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Compressive behaviour of stainless steel micro-lattice structures

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ABSTRACT

This paper focuses on investigating the mechanical static compression behaviour of 316L stainless steel micro-lattice materials manufactured using selective laser melting method. In theoretical and numerical approaches, the material overlapping effects in the vicinity of strut connection points is taken into consideration to give reasonable predictions corresponding to the initial stiffness and strength values. In theoretical studies, Timoshenko beam model is used to consider the shear effect in calculation of initial stiffness. In addition, to include work hardening of micro struts in calculation of collapse strength a model is developed. Experiments have shown that mechanical response of micro lattice structures is governed by their aspect ratio. The theoretical predictions are quite close to experiments. Finite element models simulate the initial stiffness and strength values related to experimental tests, although there are some small differences in loading history, resulting from the complex strut joint geometry and variable diameter. Also, within the scope of this paper, the stress–strain curves of an individual defected micro strut manufactured using selective laser melting method are measured using an efficient method and the elasticity modulus for the defected micro strut is found as 97 GPa, which is 60% lower than bulk material. As a result, the findings show that in the micro scaled structures, the geometry of connection points and material overlapping should be taken into account to find the proper results in terms of mechanical responses in theoretical studies as well as finite element models.

1. Introduction

Cellular materials have been receiving considerable attention for a few decades in various application areas such as the cores of sandwich panels, thermal insulation, packaging and some automotive parts because of their superior specific stiffness and strength properties. These properties are defined by the internal architecture of the cellular structure and base or bulk material properties. Cellular materials are topologically stochastic (e.g. open and closed cell stochastic foams) or periodic. Periodic materials are characterised by a unit cell that is repeated in two directions (like Honeycomb) or three directions (truss or lattice materials) [1].

The stiffness and strength of conventional foams with cell wall bending for all loading options scales as $\overline{\rho}^2$ and $\overline{\rho}^{3/2}$, respectively, where $\overline{\rho}$ is relative density of the foam [2]. Deshpande et al. [3] analysed the topological criteria for cellular solids and showed that the minimum node connectivity for a special class of lattice structured materials to be stretching-dominated is 6 for 2D foams and 12 for 3D foams.

The effective mechanical properties of the stretching-dominated octet-truss lattice material have been investigated in Deshpande et al. [4] through analytical and finite element calculations. Also, Wallach and Gibson [5] analysed the elastic module as well as the uniaxial and shear strengths of a particular geometry of 3D truss material, as a function of the aspect ratio of the unit-cell. A combination of experiments and numerical simulations was used by Zhou et al. [6] to explore the effects of strut properties on the deformation behaviour of lattice block structures. Zhu et al. [7] investigated the elastic constants of an open-cell foam model, having tetrakaidecahedral cells on a BCC lattice. The Young's modulus, shear modulus and Poisson's ratio were derived, as functions of the edge cross section and the foam density, by considering the bending, twisting and extension of the cell edges. A parametric investigation was conducted by Doyoyo and Hu [8] to understand the multi-axial failure of strut lattices composed of slender and short struts. Parameters included the strengthening and the classical slenderness ratios at the strut level were studied for a three-dimensional Warren truss that can be partitioned into a stretching-dominated octet-truss and a combined stretching and bending-dominated cubic truss. The theoretical failure envelopes were derived based on the

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mechanics of the truss lattice at the level of struts. The theory was compared to numerical data from finite element analysis and a close comparison was obtained between the theory and numerical simulation. Xie and Chan [9] carried out a micromechanical analysis to investigate the effect of strut geometry on the yielding behaviour of open-cell foams. It was found that the strut geometry significantly affects the plastic-yielding behaviour of open-cell foams. Also the shape of the plastic-yield surface was found to depend not only on relative density but also on the cross-sectional shape of the struts. The stiffness and the strength of block lattice truss materials were derived by Fan et al. [10], as well as polyhedrical yield surfaces. They showed that when the relative density of the lattice is smaller than a critical value, micro compression buckling of struts will dominate the macro failure mode of the material under macro shearing loading or even macro tensile loading. Also, there are many articles to experimentally, numerically and theoretically investigate the mechanics properties of sandwich beams with truss core in the literature [11–16].

An equivalent continuum method is developed by Hualin and Wei [17] to analyse the effective stiffness of three-dimensional stretching dominated lattice materials. The strength and three-dimensional plastic yield surfaces are calculated for the equivalent continuum. A yielding model is formulated and compared with the results of other models. The work by Mohr [18] deals with the development of mechanism-based constitutive models for ideal truss lattice materials and their application to the octet-truss lattice material.

Luxner et al. [19] used the finite element method to determine the elastic properties and the level of anisotropy for four different geometrical configurations, using beam elements for the core structure model and solid elements for the periodic unit-cell model. To generate theoretical results for random models the finite element method (FEM) was used by Roberts and Garboczi [20] to study the elastic properties of open-cell solids. They computed the density and microstructure dependence of the Young's modulus and Poisson's ratio for four different isotropic random models based on Voronoi tessellations, level-cut Gaussian random fields, and nearest neighbour node-bond rules.

Recently, the University of Liverpool realised micro scaled lattice structures by using the rapid prototyping manufacturing process of selective laser melting (SLM). Therefore, a few articles such as those investigating the experimental mechanical properties of micro lattice blocks under compression [21,22] and impact load [23] and sandwich panels with micro lattice cores during indentation [24] were published. In addition to these studies, Ushijima et al. [25] has developed a theoretical analysis using classical beam theory for predicting the initial stiffness and plastic collapse strength of BCC micro lattice block under compression. Their analysis was also verified by finite element predictions and experimental data for a wide range of strut aspect ratios, d/L. Whereas their theoretical and numerical predictions for initial stiffness and collapse strength are very consistent to experimental results for micro lattice blocks with aspect ratio smaller than especially 0.1 value, they give quite low predictions for moderately large ratio ranges.

Therefore, this study focuses on both investigating the mechanical behaviour of stainless steel micro-lattice blocks under static compression and developing the satisfying theoretical and numerical models for all aspect ratio ranges. So, here, in theoretical and numerical approaches the material overlapping effects in the vicinity of strut connection points is taken into consideration to find the more reasonable predictions corresponding to both initial stiffness and collapse strength values especially for moderate large aspect ratio ranges. In the analytical modelling, Timoshenko beam theory is used to determine the initial stiffness by taking into account the bending behaviour of individual strut whereas to predict the plastic collapse strength the fully plastic moment concept is used. Finite element simulations were separately performed for both continuum based solid element and beams. To show the validation of theoretical and numerical results and to gain insight to mechanical behaviour of micro-lattices, the experimental tests are also carried out under static compressive loading. To take into account the work hardening in calculation of initial plastic collapse, a new method is suggested here. In addition, in this study the stress–strain curve of an individual strut is experimentally determined using an efficient experimental method. All results are evaluated in terms of initial stiffness and strength variations and deformation modes for lattice blocks.

2. Mathematical analysis of lattice block

2.1. Physical analysis of individual strut and cell

The geometry of the body centred cubic (BCC) unit-cell is given in Fig. 1. To mathematically analyse a lattice block or unit-cell, the individual lattice strut shown in Fig. 2b is considered. In Fig. 2a, joints connecting struts to each other were assumed the rigid to consider the joint effect in micro blocks. So, deformations and bending moment are assumed to occur in a place near to the joint. These assumptions agree with the experimental result given in Fig. 3 [21]. A little deformation and rotation exist in the joints. Hence, there is a need to define a new moment arm or span

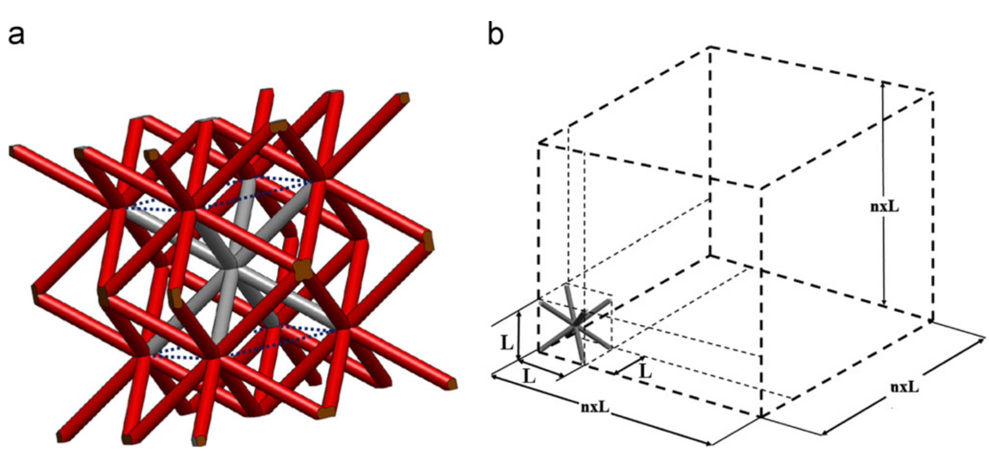

Fig. 1. Definition of body centred cubic; (a) unit-cell in light grey and (b) lattice block.