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Impact strength enhancement of aluminum tetrahedral lattice truss core structures

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ABSTRACT

The present study aimed at understanding the behavior of tetrahedral lattice truss core structures under impact loading. Experimental investigations on tetrahedral lattice truss core structures made of aluminum 3003-O were performed using a standard testing machine and nylon split Hopkinson pressure bars. Results showed that the peak force increased about 23% from quasi-static loading to dynamic loading while the base material is hardly rate sensitive. In order to prove such a peak force increase was due to the lateral inertia effect, digital photography techniques were used to catch the deforming process of the core. A quantitive measurement of this process (length, shape) was extracted by a digital image analysis based on the edge detection algorithm. It was observed that the beams of the core were simply compressed at the early stage of loading before bending prevailing and this turning point took place much later under impact loading than the case of quasi-static loading. It was found that the beams were consequently more compressed before the occurrence of buckling during impact loading. This is the direct proof of the existence of the lateral inertia effect. Because of its important strain hardening capacity of base material (aluminum 3003-O), the observed peak force increase can be explained by this lateral inertia effect. Furthermore, numerical simulations using Abaqus code were also carried out to understand thoroughly the role of the lateral inertia effect played on the lattice truss core structures.

1. Introduction

Cellular materials (honeycomb, foam and hollow sphere agglomerates, etc.) combining both lightweight and high energy absorbing capacity are widely used in various industrial areas, such as automobiles, naval vehicles, aircrafts [1]. They provide high strength/density ratios and good energy absorbing abilities in these applications. Among different cellular materials, it has been reported that periodic cellular structures, for instance, honeycomb, have superior features to stochastic foams. This is because their manufacturing and optimization design process are more controllable [2]. That is to say, the actual mass distribution in periodic cellular structures is much more consistent with the ideal one.

Honeycombs are the current state-of-the-art choice for weight sensitive applications [3,4]. However, sandwich panels with honeycomb cores are difficult to fabricate into complex curved shapes because of the induced anticlastic curvature, and they also trap moisture, due to their close-cell structure, which leads to internal corrosion and facesheet debonding (indicated by Sypeck and Wadley [4]). With the development of manufacturing techniques such as investment cast [5,6], perforation and folding [4] and combination of extrusion and electrodischarge machining [7], lattice truss core structure (another periodic cellular structure) attracted a lot of attentions of researchers in the past decade. Lattice truss core structure avoids the drawbacks of honeycomb aforementioned, and furthermore, as an open cell periodic structure, they can also be exploited to multifunctional applications, for example, heat exchange media [8]. Therefore, lattice truss core structure is supposed to be a promising substitute in the future.

Lots of theoretical works on the mechanical responses of lattice truss cores structures can be found in open literature [5,6,9–12]. A comprehensive review was carried out by Ref. [13]. The preliminary constitutive laws for this type of structure were reported as well

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[14–16]. For the energy absorption applications such as protective designs for accidental collisions of high speed vehicles, and even the armor of military vehicles and warships, the mitigation of blast wave was investigated theoretically [17], experimentally [18–20] and numerically [19,20]. The results showed that the use of lattice truss core sandwich panel significantly decreased the vertical transmit component forces to the supports compared to equivalent monolithic plates.

The researches on the behavior of lattice truss core structures mentioned above focused on either the quasi-static properties like stiffness and strength or the resistance to the intensive pressure pulse. Between these two extreme conditions, the resistance to medium speed crash was rarely reported. Lee et al. [21] executed a comparative experiment on pyramidal truss core under quasi-static loading ($7 \times 10^{-3}\ s^{-1}$) and medium loading rate (from 263 s^{-1} to 550 s^{-1}). They found that the peak force under impact loading was 60% larger than the one under quasi-static loading. Generally, the strain rate sensitivity of cellular materials under medium speed impact is due to two factors: (i) the rate sensitivity of base material and (ii) the inertial effect of core which delays the onset of buckling. Actually, the inertial effect was reported to play a significant role in dynamic enhancement of cellular materials, such as square tubes [22], circular tube [23] and honeycomb [24,25]. The influence of inertia effect on the lattice truss core structures was reported in a few literature. Vaughn et al. [26] numerically analyzed the role played by coupled plastic wave propagation and column buckling on tetrahedral truss core and pointed out that the strength enhancement of structures was partially from the lateral inertia effect and strain hardening of base materials. Tang et al. [27] investigated the response of an unit cell tetrahedral truss core specimen using steel Hopkinson bar. They found an elevation of the peak force from the quasi-static loading to impact loading, and they attributed this elevation to the inertia effect. Most recently, McShane et al. [28] performed a series of numerical simulations on an inclined strut (a 2D simplification of corrugated plate) to investigate the strain hardening and strain rate hardening effects on its dynamic collapse.

Even though the inertia effect was claimed to be responsible for the strength enhancement of lattice truss core structures under impact loading, its experimental explanation was still unachieved, only the force–displacement curves were reported. In the present paper, the lateral inertia effect exerting on the lattice truss core structure is highlighted. The specimen with six tetrahedral truss cores made of rate-insensitive aluminum 3003-O is studied under quasi-static loading and impact loading. Under impact loading, a large diameter nylon Hopkinson bar setup is used to achieve a more reliable testing results on considering the very low impedance of specimen. Moreover, digital photography is used to record the deforming process during loading. Further image analysis is conducted to measure the actual beam length before its buckling. At last, the numerical virtual experiments are also carried out to confirm and extend the results from real experiments.

2. Experimental study of the rate sensitivity

2.1. Tetrahedral truss core structure specimen

The present specimen (see Fig. 1(a)) is composed of two face sheets and the cores sandwiched between them. The core is made of three beams which cross together as a regular tetrahedron (Fig. 1(b)) with a manufacturing procedure of sheet perforating and node folding method [4]. The designed parameters of the lattice truss core are 15.31 mm in length (l), 2 mm in width (w) and 1 mm in thickness (t). The height of the core is thus 12.5 mm and the theoretical relative density of the core is 3.6% following [13]:

$$\bar{\rho}_c = \frac{3\sqrt{2}wt}{l^2} = 3.6\% \quad (1)$$

The cores are then brazed to two face sheets (1 mm in thickness) in inert gas atmosphere. Both the face sheets and the cores are fabricated from aluminum 3003-O with a density of 2730 kg/m^3. The quasi-static and dynamic uniaxial tensile experiments of the base material have been performed on Instron 5882 testing system and 10 mm diameter Hopkinson tensile bars [29], respectively. A dog-bone specimen (see in Fig. 2(a)) of 30 mm in effective length and 5 mm in width is used. In order to obtain accurate experimental curves of the base materials, digital image correlation method [30] is employed to measure the strain field on the specimen directly, instead of the displacement given by the testing equipment, which is potentially less accurate considering the probable slip between the specimen and clamps.

The stress–strain curves of aluminum 3003-O under two different strain-rates, $4 \times 10^{-4}\ s^{-1}$ and 80 s^{-1}, are plotted in Fig. 2(b). The gap between these two curves is about 10%. It manifests that the strain rate effect of this kind of aluminum is not so important though the strain-rate range has covered 6 orders, from $10^{-4}\ s^{-1}$ to $10^2\ s^{-1}$. Similar conclusions can also be found in the literature [31–33]. Meanwhile, it also reveals that aluminum 3003-O has strong strain hardening capacity and the strength at the strain 4% doubles the yield strength.

2.2. Experimental set-up

Quasi-static compression tests are performed on MTS 810 material testing system while the dynamic loading is executed on the nylon Hopkinson bar. Actually, two 3 m long nylon bars of

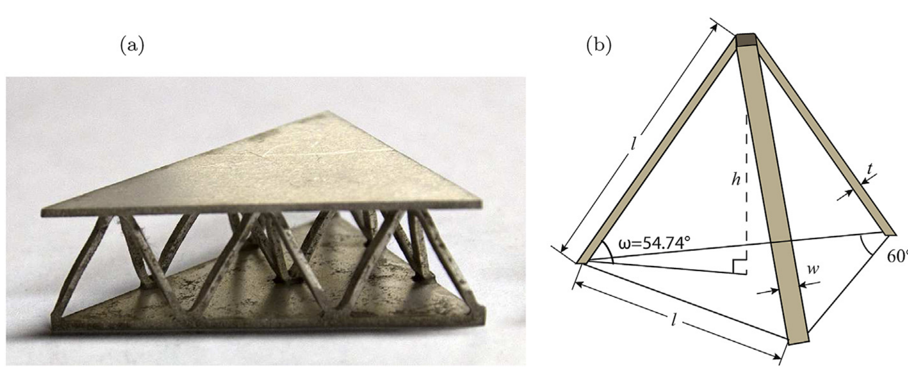

Fig. 1. (a): The 6-core specimen of tetrahedral truss core lattice structure; (b): The model of tetrahedral truss core.