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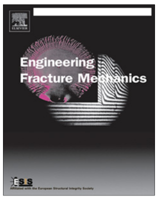

Modified two-parameter fracture model for bone

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ABSTRACT

The analysis of the bone fracture behaviour is fundamental for prevention, diagnosis and treatment of traumas. In the present paper, an experimental campaign on fracture behaviour of bovine femoral cortical bones is conducted to characterise the fracture toughness, K_{IC}^{S}, which is related to the structure and load-bearing capacity of bones. Firstly, K_{IC}^{S} is evaluated through a two-parameter model originally proposed for quasi-brittle materials. To take into account the crack deflection (kinked crack) due to osteons orientation, the two-parameter model is modified by applying the Castigliano theorem. Fracture toughness results here obtained are compared with those related to a femur of an 18-month-old bovine, available in the literature.

1. Introduction

Bone is a specialised tissue which has important functions, both metabolic and mechanical [1–3].

The load-bearing capacity of bones is limited up a certain extent, beyond which they fail in a brittle manner [4,5]. The analysis of the bone fracture behaviour is fundamental for prevention, diagnosis and treatment of traumas. Basic parameters which represent the structure and functions of bone have to be measured, such as its fracture toughness [6–16].

Depending on the skeletal locations, bones may be: (i) long bones (limbs, ribs, clavicles); (ii) flat bones (skull, scapula, pelvis); (iii) short bones (vertebrae, sternum). Generally most of fractures occur in long bones due to their skeletal locations, and more precisely in the diaphysis of such bones, i.e. in their central part, which represents the longest one (Fig. 1).

In the present paper, an experimental analysis of the fracture behaviour of bovine cortical bones is carried out, where specimens are extracted from diaphysises. The experimental programme is conducted to characterise the fracture toughness by employing a Two-Parameter Model (TPM), originally proposed for concrete [17–19], that is, for a quasi-brittle material showing a non-linear slow crack growth before the peak load is reached. In bones, such a behaviour is produced by mechanisms of extrinsic toughening categorised in four classes [11]: (i) constrained microcracking; (ii) crack deflection and twist; (iii) uncracked-ligament bridging; (iv) collagen-fibril bridging.

The above TPM is based on experimental data obtained from three-point bending tests by using single edge-notched specimens, and employs linear elastic fracture mechanics expressions valid for Mode I loading. However, for the bone material, such a model cannot be applied in its original formulation since the crack starting from notch may deflect.

In order to understand the cause of such a deflection under Mode I loading (three-point bending), the hierarchical structure of bone has to be briefly examined. More precisely, five levels can be listed [3,20,21]: (1) whole bone at the

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Nomenclature

a_0	notch-depth
$a_1,\ a_2$	segments of the kinked crack branch
$\underline{a}$	effective critical crack length
B	specimen width
C_i	linear elastic compliance or initial compliance
C_u	unloading compliance
E	elastic modulus
F	virtual force
G	total energy rate
K^S_{IC}	critical stress-intensity factor under Mode I (fracture toughness)
$K^S_{(I+II)C}$	critical stress-intensity factor under mixed mode
l_i	i-th deflected segment along the kinked crack path
L	specimen length
$P_{\max}$	peak load
S	loading span
U_T	total strain energy
W	specimen depth
Δ_F	relative displacement of the crack surfaces

macrostructural level; (2) compact bone and cancellous bone block at the architecture level; (3) osteon and trabecula at the microstructural level; (4) lamella at the sub-microstructural level; (5) collagen fibril, non-collagenous and mineral components at the ultra-structural level.

Osteons are more or less regular cylindrical structures, whose length ranges from 3 to 12 mm (Fig. 2). The osteons are oriented parallel to the bone axis, which consists of a vascular canal (named Haversian canal) surrounded by concentric lamellae. The interface between osteon and interstitial lamellae is called cement line (Fig. 2).

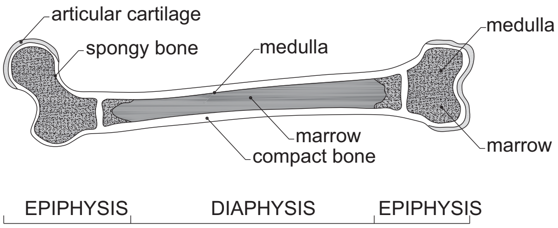

Fig. 1. Schematic illustration of a long bone.

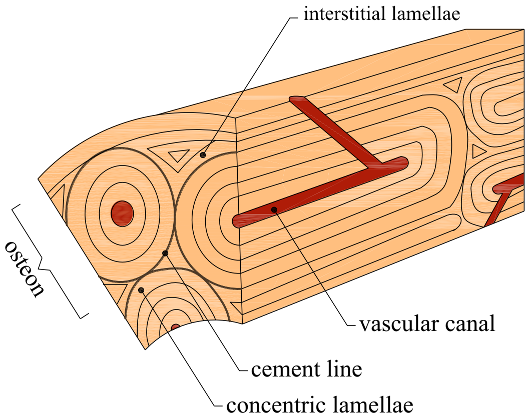

Fig. 2. Cortical bone microstructural level.