

A finite element study on the effects of disorder in cellular structures

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Received 23 November 2007; received in revised form 27 June 2008; accepted 17 July 2008

Available online 3 August 2008

Abstract

The susceptibility to deformation localization of simple cubic arrangements of struts, which are a simple approximation of the micro-architecture in cancellous bone, is analyzed. The coherence between structural disorder and the tendency towards deformation localization is investigated and its relevance from a biological point of view is discussed. A systematic study on the spatial deformation distribution of regular and disordered open cell structures is carried out. To this end, finite element models are employed which account for elastic–plastic bulk material and large strain theory, and a methodology for the estimation of the degree of deformation localization is introduced.

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Keywords: Cellular materials; Bone; Biomaterials; Finite element modeling; Deformation localization

1. Introduction

Many biological materials (e.g. wood, trabecular bone, marine skeletons) have a hierarchical structure with a cellular architecture at the micron to millimeter level [1]. A vertebra, for example, consists of a network of 200 µm thick struts inside a cortical shell. Cellular architectures [2] have several advantages. They can bear mechanical loads using a minimum of bulk material, thus allowing the use of lightweight design principles. The structures are accessible to body fluids, which deliver the required nutrients. Furthermore, cellular architectures can grow organically by the addition or removal of individual struts or by changing the shape of the constituent elements. Most interestingly, these cellular architectures are in general neither comparable

to a random foam nor correspond to a perfect regular lattice.

The role of the degree of regularity in such structures is not evident. Certain structures, such as the skeleton of radiolaria (Fig. 1b) or of the deep-sea sponge euplectella [3], exhibit a rather periodic micro-architecture. In the case of cancellous bone (Fig. 1a), the struts in the micro-architecture generally follow the trajectories of applied mechanical stresses. This effect has been known for more than 100 years and has been coined “Wolff’s law”, following its description by a 19th-century anatomist [4]. However, a detailed analysis of these structures shows that they have a large number of defects and irregularities [1,2]. The role of such defects is not clear. They may be deleterious for the mechanical stability by acting as crack initiators or, on the contrary, may be advantageous by preventing the collective failure of many struts in a strain localization event. Moreover, defect tolerance is a major requirement for all biological structures, which are usually not perfect.

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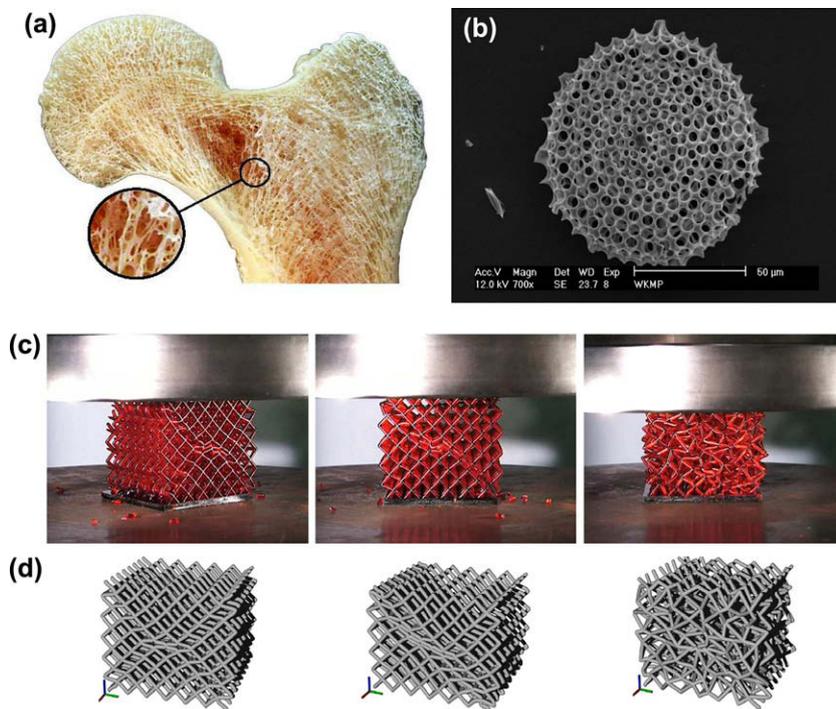


Fig. 1. Biomaterials like trabecular bone (a) or diatoms (b) are based on cellular architecture. Using solid freeform fabrication methods (c) and finite element modelling (d), the mechanical behavior of such materials can be analyzed.

The influence of structural disorder and different kinds of structural imperfections on the effective mechanical properties of two- and three-dimensional cellular solids has already been widely investigated. In [5], the effects of a non-periodic microstructure and missing cell walls on elastic moduli, plastic collapse strength, and localization of deformation of two-dimensional cellular solids by means of the finite element method (FEM) are investigated. In [6], FEM is employed to study the localization behavior of two-dimensional honeycombs with and without defects. Regular and disordered low-density, two-dimensional foam models subjected to large deformations are investigated numerically in [7]. In the case of three-dimensional structures, mostly Voronoi foams are utilized. In [8,9], the Voronoi tessellation technique and FEM are utilized to analyze the effect of disorder in cell shapes, non-uniform cell wall thickness and strut cross-sectional area variations on the elastic properties of two-dimensional honeycombs. The elastic behavior of three-dimensional random foams is investigated using FEM in [10]. The effect of cell disorder on the elastic properties of three-dimensional, low-density, open-cell Voronoi foam models is analyzed in [11]. In [12], the high strain compression of three-dimensional, low-density, open-cell polymer foams is modeled using FEM. The mechanical behavior of linear elastic open cell foams is investigated in [13] using three-dimensional FEM Voronoi models. In [14 and 15], FEM is used to predict the linear and nonlinear mechanical behavior of open cell foams under compressive loads. Studies on the overall nonlinear response of regular and disordered simple cubic and Kelvin structures are presented in [16,17].

In the present paper, we ask the question to which extent the simple cubic arrangement of struts, which is a simple approximation of the micro-architecture in cancellous bone, is susceptible to strain localization and how this is affected by disorder in the structure.

2. Modelling approach

2.1. Mechanical models

To overcome the limits of unit cell models [18,16], i.e. to allow for arbitrary deformation (localization) patterns, finite structures are modeled. Out of the six generic structures (simple cubic, body-centered cubic, reinforced body-centered cubic, Gibson Ashby, Kelvin, and Weaire Phelan) presented by Luxner et al. [16], the simple cubic (SC) structure is selected for the present investigations on account of its distinct anisotropy and its various deformation modes for different load directions.

The SC structure exhibits a relative density of 12.5% and consists of struts with circular cross-sections with constant diameter. Fig. 2 shows the regular base cell that represents the smallest periodic geometric unit of the investigated structure. The dimensions of the base cells are $4 \text{ mm} \times 4 \text{ mm} \times 4 \text{ mm}$. The (regular) base cell possesses cubic material symmetry. Note that only struts belonging to a single base cell are shown in Fig. 2. This may appear incomplete at first sight; in periodic repetition, however, the structural geometry becomes obvious.

The bulk material of the structures is a cross-linked photopolymer for which isotropic, elastic–plastic, strain-rate-

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