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Assessment of compressive failure process of cortical bone materials using damage-based model

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ABSTRACT

The main failure factors of cortical bone are aging or osteoporosis, accident and high energy trauma or physiological activities. However, the mechanism of damage evolution coupled with yield criterion is considered as one of the unclear subjects in failure analysis of cortical bone materials. Therefore, this study attempts to assess the structural response and progressive failure process of cortical bone using a brittle damaged plasticity model. For this reason, several compressive tests are performed on cortical bone specimens made of bovine femur, in order to obtain the structural response and mechanical properties of the material. Complementary finite element (FE) model of the sample and test is prepared to simulate the elastic-to-damage behavior of the cortical bone using the brittle damaged plasticity model. The FE model is validated in a comparative method using the predicted and measured structural response as load-compressive displacement through simulation and experiment. FE results indicated that the compressive damage initiated and propagated at central region where maximum equivalent plastic strain is computed, which coincided with the degradation of structural compressive stiffness followed by a vast amount of strain energy dissipation. The parameter of compressive damage rate, which is a function dependent on damage parameter and the plastic strain is examined for different rates. Results show that considering a similar rate to the initial slope of the damage parameter in the experiment would give a better sense for prediction of compressive failure.

1. Introduction

Investigation on mechanical behavior of cortical bone materials consists of study elastic-plastic behavior to damage evolution and fracture phenomena, are known as one of the important primary steps for analysis of bone structures that are joined to orthopedic implant structures (Brinkman et al., 2008, Gautier and Sommer, 2003, Qiao et al., 2014, Zhang et al., 2010). Optimal design of implant structures are normally performed by studying on the behavior of the bone-implants systems in desired state of operation using computational biomechanics method, therefore development of the constitutive models for mechanical behavior of bone is important (Bessho et al., 2007, Brinkman et al., 2008, Krone and Schuster, 2006, Van Den Munckhof et al., 2014). At the continuum scale, structure of bone is made of cortical and cancellous sections, and the primary constituents of bone are hydroxyapatite (HA) and type I collagen. The complexity of hierarchical arrangement and orientation of the bone structural constituents leads the bone to be heterogeneous and behave like anisotropic material as shown in Fig. 1(a) (Burstein et al., 1975, Hamed et al., 2012, Keaveny et al., 2003, Li et al., 2013b, Olszta et al., 2007, Reilly and Burstein, 1974, Rho et al., 1998, Weiner and Traub, 1992, Zimmermann et al., 2009). In meso-scale analysis, the functional unit of cortical bone is osteon constituent, which is in the form of cylindrical structure. The anisotropic behavior of cortical bone is normally dependent on the orientation of the osteon (Dong et al., 2012, Keaveny et al., 2003). Previous study has stated that strength of cortical bone is higher along the osteon direction (Longitudinal), in comparison with strength along the axis perpendicular to the osteon direction (Transverse) (Allena and Cluzel, 2014, Dall'Ara et al., 2015, Li et al., 2013b, Sansalone et al., 2010). A schematic view of the stress-strain curves of cortical bone under tensile and compressive loading conditions are shown in Fig. 1(b). Typically, cortical bone is the load bearing tissue material to carry the skeletal system and body weight for daily physiological activities. Failure events in bone could be due to prolonged or overload functioning activities (Dragomir-Daescu et al., 2011, Hambli, 2014, Hambli and Allaoui, 2013, Hambli et al., 2012). Hence, more insight into the mechanical function of the bone and fracture analysis could be used for optimal design of the orthopedic implants in long term applications. This is due to the complexity of implant-bone structure as a system which its functionality needs to be

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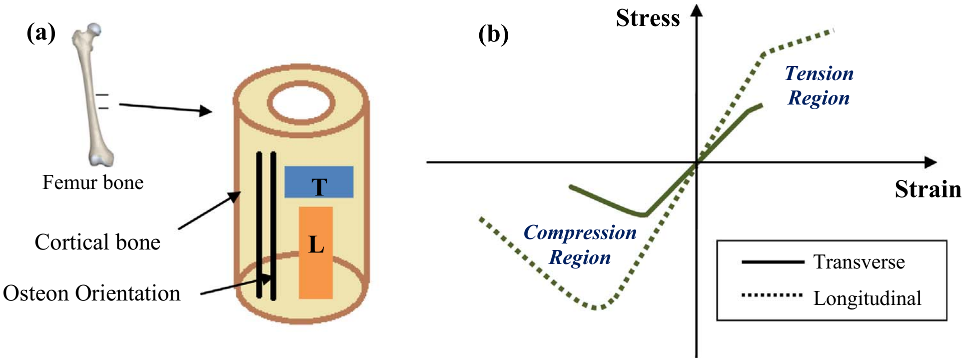

Fig. 1. (a) Schematic view of the cortical bone structure with respect to osteon orientation (L-Longitudinal, and T-Transverse directions), (b) Typical anisotropic stress-strain behavior of cortical bone materials.

examined for severe loading condition where damage and failure phenomena have to be considered in the design and analysis processes (Chakladar et al., 2016, Cordey et al., 2000, Qiao et al., 2014).

Fracture mechanics of cortical bone have been considered in many researches (Luo et al., 2010, Ritchie et al., 2009, Ritchie et al., 2008, Yan et al., 2007, Yang et al., 2006a, 2006b), including the linear elastic fracture mechanics (LEFM), which used to investigate on the fracture characteristics of bone such as applied stress and fracture toughness with the assumption of negligible plastic behavior. Some studies have indicated that bone tissue behaves as an anisotropic material that exhibits moderate amount of strain hardening prior to ultimate strength (Li et al., 2013b, Mirzaali et al., 2015, Yan et al., 2007, Yang et al., 2006a). It is shown that the accuracy of LEFM model for fracture analysis of cortical bone structure is questionable, therefore elastic plastic fracture mechanics (EPFM) is used for failure analysis of cortical bone (Luo et al., 2010, Malik et al., 2003, Ritchie et al., 2009, Yan et al., 2007). EPFM is used to characterize the material behavior through consideration of damage evolution process. The studies that utilizes fracture mechanics approach, normally deal with structures with initial crack in damaged state rather than pristine condition (Currey et al., 2004, Morais et al., 2010, Silva et al., 2015, Taylor and Lee, 2003, Ural and Vashishth, 2006, Ural and Vashishth, 2007, Vashishth, 2004, Vashishth et al., 2003, Wang, 2005, Wang et al., 2001), which prediction of the crack propagation is the major concern. The mechanical properties of bone could degrade due to the propagation of the natural micro-cracks under severe load, which lead to damage accumulation and fatal crack. Some studies have investigated on such phenomena by examining the fatal crack patterns to predict the separation and failure of bone using experimental approach (Ebacher et al., 2007, Ebacher and Wang, 2009, Nalla et al., 2005, Wang and Gupta, 2011, Wang et al., 1995, Zioupos et al., 2008). The limit of such approach in assumption of preexisting crack in the structure, and the lack of crack initiation criterion is considered as disadvantage of such approach for bone failure analysis. On the other hand, continuum damage mechanics approach uses the initiation and propagation criteria to address the elastic, plastic, damage and failure of materials (R. Koloor, 2016). Such criteria could be developed by investigation on yield and post-yield behaviors of bone material. In this respect, pressure dependent yield phenomenon has been considered in the inelastic behavior of bone due to the microstructural construction of the bone as cellular or porous material (Mullins et al., 2009, Öchsner and Hosseini, 2010). Then, further investigations have been performed on the post yield behavior through consideration of various failure criteria such as von-Mises, Drucker-Prager, Tsai-Wu and Hill failure criterion (Adam and Swain, 2011, Carnelli et al., 2010, 2011, Kelly and McGarry, 2012, Lucchini et al., 2011, Sharma et al., 2012, Wang et al., 2008). Most of these models such as Von Mises and Drucker-Prager criterion are defined based on the isotropic material property definition. However, the limit of the previous studies is the consideration of the post-yield behavior rather than the post-failure or damage evolution process that lead to prediction of material fracture. (Bessho et al., 2007, Dragomir-Daescu et al., 2011, Keyak and Falkinstein, 2003, Mercer et al., 2006, Mullins et al., 2009). Consequently, study on the progressive failure process of cortical bone in the form of quasi-brittle materials are still an open topic for investigation. Therefore, continuum damage mechanics approach that uses the damage initiation criteria along with a softening law to predict the evolution of damage to full failure is recommended (R. Koloor, 2016).

In this paper, failure assessment of cortical bone material is investigated under compressive load using continuum damage mechanics and finite element method (FEM). The mechanical behavior of cortical bone including elastic-plastic responses as well as the damage evolution process that leads to fracture event are studied using a brittle damaged plasticity model. In this respect, the mechanism of damage in cortical bone is examined using both FE simulation and experiment. The experiment is performed on a specially prepared sample of cortical bone under compression, to exhibit monotonic linear-nonlinear structural behavior that leads to vast damage accumulation in the structure. The failure process of the cortical bone is quantified in terms of the compressive stiffness, the evolution of internal states of stress, the progression of damage, and variation of damage dissipation energy under monotonic compressive-loading condition. The accuracy of the model in prediction of the softening process and fracture of cortical bone is examined through investigation on the effect of compressive damage parameter.

2. Brittle damaged plasticity model

Previous studies shown that cortical bone behaves as elastic-plastic material while it deform under compressive load, therefore considering the plasticity yield criterion is important to account for plastic deformation and hardening process (Jepsen et al., 2001, Li et al., 2013b, Reilly and Burstein, 1974, Yan et al., 2007, Zhang et al., 2010). On the other hand, it does not show plastic behavior while it is under tensile load as depicted by its quasi-brittle behavior (Zhang et al., 2010). Additionally, estimation of the equivalent yield strength in the element of the material under biaxial tensile and compressive loads is important (Sharma et al., 2012). The present study uses a brittle damaged plasticity model that has been established in the form of plastic damage model by Lubliner et al. (1989) research, and modified by Lee and Fenves (1998) for FE simulation process. The constitutive model is described in terms of stress-strain relation (Section 2.1), yield criterion, flow rule and the evolution laws of plastic hardening variables (Sections 2.2–2.4). The yield criterion is used to define the state of yielding for different evolution of material strength under tri/bi-axial compression and tension loads. Plastic behavior of the material is accounted if the yield limits exceeded, and the plastic strain is used to determine the evolution law of plastic hardening variables. Subsequently, the type of damage either in tension or compression condition is characterized. The flow rule is utilized to account for the