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# Role of porosity and matrix behavior on compressive fracture of Haversian bone using random spring network model

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ABSTRACT

Haversian remodeling is known to result in improved resistance to compressive fracture in healthy cortical bone. Here, we examine the individual roles of the mean porosity, structure of the network of pores and remodeled bone matrix properties in the fracture behavior of Haversian bone. The detailed structure of porosity network is obtained both pre- and post-testing of dry cubical bone samples using micro-Computed Tomography. Based on the periodicity in the features of porosity along tangential direction, we develop a two dimensional porosity-based random spring network model for Haversian bone. The model is shown to capture well the macroscopic response and reproduce the avalanche statistics similar to recently reported experiments on porcine bone. The predictions suggest that at the millimeter scale, the remodeled bone matrix of Haversian bone is less stiff but tougher than that of plexiform/primary bone.

## 1. Introduction

Cortical or compact bone, typically found in mid-shaft of long bones such as femur, tibia etc. is a porous bio-material whose primary role is to bear load and support the anatomical framework amongst other physiological functions. Its microstructure adapts dynamically to the local loading environment by modifying bone material and structure of the network of pores which results in variation of local mechanical properties. Understanding the structure-property relations in cortical bone is crucial to applications such as extraction of bone grafts (Pearce et al., 2007; Conward and Samuel, 2016), in design of mechanically compatible implants (Hing, 2005; Bansiddhi et al., 2008; Libonati and Vergani, 2016) and porous scaffolds (Chen et al., 2005; Liu et al., 2013), to interpret loading history (Keenan et al., 2017; Zedda et al., 2017; Mitchell et al., 2017), to evaluate bone healing therapeutical techniques (Claes et al., 1995; Gocha and Agnew, 2016) etc. A significant aspect of understanding the role of microstructural features in variation of mechanical properties is the development and testing of predictive models. While several studies have modeled the elastic behavior, fewer models examine the fracture of cortical bone. Thus, developing microstructure based models to study the fracture behavior in cortical bone is desirable to gain insights into bone adaptation. Also, such predictive fracture models can be used in understanding the failure behavior of other brittle heterogeneous materials with well-defined porosity such as wood, rock etc (Meyers and Chawla, 2009; Shojaei et al., 2014).

Histological studies have shown the existence of two distinct microstructural forms in mammalian cortical bone: (i) plexiform/primary bone which is brick shaped and is due to radial laying of new bone material and (ii) Haversian/secondary bone which has several circular features called osteons resulting from the remodeling of existing bone by resorbing and despositing new bone material (Currey, 2002). The differences in microstructure manifest as differences in overall porosity and thus, in mechanical properties (Martin and Ishida, 1989; Trębacz et al., 2013; Li et al., 2013; Mayya et al., 2013; Cooper et al., 2016). Haversian bone is known to have higher porosity (Trębacz et al., 2013; Li et al., 2013) and lower elastic and failure properties such as Young's modulus, Poisson's ratio, ultimate strength, fracture toughness and even fatigue strength compared to plexiform bone when subjected to tensile loading (Reilly and Burstein, 1975; Lipson and Katz, 1984; Katz et al., 1984; Shahar et al., 2007; Martin and Ishida, 1989; Martin and Boardman, 1993; Norman et al., 1995; Reilly and Currey, 1999; Kim et al., 2005, 2007; Carter et al., 1976; Li et al., 2013). However, in compression, Haversian bone has higher strength than plexiform bone (Mayya et al., 2016a). Further, the fracture surfaces resulting from compression failure are different – plexiform samples has prismatic fracture surfaces while Haversian samples has three-dimensional fracture surfaces implying differences in the failure behavior.

Several studies have attributed the resistance to failure in cortical

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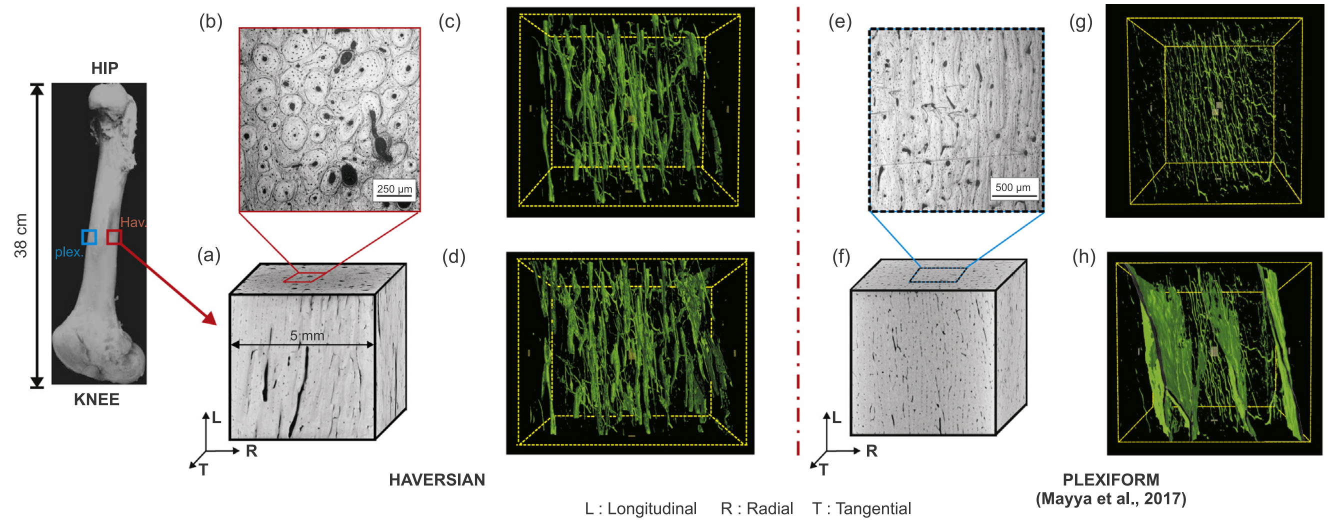

**Fig. 1.** (a) Cubic sample from posterior cortex at mid-diaphysis with faces perpendicular to the longitudinal, radial and transverse directions. (b) Optical micrograph of the sample surface showing Haversian bone. CT scan images (tangential view) of a typical Haversian (sample II) bone specimen (c) before fracture and (d) after fracture. The green regions correspond to regions of higher porosity. For comparison, CT scan images of a typical plexiform bone specimen shown in (e) and (f) are also presented in (g) before fracture and (h) after fracture (Mayya et al., 2017).

bone to toughening mechanisms involving intricate microstructural features such as cement lines, micro-cracks, collagen fiber orientation, size and shape of osteons etc. (Peterlik et al., 2006; Koester et al., 2008; Launey et al., 2010; Schwiedrzik et al., 2014). However, the number of microscopic models that incorporate such features and reproduce the characteristic failure paths during complex fracture process are fewer. In complex quasi-brittle heterogeneous materials such as cortical bone, fracture involves stochastic interactions of multiple porosities and micro-cracks before final failure (Bažant, 2004). Using standard finite element methods and classical fracture mechanics theory to model the failure behavior of such materials would restrict the scope to estimating effective homogenized elastic properties and crack growth resistance of a single defect (Budyn and Hoc, 2010; Abdel-Wahab et al., 2012; Brown et al., 2014). Thus, failure in such heterogeneous systems are better examined using discrete statistical models like the random spring network model (RSNM) (Pan et al., 2017). By approximating the continuum as a network of springs with statistically distributed characteristics, RSNM has been previously used to gain insights into fracture behavior of heterogeneous media with no preexisting crack (Alava et al., 2006), to reproduce the brittle to non-brittle transition of macroscopic response with increasing disorder (Curtin and Scher, 1990), avalanche size distribution similar to acoustic emission events (Ray, 2006) and fracture of composite materials (Moukarzel and Duxbury, 1994; Urabe and Takesue, 2010; Boyina et al., 2015; Libonati et al., 2017). In case of bone, the characteristic quasi-brittle softening observed during tension and bending (Krajcinovic et al., 1987) as well as in compression testing of cortical bone (Schwiedrzik et al., 2014) has been simulated using simple one-dimensional models of parallel springs with statistically distributed properties. Further, in cancellous bone, the spongier bone found near joints, the power-law variation of strength with porosity was re-examined accounting for percolation effects using a three-dimensional RSNM (Gunaratne et al., 2002; Rajapakse et al., 2004). However these studies consider the porosity to be homogeneously distributed in the bone material, thereby accounting for mean porosity but neglecting the role of the structure of the porosity network.

Recently, to model the macroscopic response of bone under external loading, we introduced a porosity-based two dimensional RSNM that incorporates the structure of porosity network by using the data obtained from micro-Computed Tomography (CT) scan images of the bone sample as input to determine the values of the spring constants. The model was shown to successfully capture the qualitative experimental fracture paths, avalanche exponents from acoustic emission data, as well as capture the effect of the variations of the porosity network on the strength when applied to samples from the same bone (Mayya et al., 2016b). To compare the strength across samples from different bones, it was shown that it is crucial to incorporate bone-dependent material properties at the microscale (Mayya et al., 2017). However, the study focused on plexiform microstructure which has a distinctly different microstructural appearance as well as mechanical properties compared to Haversian bone.

In this paper, we study the macroscopic response of Haversian bone using a combined experimental and modeling approach. The fracture process is controlled by several factors such as overall mean porosity, the networking of the porosity, and the elastic and failure behavior of the nonporous matrix. We ask the following questions. How does the porosity network of Haversian bone differ from that of plexiform bone? Is the porosity-based RSNM model able to capture the effect of porosity network on the macroscopic response by reproducing the variation of strength across samples of Haversian bone from the same animal? Can the higher compressive strength of Haversian bone, despite its higher porosity, be accounted for solely in terms of remodeling of the porosity network or does the newly laid matrix have much larger strength than the original matrix?

The details of the structure of the network of pores are obtained, both pre- and post- compression testing of bone samples, using micro-CT scan images. When compared to plexiform bone, we find that the porosity network has higher overall porosity but the pores are not aligned in any particular planes. Further, a periodicity of the pores is observed in tangential direction based on which a two dimensional porosity-based RSNM for Haversian bone is developed. Bone-specific elastic properties of Haversian bone are determined using energy dispersive spectroscopy. The data shows that the elastic modulus of the matrix is lower than that of plexiform bone samples and unlike plexiform bone, does not vary significantly across different samples. To obtain the experimental macroscopic response from the RSNM model, the sample-dependent strain thresholds are iteratively determined, and found to be significantly higher than strain thresholds for plexiform samples samples corresponding to anterior regions of the same cross-section. The predictions suggest that at the millimeter scale, the remodeled bone matrix of Haversian bone is less stiff but significantly stronger than that of plexiform bone.