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Determination of mode II cohesive law of bovine cortical bone using direct and inverse methods

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ABSTRACT

This study presents two alternative methods to determine the cohesive law of bovine cortical bone under mode II loading, employing the End Notched Flexure (ENF) test. The direct method results from the combination of the progress of the mode II strain energy release rate with the crack tip shear displacement, obtained by digital image correlation. The resulting cohesive law is determined by differentiation of this relation relatively to the crack shear displacement. The inverse method employs finite element analyses with cohesive zone modelling, in association with an optimization procedure. The resulting strategy enables determining the cohesive law without establishing a pre-defined shape. The significant conclusion that comes out of this work is that both methods offer consistent results regarding the estimation of the cohesive law in bone. Given that the inverse method dispenses the use of sophisticated equipment to obtain the cohesive law in bone, it can be used as a more convenient procedure to accomplish efficient studies in the context of bone fracture characterization under mode II loading.

1. Introduction

Fracture characterization of cortical bone is of great interest to those who attempt to model bone damage resulting from accidental involuntary bad falls, road accidents (powerful impact), blast or ballistic trauma [23], as well as those interested to develop material substitutes to mimic bone functions [3], or fabricate prosthetic devices to promote a more adaptive bone remodelling activity (healing) in complex bone fractures [2]. Another area of major interest concerns the development of rigorous techniques to evaluate the fracture risk in bone tissue, as a complementary method to assess bone quality [14]. This important indicator is mostly appropriate in the framework of clinical tests promoted by the pharmaceutical industry, within regular drug delivery protocols. The design of bio-inspired engineering materials presenting higher fracture toughness is also a field of foremost concern, namely for manufacturing exoskeleton structures for many military and civil applications.

Following a very long period of natural selection, bone and bone-like biological tissues (holding an organic matrix and a reinforcement phase, e.g., antler and dentin) have developed a very complex hierarchical microstructure. In fact, similarly to most biological tissues, bone exhibits a microstructure formed by collagen, mineral hydroxyapatite (HA) and water, disposed into distinct length scales: the nanoscale (mineralized collagen fibrils with nanoscopic platelets of HA), the sub microscale (single lamella), the microscale (lamellar structure), the mesoscale (lamellae arranged concentrically around blood vessels, forming osteons) and the macroscale (entire bone) [16]. This material hierarchical arrangement contributes to increase fracture toughness in bone. In fact, when crack propagates in bone tissue, numerous interactions occur between stress singularities and the material microstructure. Because of these interactions, different failure mechanisms can be identified: diffuse microcracking, crack deflection and fibre-bridging [32,33]. These toughening mechanisms are responsible for development of a remarkable fracture process zone (FPZ) leading non-linear fracture mechanics behaviour. The consequence of these failure mechanisms is the development of a pronounced *Resistance*-curve (*R*-curve), in which fracture resistance is defined as a function of crack length as it propagates in a stable manner. Consequently, a valuable option to deal with such nonlinear behaviour is the employment of cohesive zone modelling (CZM). These approaches replicate the development of the significant FPZ typically occurring during bone fracture, by means of a softening law usually called cohesive law (CL). Generally, this softening relationship is assumed *a priori* [6,18,20,28] and the respective cohesive parameters are identified by inverse procedures using global [6,17,19] or local [12,15] data. In the former, the experimental load-displacement (P–δ) curve is fitted numerically through an optimization method. A drawback inherent to this approach lies in the fact that the uniqueness of the obtained solution is not assured, since the fitting is performed employing global data (i.e., P–δ curve). The later aims to reproduce numerically the ex-

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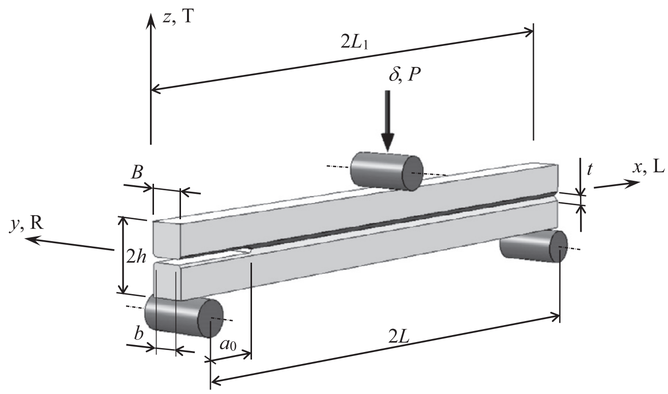

Fig. 1. Schematic representation of the ENF test specimen. ($2L_1 = 65$; $2L = 60$; $2h = 6$; $t = 1$, $B \approx 2.5$; $b = 2.3$; $a_0 = 18$ mm).

perimental P–δ curve using the local displacement field measured at the crack by optical methods [5,31]. Alternatively, the CL can be directly obtained combining the experimental P–δ curve with displacement values measured close to the crack tip [1,29]. The last two techniques require high-performance optical equipment and more complex experimental procedures than the former one. In addition, most of these methods require sophisticated optimization algorithms leading to important computational costs.

In this work, the determination of the cohesive law representative of bone fracture under pure mode II loading using the End Notched Flexure (ENF) test is addressed. Two different methods are employed. The direct method is an experimental procedure involving determination of the development of strain energy release rate and crack tip shear displacement. The differentiation of such relation gives rise to the cohesive law. The inverse method was already successfully applied in the context of mode I fracture characterization [21]. It consists in the combination of a finite element analysis including CZM and an optimization method, targeting the minimization of the difference between the numerical and experimental load-displacement curves. A cohesive zone analysis was accomplished aiming to validate the inverse method. The cohesive laws resulting from both methods are compared as well as the advantages and drawbacks of both methods.

2. Experiments

Bovine cortical bone utilized in this work was provided by an accredited local abattoir. Bone femurs were removed from a one day post-mortem bovine cadaver local slaughterhouse. Current Portuguese ethical protocols have been scrupulously followed during the specimens'

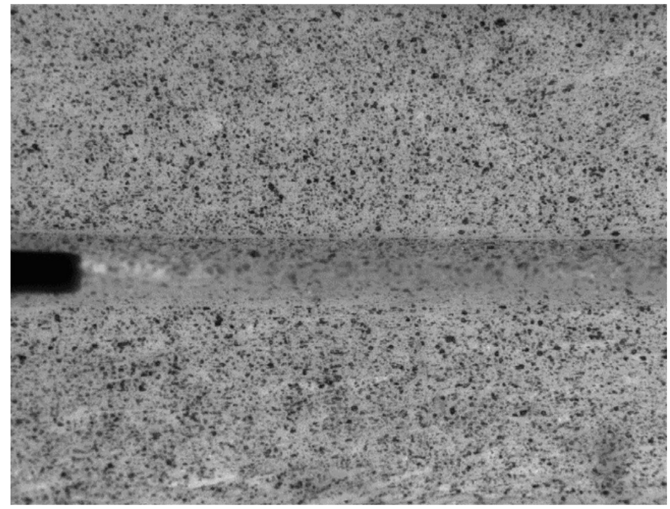

Fig. 3. Example of a *speckle* pattern.

preparation phases. These specimens were shaped from the bulk of femur mid-diaphysis to fit the final dimensions and material orientations shown in Fig. 1 (i.e., longitudinal (L)–transverse (T) plane) and stored at −20° within a gauze immersed in a solution of NaCl (0.9%).

The pre-crack (a_0 in Fig. 1) was executed at the specimen half-height (h) using a fine (0.3 mm thickness) diamond disk along the longitudinal direction. Then, a sharp cutting blade was rigidly tighten to a grip of the testing machine and moved towards the notch root at 100 mm/min, thus inducing a penetration of 0.15 mm. Subsequent to this procedure a V-notch (30°) groove was machined along the specimen length on both sides of the specimen (0.5 mm depth). This method aims to impede crack deflection from the specimen mid-height to assure pure mode II propagation.

Spurious friction in the notched region was reduced by inserting two fine Teflon® bands in the pre-crack, with a thin lubricant layer between them. Fracture tests were performed in a servo-electrical testing machine (Micro Tester INSTRON® 5848) following the setup shown in Fig. 2. The acquisition frequency was set to 5 Hz to register the P–δ curves, employing a 2 kN load-cell. The loading displacement was applied with a rate of 0.5 mm/min to assure stable crack growth. Indentation effects in bone were found negligible, taking into consideration the maximum loads attained during the fracture tests (around 100 N).

The crack tip shear displacement (CTSD) was measured by digital image correlation (DIC) using a speckled pattern painted on the surface of each specimen (matte black ink), before conducting the mechanical test (Fig. 3). The CTSD (i.e., w_{II}) is measured at a pair of equidistant points located close to the crack extremity, being subsequently correlated with

Fig. 2. Testing setup of the ENF test showing the speckle pattern.