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The predicted compressive strength of a pyramidal lattice made from case hardened steel tubes

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ABSTRACT

A sandwich panel with a core made from solid pyramidal struts is a promising candidate for multifunctional application such as combined structural and heat-exchange function. This study explores the performance enhancement by making use of hollow struts, and examines the elevation in the plastic buckling strength by either strain hardening or case hardening. Finite element simulations are performed to quantify these enhancements. Also, the sensitivity of competing collapse modes to tube geometry and to the depth of case hardening is determined. A comparison with other lattice materials reveals that the pyramidal lattice made from case hardened steel tubes outperforms lattices made from solid struts of aluminium or titanium and has a comparable strength to a core made from carbon fibre reinforced polymers.

1. Introduction

In recent years, there has been significant research progress in the development of lightweight sandwich panels with lattice core topologies. Such sandwich panels are subjected to quasi-static service loads, or to dynamic loads associated with various threats such as waster blast and sand blast in military applications. The strength of the core depends upon its topology, relative density and the mechanical properties of the parent solid, see Ashby (2006). Type 304 stainless steel is a promising core material, particularly for marine applications due to its high strain hardening capacity and its high corrosion resistance. Over the last decade, several core topologies have been manufactured from type 304 stainless steel, for example the corrugated core (Côté et al., 2006), square honeycomb core (Côté et al., 2004) and the pyramidal core made from solid struts (Zok et al., 2004) or hollow tubes (Queheillalt and Wadley, 2005, 2011). For each core topology, the measured compressive strength $\overline{\sigma}_{pk}$ (defined as the ratio of the maximum force sustained by a single unit cell of the core and the unit cell cross-sectional area) is plotted in Fig. 1 as a function of relative density $\overline{\rho}$ (defined as the ratio of the density of the lattice core to that of the solid). The compressive strength is normalised by $\overline{\rho}\sigma_Y$, where σ_Y is the yield strength of the parent material. The results indicate that the hollow pyramidal core is stronger than other core topologies, particularly at low values of relative density.

The unit cell of a hollow pyramidal lattice is shown in Fig. 2; its geometry is defined by the inclination angle ω, the tube length l, the external diameter d and wall thickness t. Pingle et al. (2011a) used the finite element method to examine the influence of tube geometry upon the collapse mode of a hollow pyramidal lattice for the choice $\omega = 55^\circ$. Their results are presented in the form of a collapse mechanism map[1] and this is reproduced in Fig. 3. Six collapse modes are identified, and the active mode depends upon the tube slenderness ratio l/d and the normalised wall thickness t/d. This map was developed for a hollow pyramidal lattice made from annealed type 304 stainless steel, of yield strength 180 MPa, and high strain hardening capacity. The stress vs. strain response as used by Pingle et al. (2011a) is reproduced in Fig. 4.

In the first part of this study, the effect of strain hardening upon the collapse mode and compressive strength of a hollow pyramidal lattice will be evaluated. In the second part, the effect of surface carburisation will be investigated. A low temperature carburisation treatment has been developed recently for stainless steel and, depending on the duration of the treatment, carburisation depths of 25–70 µm can be achieved (Cao et al., 2003; Michal et al., 2006). The potential of carburisation to increase the strength of lattice materials made from stainless steel has not been investigated before; however, other surface treatments, such as plasma electrolytic oxidation and electrochemical anodizing, have been used recently to increase the compressive strength of aluminium metal

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[1] Similar collapse mechanism maps were developed experimentally for vertical tubes made from aluminium alloy by Andrews et al. (1983) and Guillow et al. (2001). Maps can also be developed for other loading conditions; see for example Pingle et al. (2011b) for a map of the hollow pyramidal lattice under transverse shear.

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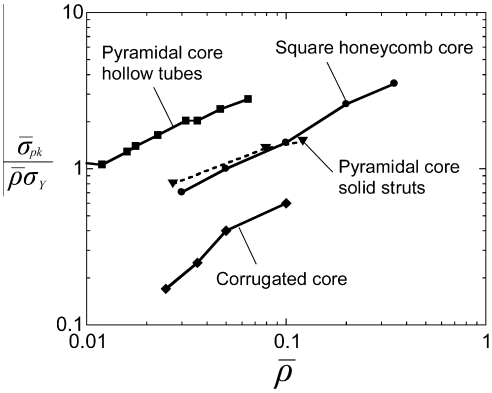

Fig. 1. The measured normalised compressive strength as a function of relative density for four different lattice core topologies made from type 304 stainless steel. Data taken from Côté et al. (2004, 2006), Queheillalt and Wadley (2011) and Zok et al. (2004).

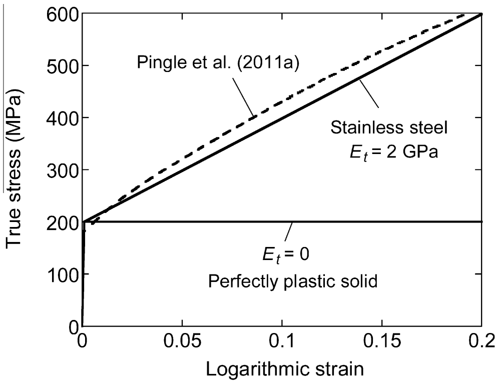

Fig. 4. Uniaxial tensile responses of the two material models employed in the finite element simulations to analyse the influence of strain hardening. The measured response of type 304 stainless steel, which was employed in the simulations of Pingle et al. (2011a), is also included for comparison.

foams (Abdulla et al., 2011; Bele et al., 2011; Dunleavy et al., 2011). The parameter space for the design of a pyramidal lattice is large with choices to be made with regards to the geometry, materials and coatings. The objective of this numerical study is to provide guidance that will help future experimental work to narrow down regimes that are expected to be of practical relevance.

The effect of strain hardening and carburisation upon the compressive strength of a pyramidal lattice is studied below, with a focus on two vertical trajectories on the collapse mechanism map in Fig. 3: the left-hand trajectory, marked by a dashed line, represents tubes with a normalised wall thickness $t/d = 0.1$, whereas the right-hand trajectory denotes pyramidal lattices made from solid struts, $t/d = 0.5$. For both trajectories, the slenderness ratio l/d is varied from 1 to 100.

This paper is organised as follows. First, the geometry of the hollow pyramidal lattice is presented in Section 2. Second, the effect

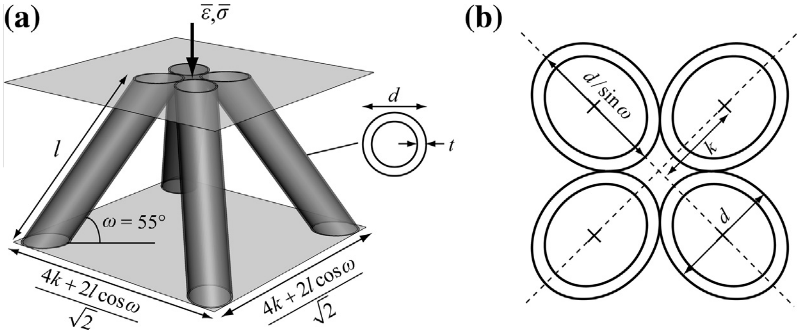

Fig. 2. (a) Unit cell of the hollow pyramidal lattice. (b) Top view of the lattice.

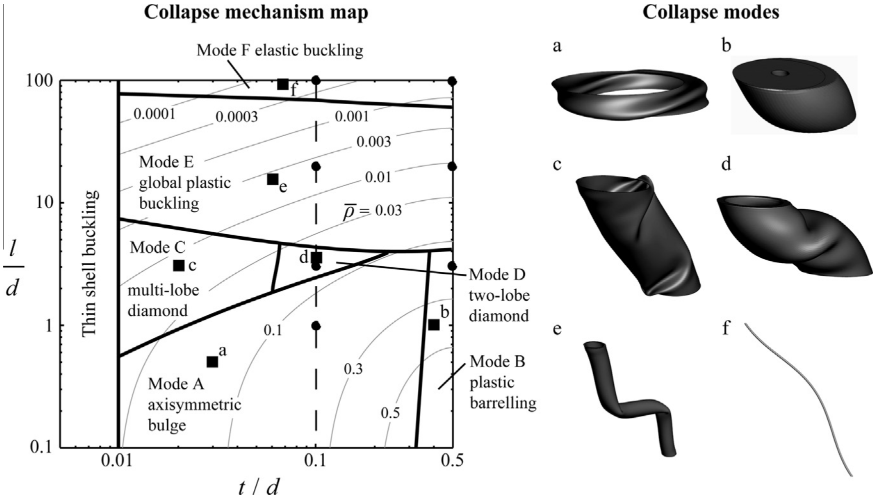

Fig. 3. Collapse mechanism map for a hollow pyramidal lattice made from type 304 stainless steel. There are six collapse modes (A–F) exemplified by the six selected geometries (a–f) that are marked on the map using square symbols. The representative geometries considered in this study are indicated by circular symbols. Adapted from Pingle et al. (2011a).