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Energy absorption in lattice structures in dynamics: Experiments

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ABSTRACT

Lattice structures offer the potential to relatively easily engineer specific (meso-scale properties (cell level)), to produce desirable macro-scale material properties for a wide variety of engineering applications including wave filters, blast and impact protection systems, thermal insulation, structural aircraft and vehicle components, and body implants. The work presented here focuses on characterising the quasi-static and, in particular, the dynamic load-deformation behaviour of lattice samples. First, cubic, diamond and re-entrant cube lattice structures were tested under quasi-static conditions to investigate failure process and stress–strain response of such materials. Following the quasi-static tests, Hopkinson pressure bar (HPB) tests were carried out to evaluate the impact response of these materials under high deformation rates. The HPB tests show that the lattice structures are able to spread impact loading in time and to reduce the peak impact stress. A significant rate dependency of load-deformation characteristics was identified. This is believed to be the first published results of experimental load-deformation studies of additively manufactured lattice structures. The cubic and diamond lattices are, by a small margin, the most effective of those lattices investigated to achieve this.

1. Introduction

The choice of material for a given structural problem requires a careful balance of strength, stiffness, cost, durability and relative static and dynamic properties. Lattice structures are multi-functional materials that can offer a range of these desirable properties. They are commonly constructed by duplicating three-dimensional meso-scale unit cells, typically at the scale of a few mm. The stiffness and strength of these materials depend on relative density, strut aspect ratio (radius/length), unit cell geometric configuration, unit-cell size, properties of parent material, and rate of loading [1]. By changing the spatial configuration of struts and/or strut diameters, different geometries with different material properties can be produced, which will be explored herein the context of protection against blast and impact loading.

Although lattice structures are different from cellular materials, certain concepts carry over from the well-studied cellular materials to the less well-known lattice structures, especially under transient dynamic loading conditions. It is thus worthwhile to review briefly the state of the art in cellular materials.

Properties of cellular materials have been the subject of many studies [2–6]. The mechanical response of cellular materials under intense blast and impact loading may result in localisation of deformation, densification and material resistance and stiffness leading to propagation of the deformation by a process akin the development of shock waves; this extreme localisation is typical for “sparse materials” [7] and not observed in bulk materials. In cellular solids, shock wave propagation is frequently studied using one-dimensional analytical models, spring-mass models or finite element (FE) models. Reid et al. [2] developed a theory for the propagation of structural shock waves through one-dimensional metal ring systems in order to explain the experimentally observed behaviour of such structures when subjected to end impact. More detailed dynamic crushing experiments on tightly packed arrays of thin-walled metal tubes were carried out by Stronge and Shim [3]. Reid and Peng [4] evaluated the enhancement of crushing strength of wood samples under high velocity impact with a rate-independent simple shock wave model. Since the cell sizes within wood are very small, the material behaviour was homogenised by assuming a rigid perfectly plastic locking (RPPL) material model for wood to determine the strength enhancement due to shock wave propagation. Two important parameters, namely plateau stress σ_{pl} and densification or lock-up strain ε_D, were used to characterise the constitutive behaviour of the material. By assuming a certain level of strength enhancement, critical impact velocities, at which shock propagation effects become important and the response becomes dependent upon the

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impact velocity, were defined (e.g. Deshpande and Fleck [5] adopted a criterion of a 20% elevation in strength for foams). Since these parameters cannot be easily identified from stress–strain data for shock enhancement prediction, a simple power law densification model was proposed to replace the RPPL model [8]. Tan et al. [9] used the efficiency of cellular material in absorbing energy to compute σ_{pl} and ε_D.

In addition to shock wave propagation, strength increase in cellular solids under dynamic loading conditions may be attributed to micro-inertial effects [5]. Bending dominated (Type I) structures with flat topped quasi-static stress–strain curve are slightly affected by micro-inertial effects under dynamic conditions. Metallic foams generally behave as Type I structures. Deshpande and Fleck [5] verified the rate insensitive behaviour of two particular types of aluminium foam under high strain rates by split Hopkinson pressure bar (HPB) and direct impact tests. Elnasri et al. [6] reported the existence of shock front in cellular structures under high strain rate impact loading at low critical velocities by comparing the results of direct Hopkinson bar and Hopkinson bar-Taylor tests. On the other hand, stretch dominated (Type II) structures show sharp softening behaviour after peak load. In contrast to bending dominated structures, stretch dominated structures are significantly influenced by micro-inertial effects [10]. Strength enhancement of square tubes in successive folding mechanisms under impact loading was attributed to the higher strain in edge-areas of the tube because of inertia [11].

Recent technological advances, i.e. additive manufacturing techniques, allow us to create periodic metallic lattice structures with an efficient geometry which, in principle, can minimise the material usage whilst optimising the desired mechanical properties of the material. One potentially promising application is the use of bespoke metallic lattices as sacrificially energy-absorbing layers in protection systems against blast and impact loading. However, as a sub-class of cellular solids, lattice structures are quite new materials for blast, ballistic and impact protection applications, and experimental and numerical studies on the dynamic response of such materials are very limited. McKown et al. [12] experimentally evaluated the quasi-static response and dynamic progressive collapse behaviour of steel lattice structures under impulsive loads and their associated failure modes, without focusing on the effect of lattice structures on the temporal spreading of impulse. Hasan et al. [13] compared the drop weight impact performance of sandwich panels with aluminium honeycomb and titanium alloy lattice structures in terms of specific impact energy versus dent depth. Smith et al. [14] conducted an extensive study to characterise the response of steel lattice structure samples to blast. They presented quantitative deformations of qualitative damage as a function of blast impulse. However, to date, no experimental data on the dynamic load-displacement characteristics of cellular metallic lattice materials have been presented in the literature.

In the current work, the energy absorption behaviour and failure modes of lattice structures under quasi-static and dynamic loading conditions are studied. In order to maximise the freedom in creation of potentially complex lattice structures, additive layer manufacturing techniques, where a structure is built up progressively by the selective melting of specific regions in successive layers of metal powder, are used. Titanium alloy (Ti6Al4V) is preferred due to its high specific properties, and availability of data to allow modelling of mechanical response [15,16]. Lattice structures with different unit cell geometries are fabricated using the Electron Beam Melting (EBM) technique. A series of experimental tests were performed on the lattice structure samples. First, the load-deflection response and associated failure modes of such structures were captured by quasi-static compression tests. Following the compression tests, the impact response of lattice structures under high deformation rates was evaluated by HPB tests to assess the ability of such materials to spread impact loading in time and to attenuate peak response.

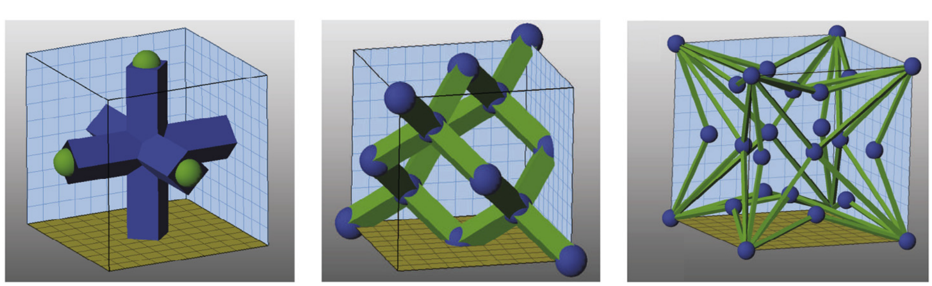
The outline of this paper is as follows. Section 2 summarises the manufacturing process of lattice structures. In Section 3, quasi-static stress–strain curves and associated failure modes of lattice structure samples are assessed. The experimental impact response of lattice structure samples is discussed in Section 4. Finally, in Section 5 some implications of the work are discussed.

A numerical modelling study of the quasi-static and dynamic collapse of these lattice materials has been conducted in parallel and the results of this will be published in a forthcoming paper.

2. Manufacturing process

A range of Additive Manufacturing techniques have been developed, and equipment is commercially available. The names used vary with equipment supplier, and there are fundamental differences between some of the techniques; for example, Selective Laser Melting (SLM) uses a laser as the directable heat source, whilst Electron Beam Melting (EBM) uses a high-energy beam of electrons. In this case EBM has been selected for use as the beam can be split and moved around the build area more rapidly, meaning samples can be produced in less time. The EBM technique can be used for the production of metallic materials of arbitrary shape. This technique does not require additional treatments (thermal, machining, etc.) to obtain the final shape or mechanical properties [17].

In this work, lattice samples are manufactured from spherical grade 5 Ti6Al4V powder with 45–110 µm particle size using an ARCAM S12 EBM machine. Three unit cell geometries of increasing complexity, shown in Fig. 1, are chosen for the lattice samples. For the cubic lattice geometry (Fig. 1a), struts run along the edges of the unit cell. The other geometries are diamond (Fig. 1b), where the struts are arranged in directions similar to the interatomic bonds in the atomic lattice of diamond, and re-entrant cube (Fig. 1c), where all edges and diagonal struts across the faces bent towards the centre.



(a) (b) (c)

Fig. 1. Representative unit cells of (a) cubic, (b) diamond and (c) re-entrant cube lattice structures. When built, the unit cell side length in the lattices is 5 mm.