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Physical Imaging of fracturing Human Cortical Bone

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Abstract — In the present study, we present a procedure associating either the eXtended Finite Element Method (XFEM) or the standard Finite Element Method (FEM) to a Digital Imaging Correlation technique (DIC) called microextensometry (CorrelmanuV) in order to investigate the local fracture toughness of micro cracks in human Haversian cortical bone at the scale of the osteons. The micro cracks are tested in tension and in compression.

Keywords — fracture, toughness, contact, bone, XFEM, imaging.

1 Introduction

Microcracks are usually involved in the bone remodelling process and fracture risk assessment [1, 2]. Better knowledge of fracture occurrence at the micro scale is then an essential step to increase diagnostic reliability. During most daily exercise such as walking, bones undergo cyclic fatigue loading that alternates between tension and compression. Therefore the present models address the determination of the stress intensity factors of the microcracks under tension and compression in posterior femur mid-diaphysis of female human cortical bone.

2 Methodology

2.1 Tension

In tension, a three point bending device for millimetric samples was built to fit under a light microscope. We considered a beam specimen of an average length of 5 mm and a square cross-section of an average 2 mm width as shown in Figure 1. The specimen were precracked by 600 μm depth calibrated incisions. The cortical bone morphology was surveyed using a digital imaging processing technique [3] in BSEM (Back Scattered Electron Microscopy) and the grey scale was correlated to the local mineralisation levels as shown in Figure 2. The local elastic moduli were measured by nanoindentation correlated to the mineralisation levels. The local Poisson ratios were extrapolated from the osteonal strain fields. A small window of observation was studied in the vicinity of the initial crack. To reconstruct the physical stress field, the following constitutive elements were included in an XFEM model: the osteons' transversal profiles, the cement lines around them,

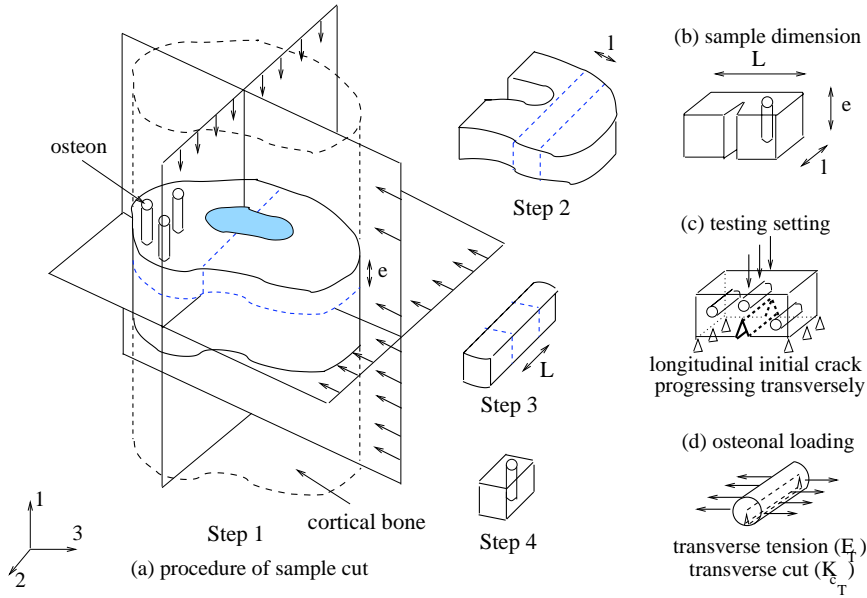


Figure 1: (a) procedure of sample cut, (b) sample dimension, (c) testing setting, (d) osteonal loading.

secondary osteons whose partial areas are recognisable inside the matrix phase as shown in Figure 3(a). The Haversian canals are represented as free boundaries inside active osteons, where *in vivo* cytoplasmic fluid would flow freely. A non-structured quadratic triangle finite element model with explicit microstructure is then constructed with Gmsh [4]. The experimental displacements were measured over a grid by the DIC technique [5] called microextensometry (CorremanuV [6]). These fields were first visualised in an homogeneous equivalent window where they were imposed at all identified triangle corner nodes as shown in Figure 3(b).

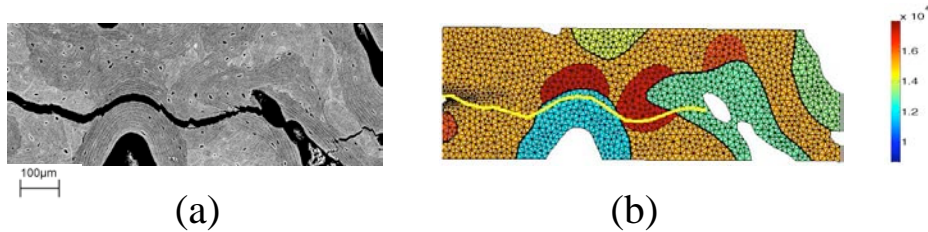


Figure 2: (a) BSEM (Back Scattered Electron Microscopy) of w06005, (b) Young's modulus map in MPa in ModNum of w06005.

In order efficiently to incorporate evolving micro cracks, we designed a procedure associating the eXtended Finite Element Method (XFEM)[7, 8] to the Digital Imaging Correlation technique (DIC) to investigate the local stress intensity factors at the scale of the osteons in human Haversian bone. The method can be related to the approach that has been applied to polycrystalline microstructures [9]. This method is able to incorporate fracture [10, 11] in explicit cortical bone microstructure as shown in Figure 3(c). Due to the small size of the observation window, the experimental displacement was applied along the edges of the explicit model. Cortical bone was considered brittle due to its high content of hydroxyapatite and under plane stress condition as the

surface of the sample is observed. The stress intensity factors were calculated using the interaction integral. The L_2 norm of the difference between the experimental and numerical fields was less than 1.3% in all cases, therefore the model adequately replicates the experiments in human Haversian cortical bone and provides valuable information on three scales.

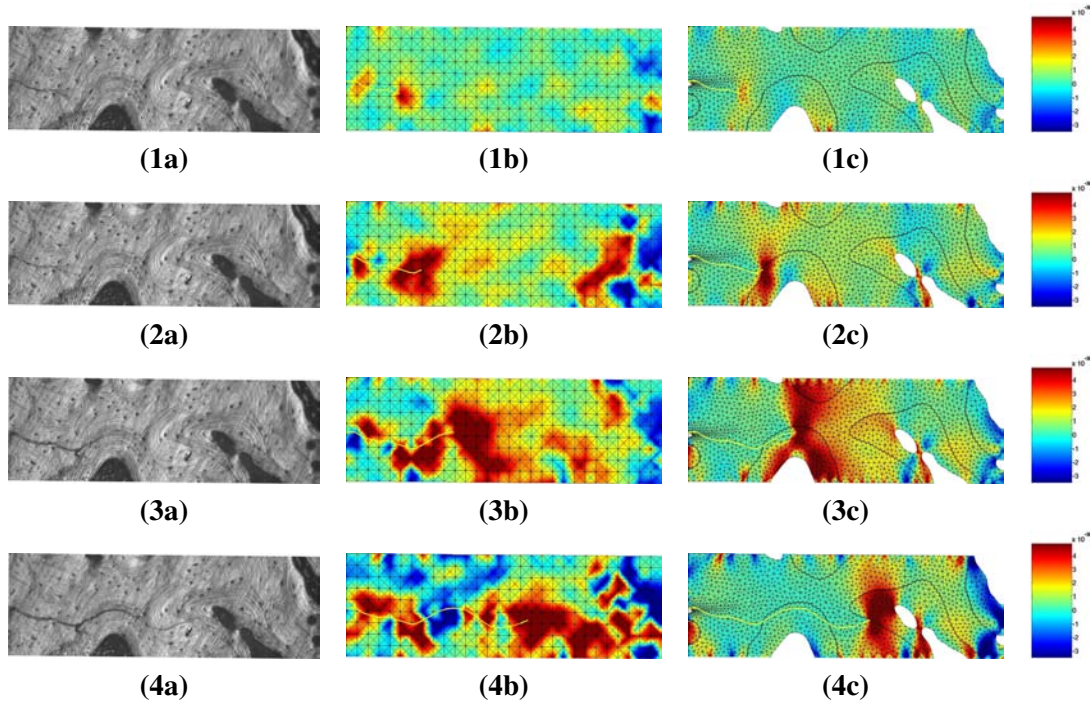


Figure 3: 1,2,3,4 (a) Light microscopy observation window of microcracks in human cortical bone specimen of 300 by 1100 μm under tension, 1,2,3,4 (b) Digital Correlation Imaging of the kinematic strain field ϵ_{22} where the displacement field is prescribed at all mesh points, 1,2,3,4 (c) Physical strain field ϵ_{22} obtained by an XFEM model of the micro cracks that reconstructs the explicit microstructure and where the experimental displacements are only prescribed along the edges. The color scale is $[-0.0035; 0.0049]$ in pictures (b) and (c).

2.2 Compression

In compression, the samples of the same size were loaded in a micro compression device without precracking. As FEM model of the cortical bone microstructure was also constructed but the cracks were explicitly discretised as shown in Figure 4(c). As the window of observation was wider, the experimental displacement field was imposed at all imaging points inside the polyphase medium. The imaging points were incorporated into the mesh using an optimised adaptivity algorithm.

The contact solution was iteratively calculated by Newton-Raphson method [12] until convergence of the displacement field. The frictional contact condition was checked at the mid-point of each element [13] and was enforced by nodal penalties along the crack edges [14].

3 Results

The model provides the fracture strength and the global response at the macroscopic scale (mm), the stress-strain fields at the microarchitectural level (10-100 μm) and the crack profiles at the

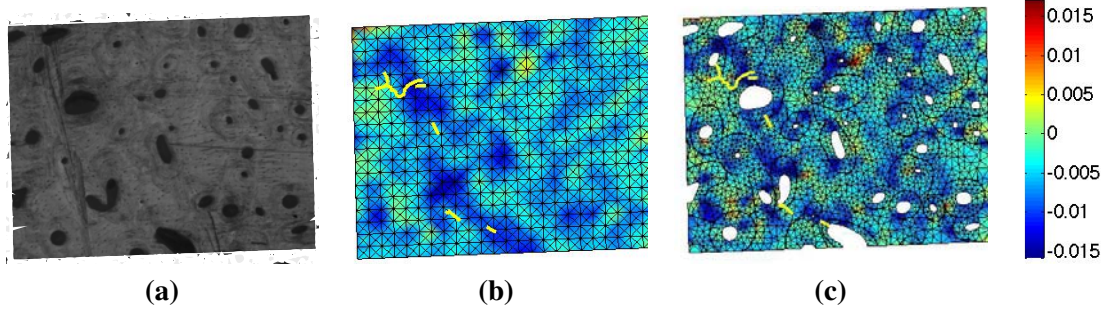


Figure 4: (a) Light microscopy observation window of microcracks in human cortical bone specimen of 1400 by 1900 μm under compression, (b) Digital Correlation Imaging of the kinematic strain field ε_{11} where the displacement field is prescribed at all mesh points, (c) Physical strain field ε_{11} obtained by an FEM model of the micro cracks that reconstructs the explicit microstructure and where the experimental displacements are prescribed at all imaging points. The color scale is $[-0.0158;0.0170]$ in pictures (b) and (c).

Table 1: Stress intensity factors in sample w06005 versus the micro cracks' lengths

	K_I $\text{MPa}\sqrt{\text{m}}$	K_{II} $\text{MPa}\sqrt{\text{m}}$	K_{eq} $\text{MPa}\sqrt{\text{m}}$	a_i mm	L_2 $\%$
<i>tension</i>					
step 1	0.33	-0.09	0.34	0.774	0.47
step 2	0.64	0.21	0.67	0.774	0.59
step 3	1.38	0.44	1.45	0.968	1.04
step 4	1.27	0.28	1.30	1.236	1.28
<i>compression</i>					
crack 1	0.01	-0.14	0.14	0.158	0.19
crack 4 ₁	-0.58	-0.22	0.62	0.11	0.19
crack 4 ₂	-0.36	-0.52	0.63	0.11	0.19
crack 6	-0.49	-1.17	1.27	0.105	0.19
crack 7	-0.6	-2.35	2.43	0.065	0.19

micron scale (1-10 μm) and fracture parameters such as the stress intensity factors. The results obtained in this work emphasise the influence of the microstructure on bone failure. The model incorporates the explicit bone microstructure with its specific microarchitecture and heterogeneous mechanical behaviour of the tissue. The model confirms the local toughening mechanism [15] that is usually observed in bone and indicates some possible explanations. The model also indicates how the fracture properties could be modified in regard to possible alterations of the microstructure integrity which are not detectable by conventional clinical tools, and proposes a new procedure to diagnose pathologies.

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