Effect of random microstructure on crack propagation in cortical bone tissue under dynamic loading

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Abstract. A fracture process in a cortical bone tissue depends on various factors, such as bone loss, heterogeneous microstructure, variation of its material properties and accumulation of microcracks. Therefore, it is crucial to comprehend and describe the effect of microstructure and material properties of the components of cortical bone on crack propagation in a dynamic loading regime. At the microscale level, osteonal bone demonstrates a random distribution of osteons imbedded in an interstitial matrix and surrounded by a thin layer known as *cement line*. Such a distribution of osteons can lead to localization of deformation processes. The global mechanical behavior of bone and the crack-propagation process are affected by such localization under external loads. Hence, the random distribution of microstructural features plays a key role in the fracture process of cortical bone. The purpose of this study is two-fold: firstly, to develop two-dimensional microstructured numerical models of cortical bone tissue in order to examine the interaction between the propagating crack and bone microstructure using an extended finite-element method under both quasi-static and dynamic loading conditions; secondly, to investigate the effect of randomly distributed microstructural constituents on the crack propagation processes and crack paths. The obtained results of numerical simulations showed the influence of random microstructure on the global response of bone tissue at macroscale and on the crack-propagation process for quasi-static and dynamic loading conditions.

Introduction

Each year, some 730,000 road casualties happen in the UK [1], and 8.4 million sport injuries were reported in the EU in 2009 [2]. More often, such traffic accidents and sport injuries would lead to orthopaedic traumas, among which, the femur fracture is one of the critical ones because femurs are the strongest bones in the human body [3]. In order to develop strategies for treatment, understanding of bone fracture processes is required. The fracture process of cortical bone tissue is directly related to factors such as mineral-density reduction (bone loss), microstructure changes, variations of its material properties, and microcracks' accumulation [4]. Although bone loss has been considered as one of the key factors that lead to the fracture of cortical bone, detailed understanding of crack propagation processes for cortical bone with regards to its microstructural constituents is still lacking [5] and in-depth investigations of effects of microstructure, material properties and propagation of microcracks are still needed [6]. The mechanical properties of cortical bone as well as crack initiation and propagation are largely affected by histological variations, such as porosity, mineralization, orientation and diameters [4, 6-7]. In order to better assess the fracture risk of cortical bone, it is important to

understand the bone's resistance to crack initiation and propagation with regards to its heterogeneous microstructure.

Due to these complex features of heterogeneous microstructure and their mechanical properties, there were only limited developments of finite-element (FE) models to investigate the effect of randomly distributed microstructural constituents on the deformation and fracture behavior of a cortical bone tissue. Abdel-Wahab *et al.* [4] used the extended finite-element method (X-FEM) to investigate the effect of microstructure constituents, especially the cement line, on the fracture process in bone. Hamed *et al.* [8] used a micromechanics method and composite-materials laminate theories to model a cortical bone's elastic response from macro-scale to micro-scale for obtaining its effective elastic constants. In another study, Budyn *et al.* [9] utilized a multiple-scale statistical X-FEM method to simulate multiple crack propagation in human cortical bone under tension loading condition. Li and his co-authors [5] evaluated the effect of microstructural transitions on macroscopic mechanical behaviors of cortical bone using three different microstructural realizations at quasi-static loading conditions. To the authors' knowledge, there is no available model to investigate the effect of random bone microstructure on crack growth in it under dynamic loading conditions. Therefore, the aim of this study is to develop such models to study the crack propagation processes for different microstructural realizations in dynamic regime and, consequently, improve our understanding of the role of microstructure in bone's failure. In order to achieve this, optical measurement was used to collect statistical data on random distribution of microstructural features in real cortical bone structures; then, a MATLAB program was designed to generate random distributions of the microstructural realizations based on quantification of real images. Finally, three FE models based on different realizations were created to investigate the effect of random microstructure on the fracture process and global responses under both quasi-static and dynamic loading conditions.

2. Material and methods

2.1. Random Microstructure

Micrographs were captured from radial-transverse cross-section of anterior cortex of bovine femur. They were used for collecting the data on statistical distribution of random microstructural features (Fig. 1). At microscale level, four microstructural features were analyzed: Haversian canals located at the center of each osteon, which are surrounded by cement line and interstitial matrix the remnants of

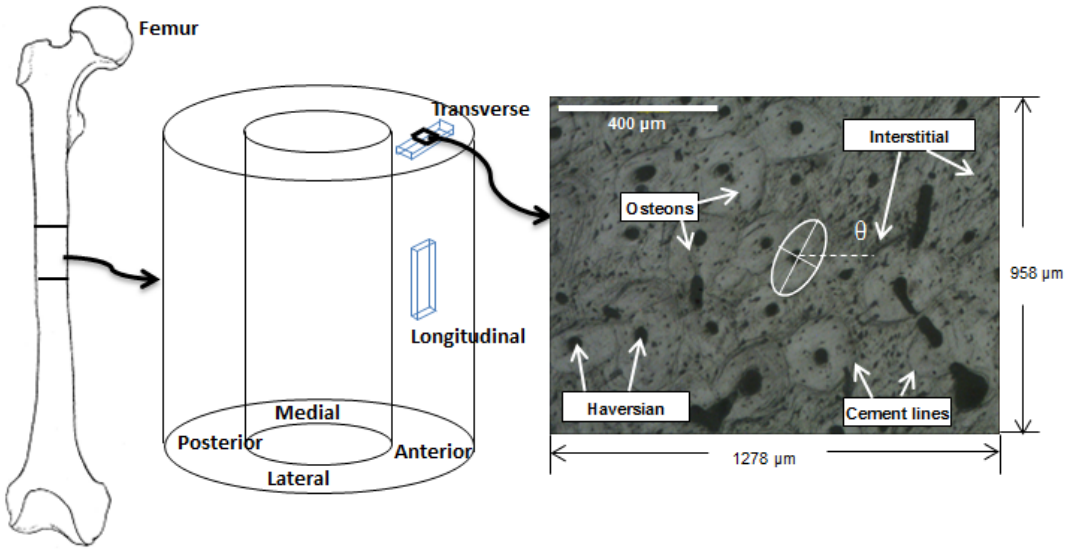

Figure 1. Microstructure of cortical bone at radial-transverse cross section.

a bone's remodelling process. Ten microstructural images (1.278 mm×0.958 mm each) were captured to obtain statistical parameters of osteonal bone, including the diameter of Haversian canals, transverse and conjugate diameters of osteons, orientation of osteons (angle between the direction of transverse diameter and the x-axis, from -90° to 90°) and positions of concentric Haversian canals and osteons. All the parameters were measured with image analysis software, Image-Pro Express [10]. The obtained data were analyzed and fitted with polynomial distribution functions to statistically describe the random distributions of the microstructural constituents.

In this study, the models of microstructured cortical bone were generated with a novel MATLAB code written by the author based on the probability density functions of the analyzed images. Statistical analysis of optical measurement showed that the volumetric ratios of osteons and porosity ranged from 45% to 58% and 2.5% to 4.6%, respectively. Therefore, three different finite-element models were developed to represent the range of the obtained data, see Table 1.

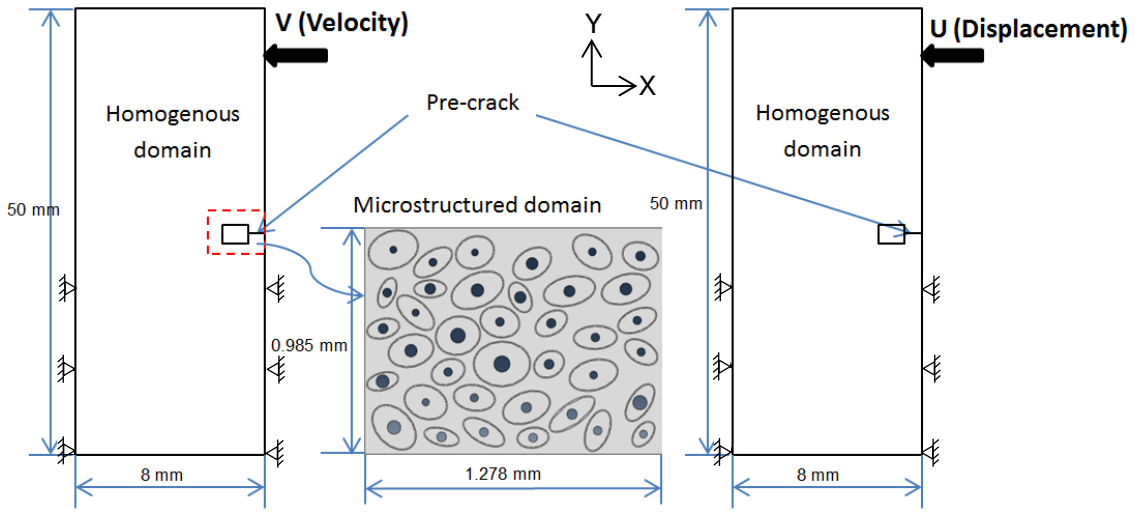

Figure 2. Geometry, boundary conditions and loading regimes of dynamic model (left) and quasi-static model (right)

Table 1. Microstructural parameters for all models

	Osteon volumetric ratio (%)	Porosity ratio (%)
Model A	46.9	4.66
Model B	51.8	3.72
Model C	57.9	4.21

2.1. Model configurations

In this study, three different two-dimensional finite-element models (FEM) were developed in ABAQUS for both dynamic and quasi-static loading regimes to investigate the effect of loading conditions on the fracture process in the cortical bone tissue at the microscale level. The models were configured based on previous Izod experimental tests performed by the same research group [11]. A full description of lzod test can be found in the previous paper by the authors [11]; the microstructured

models of 1.278 mm×0.958 mm (length × width) were embedded into a homogenized material (50 mm×8 mm) (length ×width) as shown in Fig. 2.
In the simulations, 4-node bilinear plain-strain quadrilateral (CPE4R) elements were chosen for both parts of the model due to significant difference between the element size of microstructured and homogenized domains. Based on the lzod tests, an impact velocity of 3.46 m/s was chosen to provide initial energy for crack propagation [11]. In order to compare the fracture behaviour for both dynamic and quasi-static loading conditions, the maximum displacements during the contact time in the dynamic finite-element model were used as prescribed boundary condition for quasi-static models (Fig. 2). Table 2 summarizes the loading conditions for all the used models.

Table 2. Loading conditions for both dynamic and quasi-static models

Model	Applied velocity (m/s)	Model	Applied displacement (mm)
Dynamic Model A	3.46	Quasi-Static Model A	1.90
Dynamic Model B	3.46	Quasi-Static Model B	1.61
Dynamic Model C	3.46	Quasi-Static Model C	1.65

2.2. Mechanical properties
In terms of the mechanical behavior, cortical bone can be considered as transversely isotropic material in 2D FE models [7, 12]. The material properties of osteons, interstitial bone, cement line and homogenous material media were implemented based on the previous research can be found in [4]. Following Budyn and Hoc [13], the elastic modulus of cement lines were considered to be 25% lower than that of osteons. The Poisson's ratios of each phase were obtained from literature [4]. The elastic properties used in our simulations are summarized in Table 3.

Table 3: Material properties of microstructural constituents of cortical bone tissue and homogenous material

Model	Elastic modulus (GPa)	Poisson's ratio	Strain energy-release rate (N/mm)
Homogenous material	10.46	0.167	0.422
Osteons	9.13	0.17	0.86
Interstitial matrix	14.122	0.153	0.238
Cement lines	6.85	0.49	0.146

2.3. Cohesive behaviour and fracture properties for X-FEM
An X-FEM-based cohesive technique for a crack initiation and propagation was utilized to study the crack growth along an arbitrary, solution-dependent path under various loading conditions. Belytschko and Black [14] introduced an extended-finite-element method for crack-propagation analysis without a remeshing process. In our simulations, the whole bone specimen was chosen as an enrichment region; an initial pre-crack with a length of 300 μm was placed within the homogenized media near the microstructured region and parallel to the impact/displacement loading direction, see Fig. 2. Crack initiation and evolution criteria were chosen based on the critical maximum principal strain of 0.6% and strain energy release rate reported in [4, 7].

3. Results and discussion
The effect of the random distribution of cortical bone microstructural features on the path of a

propagating crack under dynamic loading regime can be observed clearly (Figs. 3). Due to the random distribution of the microstructural features of the studied cortical bone tissue, a crack follows different paths affected by the local microstructure as shown in Figs. 3a-c. The crack deflection mechanism reported in [5] was also observed in the current simulations: the crack tends to propagate around cement lines and was attracted towards Haversian canals. The cement lines offered a weak path for cracks and acted as protective structures of the osteonal bone to prevent further damage to the cortical bone tissue [15]. It can be seen also that the crack continued to propagate in the homogenized media after crossing the microstructred domain with a practically straight path with no alternations, see Fig. 4 for both dynamic and quasi-static loadings.

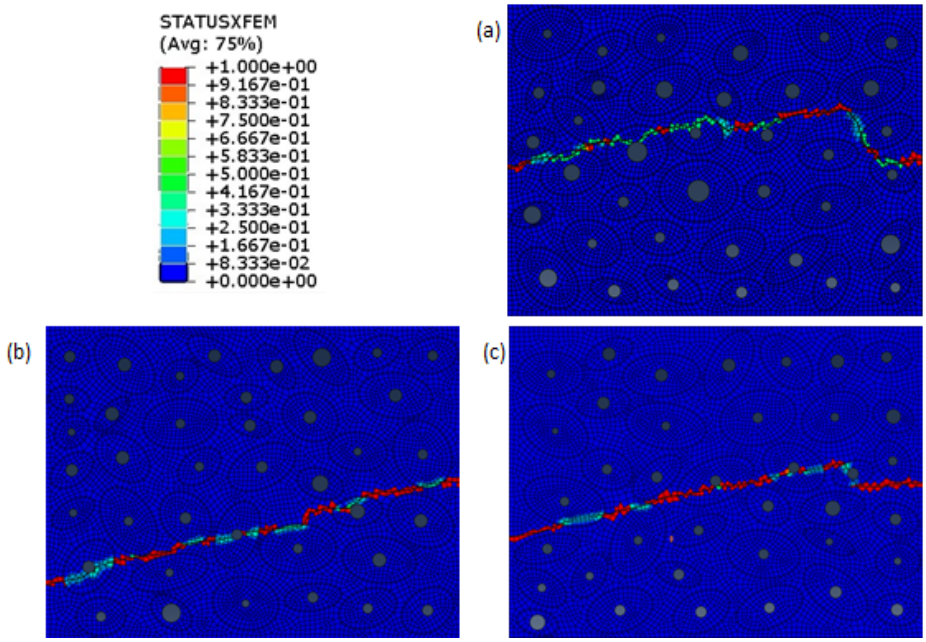

Figure 3. Final crack paths within three different random microstructures in case of dynamic loading: (a) model A; (b) model B; (c) model C

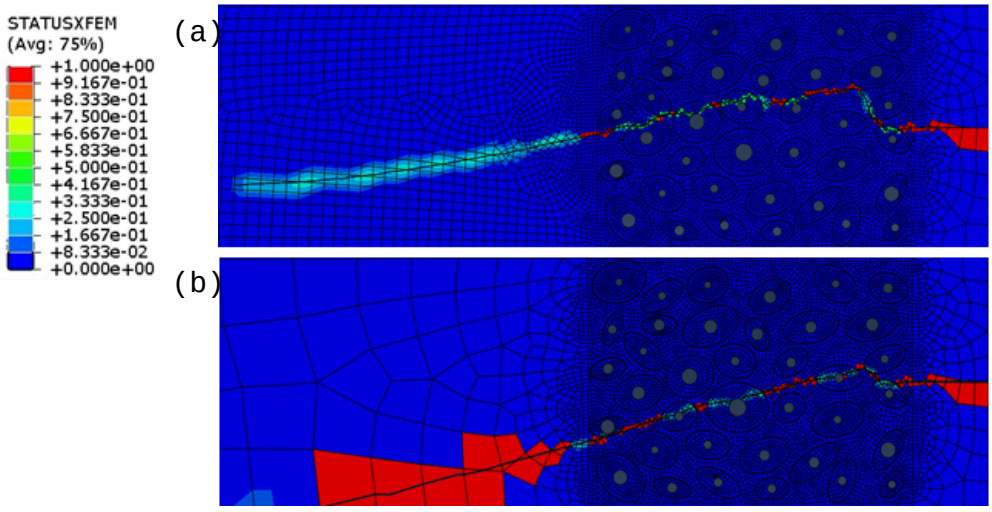

Figure 4. Final crack for Dynamic Model A (a) and Quasi-Static Model A (b)

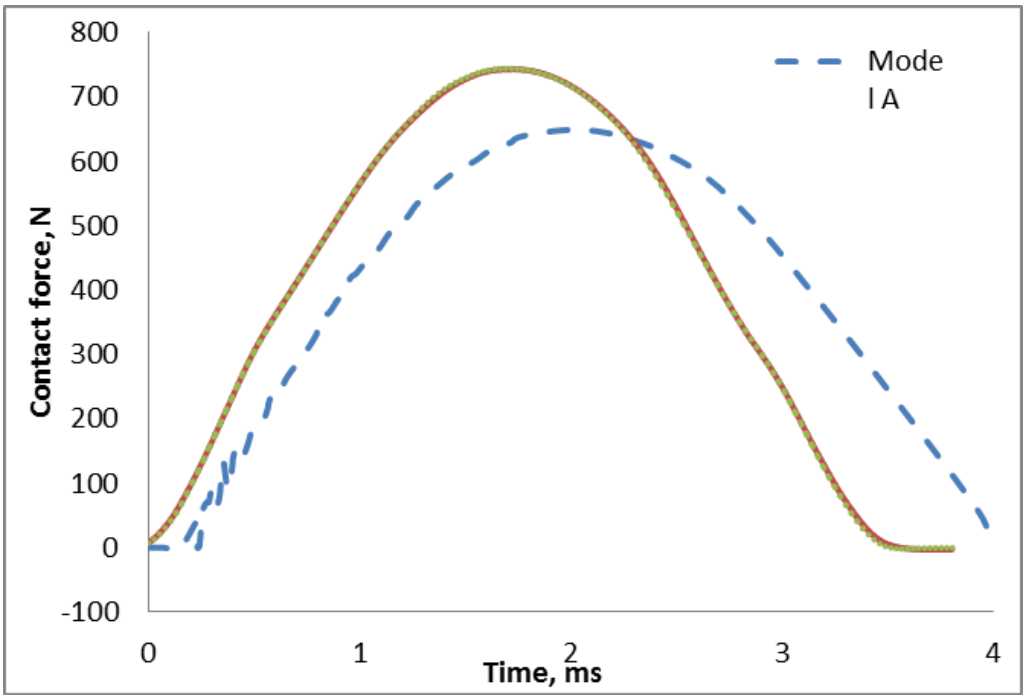

Figure 5. Contact force-time profile for dynamic loading

Although the criterion of crack initiation for all models was the same, the crack-growth rate was different for each microstructured model as shown in Figs. 6 and 7. Additionally, by comparing simulation results for the three microstructured models, Model B revealed the longest total crack length (2934.4 μm for A, 3144.5 μm for B, 2957.6 μm for C) but the shortest crack length in the microstructured part (1466.7 μm for A, 1343.7 μm for B, 1410.2 μm for C), as shown in Fig. 6. Generally, the crack propagated as the contact force increased, and it reached close to its maximum value when the force was at the peak point (671.3 N at 1.96 ms for A, 853.1 N at 1.68 ms for B, 812.1 N at 1.74 ms for C). When the force started to decrease, the crack propagated only slightly (Figs. 5 and 6). It was also observed that the evolution of contact forces for Models B and C were closer to one another compared to Model A owing to the differences in the volume fraction of the microstructural constituents. In Model A, the crack propagated towards a cement line and cut thought an osteon initially, while in Models B and C, the crack grew initially into the interstitial matrix, see Figs. 3a-c. As a result of the deflection mechanism of cement lines, the force-time response (Fig. 5) for Model A was different compared to that of two other models.

A comparison between the crack-propagation behaviors under different loading conditions shows that models subjected to quasi-static loading conditions generally had a shorter total crack length (2744.7 μm for A, 2462.4 μm for B, 2657.6 μm for C) compared to those found for dynamic loading conditions. In addition, the crack trajectories in quasi-static models were smoother than those in the models with dynamic loadings conditions. Therefore, the crack lengths within the microstructured domain (1382.6 μm for A, 1423.7 μm for B, 1410.2 μm for C) varied from those in their dynamic counterparts, see Fig. 6. It was noticed that models loaded dynamically had crack-propagation rates in the microstructured domain that tended to slow down when reaching the homogenized material as the contact force almost reached its peak point. On the other hand, variations of the crack-propagation rates in the quasi-static models extended over the whole fracture process (Figs. 5 and 6). As a whole, both the loading conditions and the variation of microstructural constituents strongly affected the crack-propagation characteristics of cortical bone.

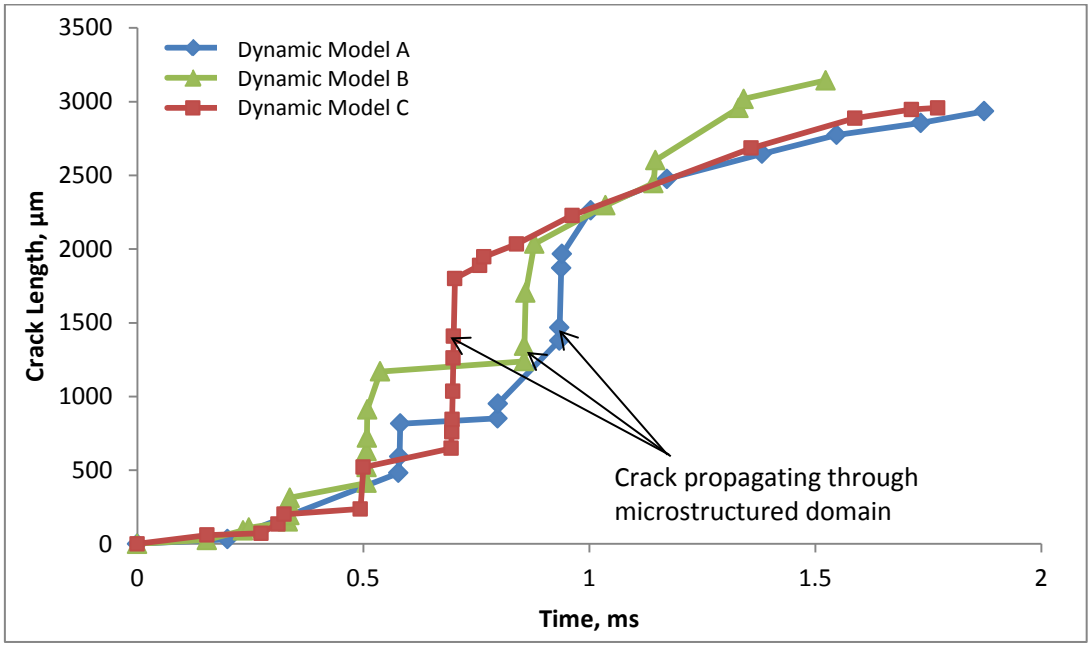

Figure 6. Evolution of crack length under dynamic loading

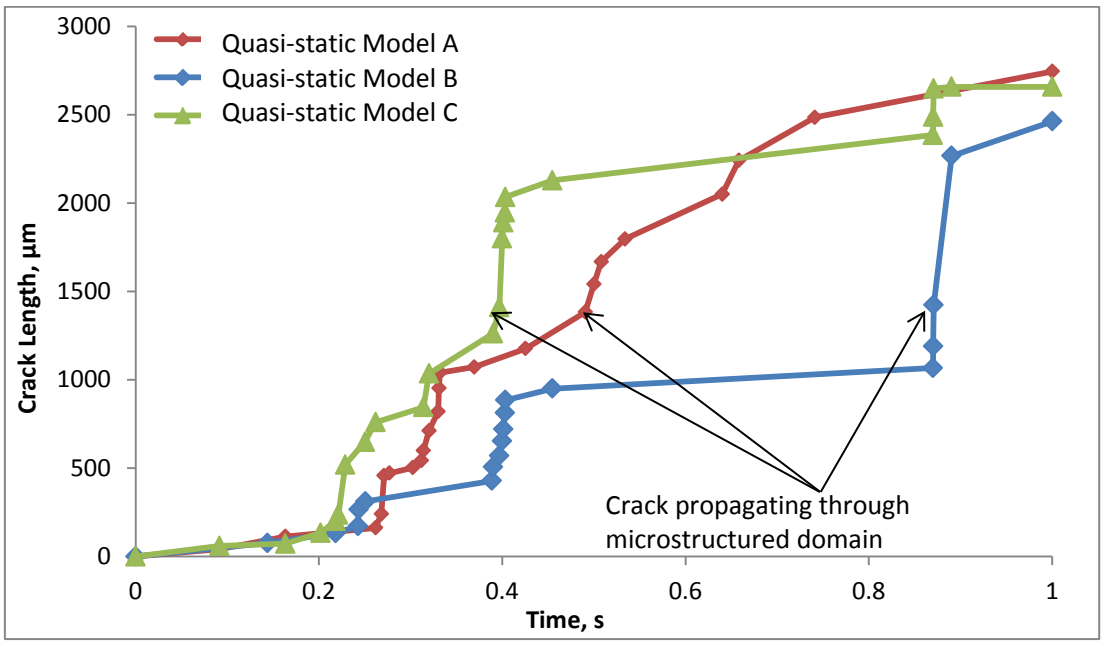

Figure 7. Evolution of crack length under quasi-static loading

4. Conclusions

The effect of the random microstructure of the cortical bone tissue on crack initiation and propagation under both dynamic and quasi-static loadings was studied using 2D FE models. Three different realizations of bone microstructure were obtained using optical measurements and used to develop the microstructured finite-element models embedded into a homogenized-material model. The obtained results demonstrated different crack-propagation behaviors for different microstructural statistical realizations. The finite-element models loaded in dynamic conditions demonstrated higher crack

lengths than those loaded in quasi-static conditions. These developed models provided a new important insight for understanding the fracture processes of the cortical bone tissue subjected to impact events and can be used for future evaluations of the age-related disease associated with fracture of cortical bone tissue.

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