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Low-velocity impact response of multilayer orthogonal structural composite with auxetic effect

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ABSTRACT

Composites with auxetic effect have been drawing more attention in recent years due to their unique features and wide applications. In this study, a kind of novel multilayer orthogonal structural composite with auxetic effect was fabricated for energy absorption and impact resistance. Non-auxetic composite with the same raw materials but with different reinforcement structure was also fabricated for comparison in order to better understand the effect of reinforced structure on the deformation mechanism and mechanical responses of the composites. Since the quasi-static compressive properties and Poisson's ratio effect of composites had been investigated previously, this paper only focused on the study of the low-velocity drop-weight impact tests of composites under impact energies from 7.25 J to 65.25 J. It was shown that both auxetic and non-auxetic composites were strain rate sensitive from 34.23 s^{-1} to 111.48 s^{-1}, but they exhibited totally different mechanical responses due to different deformation and damage mechanism. Pull out tests demonstrated that strong interfacial bonding between the reinforcements and matrix could ensure the desired deformation of structural reinforcements and auxetic effect of the composite. It was also concluded that the auxetic composite had better energy absorption performance in medium strain range.

1. Introduction

Energy absorbing materials used for impact protection generally hold the characteristics of long stroke, inelastic energy conversion, restricted and constant reactive force, light weight and high energy-absorption capacity [1]. With these features, polymeric foams have widely been used as packaging and damping materials due to their superior energy absorption capability. However, deformation, plastic collapse and fracture can easily cause fatigue even failure of the polymeric foams. Polymer type, foam density, open/closed cell content, cell size and shape, etc. are usually optimized to improve the mechanical properties of polymeric foams [2,3]. Chopped fibers [4] and nano-sized particles [5] were also used to increase the stiffness and plateau stress of the foams. However, the continuous and integral structures are seldom used as reinforcements for mechanical enhancement in case the big increase of foam weight.

In our previous work, multilayered orthogonal structural materials with light-weight and high mechanical properties were designed as the reinforcements to enhance the polyurethane foam (PU) without decreasing the strength to weight ratio [6]. Meanwhile, the negative Poisson's ratio (NPR) effect was achieved by changing the structure arrangement of the reinforcement, which further enhanced the mechanical performance of foams under compression and impact effectively. NPR, namely "auxetic", means that materials will expand transversely when pulled longitudinally or contract transversely when compressed longitudinally [7]. With the combination of structural reinforcement and matrix foam as well as the unique auxetic effect, the novel auxetic composite showed interesting mechanical performance compared with the non-auxetic composite. The multilayered orthogonal structural reinforced composite could be regarded as a kind of reinforced foam with auxetic effect. It could be used individually or serve as the core materials of the sandwich structures.

The NPR concept started to draw attention in 1987 with the advent of man-made auxetic foam [8]. Since then, a large quantity of researches covering the design [9,10], fabrication [11,12] and characterization [13,14] of auxetic materials have been conducted. These studies revealed that the auxetic effect could evidently improve the mechanical properties of materials including shear resistance [15], indentation resistance [16,17] and fracture toughness [15,18]. Moreover, the enhanced compressive properties [17], shear stiffness [15,19], impact resistance [20] and indentation hardness [17,21] of cellular foams could further lead to the improvement of energy absorption. Mechanical testing

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[14,22–24] and finite element models [25–27] have been utilized to verify this conclusion. The significant improvement of auxetic foams in dissipating energy compared to non-auxetic and iso-density foams at every number of cycles and loading levels has been proved by Bezazi and Scarpa [22]. In reference [27], finite element model for the in-plane ballistic resistance of an auxetic-cored sandwich panel was built and compared to that of an Aluminum foam-cored sandwich panel. Higher energy absorption for the auxetic-cored panel under velocity from 380 m/s to 600 m/s was identified and attributed to the local densification of materials due to the NPR effect. The quasi-static compressive behaviors [23] and dynamic crushing [14,24] of auxetic PU foams and conventional non-auxetic foams were also studied by Scarpa et al. Their comparative results showed a distinctive improvement of mechanical characteristics for auxetic foams including energy absorption.

To investigate the energy absorption and impact resistance of materials, the drop-weight impact tests are usually adopted. In our previous work, the quasi-static compression and energy absorption properties of PU foam, auxetic composite and non-auxetic composite had been investigated [6]. Results showed that the auxetic composite possessed obvious NPR effect and good energy absorption capacity. This paper presents a further study on the low-velocity impact responses of foam, auxetic and non-auxetic composites to understand their impact protection and energy absorption behaviors. The quasi-static compressive and dynamic impact properties of foams and foam-cored sandwich panels have been studied by many researchers with experimental and numerical methods [28–31]. However, few of them are about the dynamic responses of 3D integral reinforced foams and composites with auxetic effect. The low velocity impact response of rigid PU foam at velocities from 2 m/s to 4 m/s was studied by Shim [28]. The effects of impact velocity and impactor geometry on the energy absorption were studied. Similar study on the impact behavior of aluminum syntactic foams was conducted by Castro et al. In the reference [29], failure mechanisms of foams were interpreted from impact load versus displacement curves and examination of impacted aluminum syntactic foam plates. Results showed that the aluminum syntactic foam has better compression strength and energy absorption than conventional aluminum foams, but poorer than steel syntactic foam. In order to improve the energy absorption and low velocity impact resistance, Zhang et al. [30] fabricated the PU foam filled pyramidal lattice core sandwich panels and studied their quasi-static compression and low velocity impact properties. A synergistic effect was found based on the compression results. During the impact tests, the contact time between the impactor and the sandwich panels was shorter and the impact peak force of foam filled specimens was a little higher than that of unfilled specimens.

In this study, a mass dropper was used to impact the samples of foam and both auxetic and non-auxetic composites with predefined impacting energy. The impact process was analyzed and the relationships between impact contact force and compressive displacement as well as energy absorption versus compression strain were discussed. The deformation process and damage mechanism for foams and composites were also revealed. The research provides a better and fully understanding on the mechanical properties of multilayer orthogonal structural composite with auxetic effect.

2. Experimental

2.1. Samples

The samples used for drop-weight impact tests in this paper include the auxetic composite, non-auxetic composite and PU foam. The fabrications of these samples were according to the methods reported in the previous work [6]. As shown in Fig. 1, both auxetic and non-auxetic composites consist of two parts, namely the matrix and the reinforcements. The PU foam was adopted as the matrix material of composites due to its wide application, strong bonding property and quasi-zero Poisson's ratio (ZPR) under compression [32]. As one of the most widely used cushioning and packaging materials, PU foam could be produced easily and its rigidity could be designed by adjusting the ratio between polyols and isocyanates. In addition, PU foam with carbamate groups will have better bonding strength with the polyester made of carboxylate and ABS with organic links, which could guarantee good interfacial bonding among the three materials then facilitate the contraction of the reinforcement structure and obtention of NPR effect of auxetic composite under compression. As the matrix of composite, PU foam with ZPR property will also help composites achieve bigger NPR value than others with positive Poisson's ratio. The reinforcements of both composites include the light-weight high-strength polyester filaments in the x direction and the low-density high-stiffness ABS tubes in the y direction (Fig. 1). The polyester filaments and the ABS tubes are laid up alternately like wood pile.

For the auxetic composite, while the polyester filaments are arranged in the same way in all layers, the ABS tubes are arranged differently, in which a half-spacing shift exists between even layers and odd layers. Under compression, the NPR effect could be obtained due to the unique reinforcement structure arrangement and properties of constituent materials including PU, polyester and ABS as well as their interfaces as discussed below. The Poisson's ratio curve and the deformed state of the auxetic composite under quasi-static compression are shown in Fig. 2. It can be seen that the maximum NPR value of the auxetic composite is −0.105 at the compressive strain close to 50%. For the non-auxetic composite,

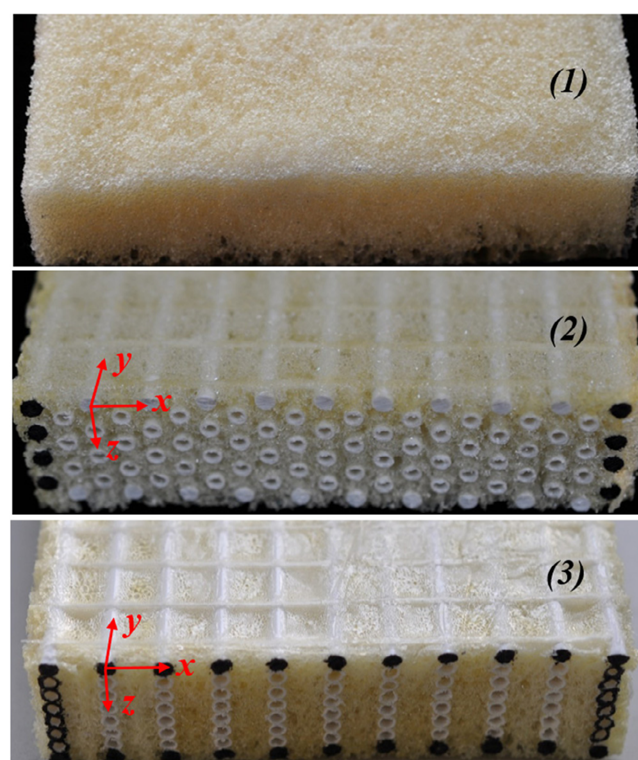

Fig. 1. Samples: (1) pure polyurethane foam; (2) auxetic composite; (3) non-auxetic composite.