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# Dynamic energy absorption characteristics of hollow microlattice structures

Yilun Liu [a,b], Tobias A. Schaedler [c], Xi Chen [a,b,d,*]

[a] International Center for Applied Mechanics, SV Lab, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China
[b] Columbia Nanomechanics Research Center, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA
[c] HRL Laboratories LLC, Malibu, CA 90265, USA
[d] Department of Civil & Environmental Engineering, Hanyang University, Seoul 133-791, Republic of Korea

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ABSTRACT

Hollow microlattice structures are promising candidates for advanced energy absorption and their characteristics under dynamic crushing are explored. The energy absorption can be significantly enhanced by inertial stabilization, shock wave effect and strain rate hardening effect. In this paper we combine theoretical analysis and comprehensive finite element method simulation to decouple the three effects, and then obtain a simple model to predict the overall dynamic effects of hollow microlattice structures. Inertial stabilization originates from the suppression of sudden crushing of the microlattice and its contribution scales with the crushing speed, $v$. Shock wave effect comes from the discontinuity across the plastic shock wave front during dynamic loading and its contribution scales with $v^2$. The strain rate effect increases the effective yield strength upon dynamic deformation and increases the energy absorption density. A mechanism map is established that illustrates the dominance of these three dynamic effects at a range of crushing speeds. Compared with quasi-static loading, the energy absorption capacity at dynamic loading of 250 m/s can be enhanced by an order of magnitude. The study may shed useful insight on designing and optimizing the energy absorption performance of hollow microlattice structures under various dynamic loads.



## 1. Introduction

Developing superior energy absorption materials and structures (EAMS) has been a research focus for both scientists and engineers (Ashby et al., 2000; Chen et al., 2006; Evans et al., 2010; Tilbrook et al., 2006). Different mechanisms, such as plastic buckling (Gibson and Ashby, 1997; Guoxing and Yu, 2003); phase transformation (Feuchtwanger et al., 2003; Frommeyer et al., 2003); frictional dissipation (Duan et al., 2006; Sun et al., 2009), and surface/interface energy trapping (Chen et al., 2008, 2006; Liu et al., 2009), have been used in advanced EAMS to absorb external mechanical energy. Cellular structures are perhaps the most widely employed platform of EAMS, thanks to their lightweight and high energy absorption density (Ashby, 2006). The external impacting energy is absorbed by either plastic deformation or viscoelastic deformation of parent materials of the cellular structures. Besides energy absorption in sporting, automotive and defense applications, cellular structures are also widely employed as building blocks of thermal management (Evans et al., 2001; Sypeck and Wadley, 2001), acoustic isolation (Davies and Zhen, 1983), catalyst supports (Banhart, 2001; Davies and Zhen, 1983) and electrodes

* Corresponding author at: Columbia Nanomechanics Research Center, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA.
*E-mail address:* xichen@columbia.edu (X. Chen).

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(Banhart, 2001). In periodic cellular structures (Evans et al., 2010; Gibson and Ashby, 1997), the performance can be further optimized by placing material at desired locations where the mechanical and other indices are simultaneously maximized (Evans et al., 2001).

Hollow microlattice cellular structures have attracted recent attention, due to their improved energy dissipation and heat transfer properties (Queheillalt and Wadley, 2005). Recently Jacobsen et al. (2007, 2008) have developed a new method to fabricate hollow metallic microlattices with cell sizes in the 0.1–10 mm range and wall thickness from 0.1 → 100 μm. Ultralight metallic microlattices with relative density lower than 0.001 have recently been demonstrated (Schaedler et al., 2011). The quasi-static energy absorption characteristics of the microlattice structures were investigated experimentally (Evans et al., 2010) and theoretically (Liu et al., 2014), which demonstrate promising performance indices. However, a detailed study on their dynamic responses and energy absorption characteristics is still lacking.

Under dynamic loading, the cellular structures show progressive collapse which is completely different from the cases under quasi-static loading (Pal et al., 2010). Therefore the load capacity and energy absorption of cellular structures usually show significant improvements (Fang et al., 2010; Hanssen et al., 2000; Hou et al., 2011; Zhao and Abdennadher, 2004). For instance, the energy absorption density of cylindrical shells can be improved more than 30% by increasing the crushing speed (Karagiozova and Jones, 2001; Yu et al., 2006). In general, the energy absorption enhancements are caused by three factors: inertial stabilization; shock wave effect, and material strain rate hardening (Deshpande and Fleck, 2000; Zhao et al., 2006). However the three effects are integrated under dynamic loading, so that the dynamic effects of cellular structures are usually complicated. A general model to decouple the three effects and exploring the influence of individual effect on the energy absorption of microlattice structures is still lacking.

The present paper aims to close these two gaps by first developing a unified model including the contributions of the three dynamic factors, and then specified for microlattice structures through extensive finite element method (FEM) simulations and parametric studies. Besides elucidating the dynamic energy transfer mechanisms, the study may shed some useful insight on designing and optimizing the hollow microlattice structures for dynamic energy absorption and mitigation. In Section 2, a one dimensional crushing model is developed to analyze the dynamic responses of a cellular buffer, based on which the dynamic energy absorption enhancement is divided into three parts: inertial stabilization, shock wave effect, and strain rate hardening effect. These three factors are specified for hollow microlattice structures through extensive and parametric FEM simulations in Section 3. Discussions of the dominant dynamic factor in respective crushing speed regions are presented in Section 4, followed by concluding remarks in Section 5.

Two examples of hollow microlattice cellular structures are shown in Fig. 1. One typical structure exhibits large vertical trusses $\theta = 90^\circ$ connected by inclined trusses $\theta = 60^\circ$ with a smaller diameter (Fig. 1(a)). Another example has hollow trusses (connected at both ends) with an inclination angle $\theta$ of 60° (Fig. 1(b)). The corresponding computational cells employed in this paper are shown in Fig. 1(c) and (d), where $\theta = 60^\circ$ corresponds to the 60° microlattice structure in Fig. 1(b). Here for the 90° microlattice structure the role of the small inclined truss is connecting and stabilizing the large vertical truss. In this work as a model system to study the dynamic response of microlattice structure we only consider the deformation and energy absorption of the large vertical truss in our FEM simulation. While for the 60° microlattice structure as the symmetry of the unit cell, we only consider one inclined truss member (1/4 unit cell) and symmetrical boundary conditions are applied to the truss member. We further ignore any fracture process and temperature raising that may occur during the process.

## 2. Theoretical model

Inspired by the one dimensional crushing model proposed by Evans et al. (2010), in Fig. 2(a) an EAMS (e.g. a hollow microlattice cellular structure) is compressed by an external pressure through the attached buffer. Considering the high speed compression, the crushing is progressively developing from the buffer toward the stationary structure through the shock front. As the plastic deformation dominates the compression process of the cellular medium, we assume the constitutive relation is ideal rigid-plasticity same as the previous reference Evans et al. (2010). The upstream of the shock front is assumed to reach complete densification and moves at the same velocity $v$, whereas the downstream does not deform and keeps stationary. For the microlattice structure studied in this work, these assumptions are acceptable when the crushing speed is larger than 100 m/s.

### 2.1. Dynamic energy absorption

The one dimensional crushing model is shown in Fig. 2(a). The cellular medium is bounded by two buffers; one buffer is stationary and the other is pushed by the external $P$ towards the stationary one. During high speed compression the plastic shock wave propagates from the pushed buffer to the stationary buffer and the cellular medium shows progressively collapse. The validation of the progressively collapse for hollow microlattice structures will be discussed in Section 3. The cellular medium in upstream of the plastic shock front moves with uniform velocity $v$, so the momentum $M$ is

$$M = (m_b + \rho s)v, \tag{1}$$

where $m_b$ is the mass per area of the buffer, $s$ is the crush length of the microlattice, $\rho$ is density of the cellular medium. The differential of the momentum corresponding to time equals to the force acting on the buffer and cellular medium. Based on the previous reference Evans et al. (2010) the constitutive relation of cellular medium is assumed as ideal rigid-plasticity, so the stress acting on