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Dynamic crushing and energy absorption of regular, irregular and functionally graded cellular structures

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ABSTRACT

The in-plane dynamic crushing of two dimensional honeycombs with both regular hexagonal and irregular arrangements was investigated using detailed finite element models. The energy absorption of honeycombs made of a linear elastic-perfectly plastic material with constant and functionally graded density were estimated up to large crushing strains. Our numerical simulations showed three distinct crushing modes for honeycombs with a constant relative density: quasi-static, transition and dynamic. Moreover, irregular cellular structures showed to have energy absorption similar to their counterpart regular honeycombs of same relative density and mass. To study the dynamic crushing of functionally graded cellular structures, a density gradient in the direction of crushing was introduced in the computational models by a gradual change of the cell wall thickness. Decreasing the relative density in the direction of crushing was shown to enhance the energy absorption of honeycombs at early stages of crushing. The study provides new insight into the behavior of engineered and biological cellular materials, and could be used to develop novel energy absorbent structures.

1. Introduction

Emergence of robust methods for fabrication of cellular structures, such as wire assembly and perforated sheet folding technique, have augmented their usage as lightweight multifunctional materials. From the structural point of view, cellular structures have properties that are much superior compared to the properties of the material that they are made of, including high strength to weight ratio and energy absorption (Gibson and Ashby, 1997; Xiong et al., 2010). The application of cellular structure ranges from architectural masterpieces of Antonio Gaudi (Nonell and Levick, 2001) to thermal insulators (Lu and Chen, 1999) and three dimensional scaffolds for tissue engineering (Hollister, 2005; Hutmacher, 2000).

One of the key applications of the cellular materials is in structural protection due to their superior energy absorption and impact resistance. The basic applications pertaining to these characteristics are packaging of fragile components (e.g. electronic devices) and various protective products like helmets and shielding. Another emerging application is usage of cellular structures as the core material for metal sandwich panels, which are shown to have superior performance over the counterpart solid plates of equal mass under shock loading (Dharmasena et al., 2009; Liang et al., 2007; Mori et al., 2007, 2009; Rathbun et al., 2006; Vaziri and Hutchinson, 2007; Vaziri et al., 2007; Wadley et al., 2007, 2008; Wei et al., 2008; Xiong et al., 2011; Xue and Hutchinson, 2003; Xue and Hutchinson, 2004). Core topology and relative density have considerable influence on performance of the sandwich panels, as the core crushes at an early stage of deformation and absorbs a large fraction of the kinetic energy imparted to the panel due to shock loading (Fleck and Deshpande, 2004; Hutchinson and Xue, 2005).

In the quasi-static regime, the crushing response of most metal cellular structures shows a typical stress–strain curve that includes three regimes: an elastic response followed by a plateau regime with almost constant stress and eventually a densification regime of sharply rising stress (Jang and Kyriakides, 2009a,b; Mohr et al., 2006; Papka and Kyriakides, 1998; Triantafyllidis and Schraad, 1998). Under dynamic crushing, however, the response of the metallic cellular structure is governed by complex localized phenomena that include buckling and micro-inertial resistance. The fundamental study of Vaughn et al. (2005) and Vaughn and Hutchinson (2006) has provided much insight into these effects, including the interaction between plastic waves and localized buckling under dynamic loading. Xue and Hutchinson (2006) showed that the micro-inertial resistance of core webs of a square honeycomb metal core increases its resisting force remarkably at early stages of dynamic crushing. At later stages of deformation, the dynamics effects results in suppression of the buckling of the metal webs, leading to emergence of buckling shapes with a wavelength much smaller than the core height. These effects lead

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