Thin-Walled Structures 131 (2018) 373–384

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Dynamic crushing response of auxetic honeycombs under large deformation: Theoretical analysis and numerical simulation

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ARTICLE INFO

Keywords:
Re-entrant honeycomb
Negative Poisson's ratio
Impact
Large deformation
Theoretical analysis

ABSTRACT

In order to comprehensively understand the dynamic response of auxetic honeycombs, theoretical analysis are conducted to predict the NPR effect and the crushing stress of the re-entrant hexagonal honeycomb. The honeycomb's crushing stress is a function of the cell's geometric parameters, crushing velocity and the mechanical property of the cell-wall material. Results show that the crushing stress enhances with the increasing crushing velocity. A dynamic sensitivity index is employed to quantitatively evaluate this enhancement. It is shown that small cell-wall angle, low relative density or high cell-wall length ratio of the honeycomb attribute high velocity-sensitivity to the crushing stress. The Poisson's ratio of the re-entrant honeycomb is also expressed as a function of the cell's geometric parameters. It is revealed that the NPR effect enhances with the increasing cell-wall angle and the decreasing cell-wall length ratio. All the theoretical predictions are verified by numerical simulations. Besides, an interesting phenomenon is noticed that the crushing velocity has significant influence on the honeycomb's NPR effect at the early stage of crushing. However, this influence almost vanishes when the overall strain is larger than about 0.2. This present work is supposed to shed light on the design of the auxetic honeycomb.

1. Introduction

Material with negative Poisson's ratio, also known as auxetic material, has been a hot area of research for years since the first foam structures with a negative Poisson's ratio was artificially fabricated [1]. It is believed that this kind of material has some advantages compared to conventional materials, including large shear resistance, buckling resistance, hardness improvement, lower fatigue crack propagation and so on [2–5]. Some potential applications may take advantage of these properties, such as foam anchor [6] and foam cushions [7]. Moreover, cellular materials, such as honeycombs, have been used as new engineering materials because of their high relative stiffness and strength and efficient energy absorption [8]. Re-entrant hexagonal honeycombs, as a kind of cellular material with negative Poisson's ratio, are expected to have more outstanding properties and have greatly potential uses in engineering applications.

Honeycombs and foams are the two main type of auxetic cellular materials and the negative Poisson's ratio effect (NPR effect) of them is caused by the special topologies of their microstructure. A. Javadi et al. [9] developed a method to design new auxetic materials using finite element method and a genetic algorithm. Accordingly, some kind of honeycombs with negative Poisson's ratio is designed, such as chiral honeycomb, star honeycomb, arrow-head honeycomb and re-entrant hexagonal honeycomb [10], among which re-entrant hexagonal honeycomb is the earliest example converted from the conventional hexagonal honeycomb. Based on the topology of re-entrant hexagonal honeycomb, some new types of honeycombs are devised to achieve either zero Poisson's ratio and enhanced stiffness [11] or multiple design degrees of freedom for manufacture [12]. Brighenti et al. [13] analyzed the nonlinear deformation behavior of auxetic cellular materials with an arrow-head re-entrant lattice structure and gave the geometric parameters governing the deformability of the material. In a recent study [14], a re-entrant star-like honeycomb is developed and used in the design of layered plates to achieve smart behavior.

Extensive works have been carried out to study the mechanical properties of re-entrant hexagonal honeycombs under small deformation and quasi-static loading conditions. Masters and Evans [15] developed a theoretical model to predict the elastic constants (tensile moduli, shear moduli and Poisson's ratio) of re-entrant hexagonal honeycombs. Lee et al. [16] and Scarpa et al. [17] revealed the dependence of re-entrant hexagonal honeycombs' Poisson's ratio and Young's modulus on the cell's geometric parameters using FEM analysis. The Poisson's ratio of re-entrant hexagonal honeycombs under large deflection was also studied [18]. Shil'ko et al. [19] investigated

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https://doi.org/10.1016/j.tws.2018.04.020

Nomenclature

θ_0	angle between the bevel edge and the horizontal edge of the cell
h	length of the cell's horizontal edge
b	out-of-plane thickness of the honeycomb
t	cell-wall thickness of the honeycomb
l	length of the cell's bevel edge
$\Delta\theta$	decrease in the cell-wall angle of the typical cell
ε_x, ε_y	strain of the cell along the x- and the y-directions, respectively
ν	Poisson's ratio of the typical cell
E_p	energy dissipated by the plastic hinges during the collapse of a unit cell
M_p	full plastic bending moment of the cell walls, $M_p = \frac{1}{4}\sigma_Y bt^2$
σ_Y	yield stress of the cell-wall material
W	work done by the crushing stress acting on the unit cell over the collapse process
$\bar{\sigma}_s$	honeycombs' average crushing stress during the cell's collapse process under low-velocity crushing, which is also the supporting stress applied from the bottom of the typical cell
$\bar{\sigma}_d$	average crushing stress applied on the top of the typical cell, which is also the average crushing strength of the honeycomb over a collapse period
H	total compression displacement of a typical cell, $H = 2l\sin\theta_0 - 4t$
S	section area of a typical cell
v	crushing velocity of the rigid impact plate
T	time interval of the compression process of a typical cell
p_{AB}^0, p_{AB}^f	momentum of cell wall AB at the initial and final state of crushing, respectively
ρ_s	density of the cell-wall material
ρ_*	density of the honeycomb
D	damage number of the base material of the honeycomb, $D = \frac{\rho_s v^2}{\sigma_Y}$
I_{ds}	dynamic sensitivity index

the contact deformation of auxetic composites and gave the estimation for the Poisson's ratio of quasi-isotropic and anisotropic auxetic composites. A novel re-entrant honeycomb with enhanced in-plane stiffness and buckling strength is also proposed and analyzed in our former study [20,21] under elastic and small deformation conditions. In one of our previous studies [22], the analytical model of the nonlinear shear modulus of re-entrant hexagonal honeycombs under large deformation is presented, which is dominated by the geometry of the cell structure.

However, when honeycomb is in practical application, such as a bumper to absorb impact energy, it often works under high-velocity loading condition, of which the mechanical properties can be very different from that of quasi-static loading conditions. So the dynamic behavior associated with the deformation mechanisms and the crushing strength needs to be studied in depth. Few researches have been done on this topic for the auxetic honeycombs. Chen and Lakes [23] investigated the dynamic behavior of NPR foams in dispersion of acoustic waves. In our former study [24], the indentation resistance of re-entrant hexagonal honeycombs under low-velocity (10 m/s) impact was analyzed both numerically and theoretically. The relation between indentation resistance and the honeycombs' geometric parameters was revealed by the numerical tests and explained by the theoretical analysis. In a recent study, Qi et al. [25] investigated the impact and close-in blast response of sandwich panels with re-entrant hexagonal honeycomb cores, both experimentally and numerically. Results showed that this composite material has more outstanding force mitigation and blast-resistance performances than conventional honeycomb panels. Liu et al. [26] studied the crushing pattern and energy absorption performances of the re-entrant hexagonal honeycombs using FE methods. The structural irregularity of the re-entrant hexagonal honeycomb and its influence on the dynamic crushing were also numerically investigated in their work. Based on numerical simulations, Zhang et al. [27] gave an empirical expression on the crushing stress of the re-entrant honeycombs over cell-wall angle. However, besides cell-wall angle, there are other factors that may affect the crushing stress of the honeycombs, which should be taken into consideration.

It is generally thought that the NPR effect of the honeycombs is not obvious under high-velocity crushing due to the inertial effect of the cell structure. But there is no work published to prove this statement up to now. More researches need to be carried out to further study the NPR effect and crushing stress of the re-entrant hexagonal honeycombs under dynamic loading and large deformation associated with the influencing factors on them. The quantitative relationships among them also need to be established.

In this present paper, a computational formula of Poisson's ratio of

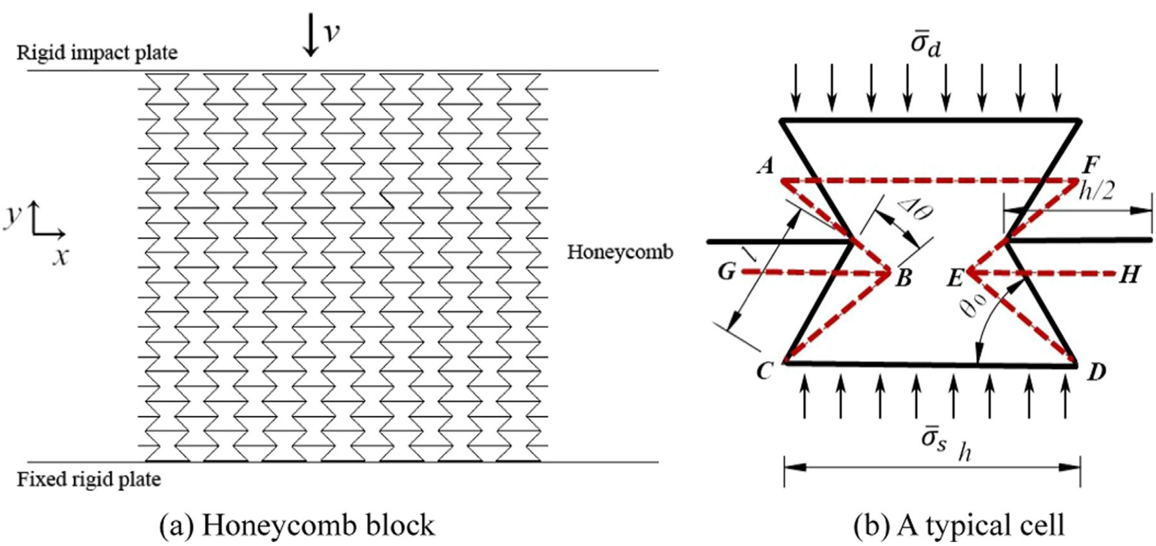

Fig. 1. Configuration of re-entrant hexagonal honeycomb.