Materials and Design 160 (2018) 527–537

Contents lists available at ScienceDirect

Materials and Design

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

# Dynamic crushing of double-arrowed auxetic structure under impact loading

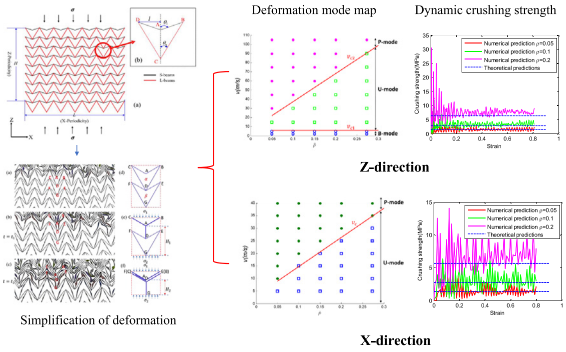
Xuan Zhao [a], Qiang Gao [b,c,*], Liangmo Wang [b], Qiang Yu [a], Z.D. Ma [c]

[a] *School of Automobile, Chang'an University, Xi'an, PR China*
[b] *Department of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, PR China*
[c] *Department of Mechanical Engineering and Applied Mechanics, University of Michigan, Ann Arbor, MI, USA*

## HIGHLIGHTS

- An empirical formula of critical impact velocity is deduced.
- A theoretical model is proposed to predict the dynamic crushing strength.
- Theoretical predictions are validated by numerical results.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 24 August 2018
Received in revised form 19 September 2018
Accepted 24 September 2018
Available online 29 September 2018

*Keywords:*
Double-arrowed auxetic structure
Negative Poisson's ratio
Deformation behavior
Dynamic crushing strength

## ABSTRACT

Double-arrowed auxetic (DAA) structures with a negative Poisson's ratio have recently drawn increasing attention. This paper deduces the empirical formula of critical impact velocity to characterize the deformation modes of the DAA structures in two in-plane directions. A method is proposed to construct a theoretical model for predicting the dynamic crushing strength of DAA structure. The theoretical model is validated by numerical results to be sufficiently accurate to predict the dynamic crushing strength. It is also found that the dynamic crushing strength is only related to the relative density and impact velocity.

## 1. Introduction

Auxetic cellular structures have gained increased attention due to their excellent performance with respect to the impact resistance [1], shear stiffness [2], indentation hardness [3] and resilience [4]. This high performance is observed because auxetic structures contract when compressed; thus, such structures are considered to possess a negative Poisson's ratio (NPR), which can contribute to the energy absorption. An auxetic foam was manufactured first by Lakes [5] in 1987. Common NPR structures with different configurations (re-entrant hexagonal [6,7], star [8,9], double-arrowed [10–13], chiral [14,15]) are illustrated in Fig. 1. Elipe and Lantada [16] compared the mechanical properties of these auxetic structures and concluded that the re-entrant hexagonal and double-arrowed auxetic structures have the highest effective Young's modulus.

An effective anisotropic continuum formulation for auxetic re-entrant cellular structures has been developed to predict the elastic

---

[*] Corresponding author at: School of Automobile, Chang'an University, Xi'an, PR China.
*E-mail address:* gaoqiangsir@163.com (Q. Gao).

https://doi.org/10.1016/j.matdes.2018.09.041
0264-1275/© 2018 Published by Elsevier Ltd.

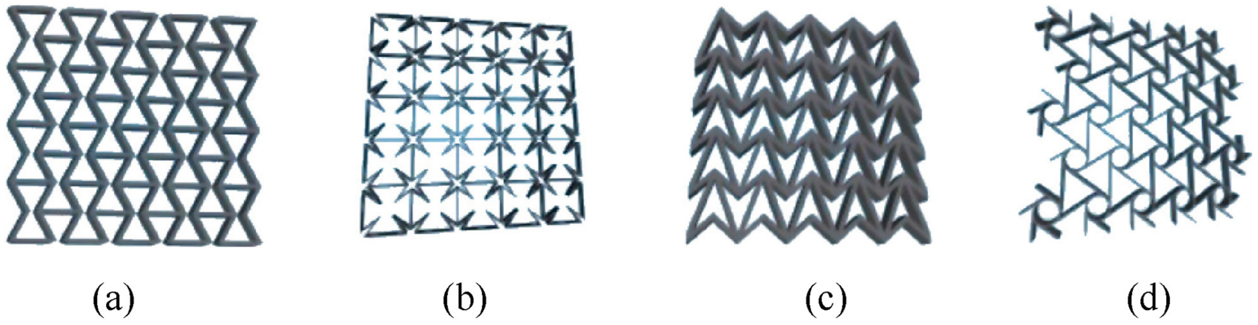


**Fig. 1.** Different configurations of auxetic structures: (a) re-entrant hexagonal, (b) star, (c) double-arrowed, and (d) chiral.

properties [17]. A compressive test on a 3D periodic re-entrant lattice structure fabricated via electron beam melting was conducted by Li [18]. The experimental results pertaining to the mechanical properties of the structure agree well with explicit analytical predictions. A novel auxetic re-entrant hexagonal honeycomb was developed by Fu [19] by embedding the rhombic configuration to enhance the in-plane stiffness and buckling strength. Gao [10] developed theoretical formulas for the effective Young's modulus and Poisson's ratio for a three-dimensional double-arrowed structure utilizing the homogenization technique. The response of the cylindrical double-arrowed auxetic structure under low-velocity impact was investigated. The multi-objective optimization algorithm was used to acquire the optimal structure that can absorb the greatest amount of energy and retain a low peak crushing force [20]. Zhou [21] applied the double-arrowed NPR structure as the core of a crash box to enhance the crashworthiness. Using a numerical method, the crashworthiness performance of a crash box with an NPR core was proven to be better than that with a foam core. The double-arrowed NPR structure has also been applied to suspension jounce bumpers, as reported by Wang [22]. An NPR suspension jounce can improve vehicle ride comfort by reducing the maximum vertical acceleration. The static low-strain properties of metamaterials as well as the role effect of large deformations on their static properties have been studied thoroughly [34–37]. The equivalent static mechanical properties of auxetic lattices and composites with auxetic inclusions have been studied by the discrete homogenization method [38,39]. Wave propagation in auxetic structures has also been investigated [40]. Furthermore, the acoustic properties of the auxetic material can be controlled by changing the level of pre-deformation [41]. Khaled [42] extended the small strain homogenization technique to predict mechanical properties of auxetic lattice materials in the nonlinear regime. K. El Nady [43] predicted the nonlinear elastic response of auxetic structures based on micropolar continuum models. To obtain an auxetic structure with an optimal in-plane Poisson's ratio, the topology optimization method was previously utilized [44]. In another study, the effective properties of textile composites were obtained computationally by an equivalent strain energy method based on the response of the representative volume unit cell (RUC) under prescribed boundary conditions [45].

Dynamic crushing of auxetic cellular structures is also a popular topic. One-dimensional shock theory was developed by investigating the features of a crushing front through the wood under uniaxial impact [23]. Ruan [24] employed ABAQUS software to investigate the influence of cell wall thickness and impact velocity on the mode of localized deformation and plateau stress. Zhang [25] investigated the effect of cell-wall angles on the dynamic crushing behavior of a re-entrant hexagonal honeycomb. Increases of the cell angle, relative density and impact velocity were shown to enhance the energy-absorbed ability of the auxetic structure. Similar work on hexagonal cellular honeycombs has been carried out by Hu [26], who showed that a honeycomb with a cell angle of 45° performs best in absorbing energy under impact. Zou [27] discussed the dynamic crushing patterns and crushing stress of cellular structures under different impact scenarios. Three different deformation patterns were characterized. The analytical formula for the dynamic crushing strength of regular hexagonal cellular structures was developed by Hu [28] based on the repeatable collapsing mechanism of cellular structures. The same group further established an analytical model to predict the dynamic crushing strength of hexagonal honeycombs under low-velocity impact. The analytical predictions were validated by numerical simulations [29]. The deformation patterns and dynamic crushing strength of double-arrowed auxetic (DAA) structures have been discussed by Qiao [30,31]. However, only two deformation modes of DAA structures compressed in the z-direction have been considered. The critical velocity that distinguishes the deformation modes has not been thoroughly discussed. In fact, if the number of cells in the x- or z-direction is not sufficiently large, the DAA structure tends to bend under low-velocity impact.

Experimental investigations have been reported in many studies. Various dynamic characteristics of open cell compliant polyurethane foam with auxetic (negative Poisson's ratio) behavior have been illustrated by F. Scarpa [46]. Qi [47] studied the ballistic resistance of sandwich panels with aluminum and auxetic honeycomb core experimentally. It is observed that the auxetic honeycomb core performs better on the ballistic resistance. 2D/3D re-entrant honeycomb lattices under quasi-static loading and dynamic are investigated compression using Split Hopkinson Pressure Bar [48]. Auxetic cellular structures build from inverted tetrapods were experimentally tested at high strain rate compression loading. It shows that shock deformation mode can enhance the stiffness in comparison to the quasi-static response [49].

This paper discusses the dynamic patterns and crushing strength of DAA structures compressed in the x-direction to fill the abovementioned research gap. Other special deformation patterns of DAA structures are also investigated utilizing one-dimensional shock theory and numerical methods.

## 2. Numerical simulation

Numerical simulations of the dynamic crushing of DAA structures are conducted with the commercial software Ls-Dyna. The DAA structure features two rigid walls at the bottom and top (Fig. 2). The bottom wall is fixed, and the top wall impacts the DAA structure with an initial impact velocity. The mass of the top wall is set to 2000 kg, which guarantees that the velocity remains nearly constant during crushing. Belytschko-Tsay four-node shell continuum elements with five integration points through the elements' thickness are adopted. The "automatic single surface" and "automatic surface to surface" contact modes are employed to simulate the contact of DAA structures in the crushing period. The "automatic node to surface" mode is utilized to model the contact between the rigid wall and the DAA structure. The dynamic and static coefficients of friction are set to 0.3 and 0.2, respectively [32]. These values can effectively prevent the interpenetration of the FE model.