysis considering a range of fracture parameters (i.e. $\sigma_{u,II}$ and $G_{IIc}$) which can be considered pessimistic in which concerns the arise of the spurious effects.
ELS

The ELS test presents a longer length relative to the ENF case for crack growing, which is advantageous considering the discussed problems affecting the self-similar crack growth. Owing to this less restrictive condition, specimens of global length of 60 mm (L1 in Fig. 2b) were used because they are easier to obtain than the ones of 70 mm. The useful specimen length (L) was set equal to 48 mm, because the load was applied 4 mm far from the specimen edge (d) and 8 mm was used for clamping embedment. A0 was assumed to be 30 mm to provide stable crack propagation conditions. However, in the ELS test the clamping conditions also require a parametric study. In fact, they depend on the tightening load exerted on the clamped region. To evaluate this effect three different tight (opposite displacements of 0.1, 0.07 and 0.05 mm applied to each clamping block (Fig. 2b)) were simulated, considering the limiting values of cohesive parameters used in the simulations of the ENF test: σult = 50 MPa and GIIc = 7 N mm⁻¹ (Fig. 7c). From Fig. 8a it can be observed that a perfect reproduction of the inputted value is attained, although the compressive stresses at clamping obtained in FEM computations (220 MPa) overcome the compressive strength of the bovine bone (a value of 146 MPa is presented in Chen et al.²⁹). In Fig. 8b and c it is observed that overestimation errors of 2–3% on GIIc are obtained with compressive stresses of 150 and 110 MPa at the clamped region, respectively.

The numerical analysis of the ELS test shows that a specimen with total and useful lengths (L1 and L) of 60 and 48 mm, respectively, with a pre-crack length (a0) of 30 mm (Fig. 2b) is appropriate. The clamping force is limited by the bone compressive strength, and a tightening of 0.05 mm applied to each clamping block should be used. These conditions provide satisfactory measurements of mode II toughness (GIIc) in cortical bovine bone using the ELS test. Once again, this conclusion is based on fracture parameters (i.e. σult and GIIc) which can be considered pessimistic, taking into account the typical values found in the literature.

CONCLUSIONS

The ENF and the ELS tests were numerically analysed in order to verify their applicability to characterize the bovine bone fracture under mode II loading. The numerical analyses were used to estimate the sensitivity of each test to the initial crack length, local strength, toughness and clamping conditions. A data-reduction scheme based on the specimen compliance and the crack equivalent concept was used to overcome the difficulties inherent to crack monitoring during its growth. A cohesive damage model was used to simulate damage initiation and propagation, thus assessing the influence of several parameters on the measured GIIc and the efficacy of the proposed data-reduction scheme. The effects of initial crack length, local strength and toughness were analysed in order to verify their influence on the measured GIIc relative to the inputted value. The present study allows identifying the limiting aspects of each test and to optimize the geometry leading to a correct estimation of the bovine bone properties under mode II loading. The critical aspect of the ENF test is related to the eventual spurious effect induced by central loading on the measured GIIc. In the ELS case special attention should be dedicated to the clamping conditions that can also affect the measured toughness values. However, the main finding of the presented work is that with careful geometry selection, good estimations of GIIc can be provided by both tests. It should be noted that pessimistic values for σult and GIIc concerning the rise of spurious effects have been considered in the numerical analysis. This means that it is expectable that real conditions (i.e. higher values of σult and lower values of GIIc) will propitiate even better performances for the selected geometries. This work can be considered a fundamental step in the study of the mode II fracture of bone, because proposed testing geometries until now cannot be considered appropriate solutions.

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REFERENCES