ARTICLE IN PRESS

International Journal of Plasticity xxx (2017) 1–35

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Simple and efficient analyses of micro-architected cellular elastic-plastic materials with tubular members

Maryam Tabatabaei*, Satya N. Atluri

Center for Advanced Research in the Engineering Sciences, Institute for Materials, Manufacturing, and Sustainability, Texas Tech University, Lubbock, TX, 79409, USA

A R T I C L E I N F O

Article history:
Received 6 June 2017
Received in revised form 28 August 2017
Accepted 12 September 2017
Available online xxx

Keywords:
Architected cellular microstructures
Large deformations
Nonlinear axial-torsional-bidirectional bending
Deformations coupling
Plastic hinge approach
Mixed variational principle
Newton homotopy methods

A B S T R A C T

In a novel way, nature evolves cellular structures to obtain mechanically efficient materials. Natural cellular materials combine low weight with superior mechanical properties to provide optimum strength and stiffness at low density such as trabecular bone, hornbill bird beaks, and bird wing bones. Inspired by these naturally architected cellular materials, humankind has also developed lightweight cellular materials for a broad range of applications consisting of structural components, energy absorption, heat exchange, and biomaterials. In this paper we present a highly efficient computational method to predict the bulk elastic-plastic homogenized mechanical properties of low-mass metallic systems with architected cellular microstructures. The proposed methodology provides a computational framework for the analysis, design, and topology optimization of such cellular materials. With a view for Direct Numerical Simulation of a cellular solid or structure with millions of cellular members, and considering the plausible deformations in each member, each such member is sought to be modeled by using only one or only a very few nonlinear three-dimensional (3D) beam elements with 6 degrees of freedom (DOF) at each of the 2 nodes of the element, and the nonlinear coupling of axial-torsional-bidirectional bending deformations is considered for each element. The effect of plasticity in each member is included using the mechanism of plastic hinges which may form at any point(s) along the length of each element or member. To make Direct Numerical Simulation of a micro-latticed cellular solid possible for its eventual applications, the tangent stiffness matrix for a spatial beam element undergoing large elastic-plastic deformation is explicitly derived using a Reissner-type mixed variational principle in the co-rotational updated Lagrangian reference frame. In order to avoid the inversion of the Jacobian matrix, a Newton homotopy method is employed to solve the tangent-stiffness equations. We are developing a code called CELLS/LIDS [CELLular Structures/Large Inelastic DeformationS] providing the capabilities to study the variation of the mechanical properties of the low-mass metallic cellular structures by changing their topology. Thus, due to the efficiency of this method we propose to employ it for topology optimization design, and for impact/energy absorption analyses of elastic-plastic micro-cellular structures, and then micro-architecting them for desired elastic-plastic properties.

* Corresponding author.

https://doi.org/10.1016/j.ijplas.2017.09.007

1. Introduction

Over the past few years, through advances in additive manufacturing technologies, more complex human-made lightweight cellular elastic-plastic materials were developed. For example, the world's lightest metal was recently fabricated at Hughes Research Laboratories (HRL) in California, based on the micro-architected cellular structures with structural hierarchy spanning three different orders of magnitude containing Nano-, Micro-, and Millimeters (Schaedler et al., 2011; Torrents et al., 2012). The bulk mechanical performances of such ultralight micro-architected cellular metallic materials can be optimized for specific applications, based on their topology, and by varying the properties of base materials in each lattice-member, thus making them interesting for use in industries such as automotive and aerospace. Therefore, the development of a novel and highly efficient method to predict and optimize the elastic-plastic properties of such structures is of interest.

Using additive manufacturing, Schaedler et al. (2011) and Torrents et al. (2012) fabricated micro-architected metallic cellular materials, with hollow tubular strut members forming an octahedral unit cell without any member in the basal plane, as shown in Fig. 1. They focused on the fabrication of nickel-based cellular microlattices with the strut member length $L = 1 \sim 4mm$, the strut member diameter $D = 100 \sim 500\mu m$, the wall thickness $t = 100 \sim 500nm$, and the inclination angle $\theta = 60^{\circ}$, and measured experimentally their compressive bulk mechanical properties (Schaedler et al., 2011; Torrents et al., 2012). The topology of these micro-architected cellular materials can be optimized independently by changing the inclination angle, strut member diameter, wall thickness of the hollow tube member, member length, the geometry of the cross section (hollow or solid), and the symmetry of the unit cell by altering the node-to-node connections to tailor the bulk elastic-plastic stress-strain response. Moreover, their structural hierarchy, spanning different orders of magnitude improves their mechanical properties. Also, their small size and light weight make them particularly suitable for the applications under space limitations and light weight considerations. All of the above-mentioned characteristics of these micro-architected cellular materials make them interesting to use in a variety of industries. In the following paragraph, some recent efforts which are under way to employ the functionality of these metallic cellular microlattices are discussed.

Schaedler et al. (2014) conducted a survey of cellular materials used to protect persons or structures from impulsive loads in automotive, sporting, and defense applications. For example, they (Schaedler et al., 2014) examined expanded polystyrene (EPS) used in bike helmets and thermoplastic polyurethane (TPU) twin hemispheres employed to absorb impact in running shoes, helmets, kneepads, blast-mitigating sheets, and seat cushions. Their survey divulged that all current absorbers are far from the ideal performance except for the pre-crushed honeycomb that still reveals another shortcoming due to its anisotropy. They (Schaedler et al., 2014) offered a pyramidal hollow nickel cellular microlattice architecture with vertical posts (the diameter of which is $D \approx 3.5mm$) connected by 60° angled struts ($D \approx 1mm$) and showed that this cellular material presents the best performance, plateau-like crushing stress under quasi-static and dynamic testing. Maloney et al. (2012) constructed a micro-scale cross-flow heat exchanger using nickel cellular microlattices, the periodic unit cell of which included tubular members with a diameter smaller than $1mm$ and a nominal pore size less than $9mm$. They (Maloney et al., 2012) demonstrated multifunctionality for these heat exchangers operating at micro-scale. For example, they showed that these metallic cellular microlattices are also capable of providing structural support. Such multifunctional heat exchangers with a small footprint would decrease system-level parasitic weight, which makes them particularly useful for applications in automotive and aerospace industries. Zheng et al. (2014) reported a class of micro-architected ultralight materials (hollow-tube octet-truss microlattices produced by atomic layer deposition) exhibiting ultra-stiff properties regardless of the constituent material, polymers, metals, or ceramics. Their experimental measurements revealed a nearly linear stiffness-density relationship for stretch-dominated materials, even at an ultralow density regime. They labeled them as mechanical

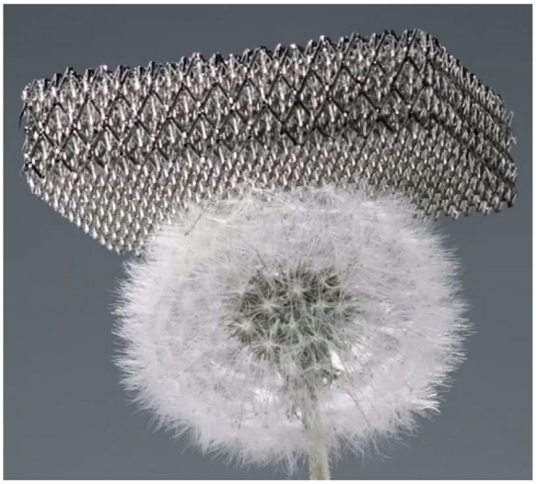

Fig. 1. The world's lightest metal fabricated at HRL Laboratories: the cellular solid supported by a dandelion (Schaedler et al., 2011; Torrents et al., 2012).