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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 are drawing more attention in recent years due to their unique features and wide applications. Herein, a kind of novel multilayer orthogonal structural composite with auxetic effect is fabricated for energy absorption and impact resistance. Non-auxetic composite with the same raw materials but different structure is also fabricated for comparison. The difference of the structures leads to quite different mechanism of deformation and mechanical response. The quasi-static compressive properties and Poisson's ratio effect of composites were investigated previously. In this paper, the low-velocity drop-weight impact tests under the impact energy of 7.25 J and 29 J to 65.25 J were conducted to study their dynamic responses. The contact force versus compressive displacement and the energy absorbed versus vertical strain curves were plotted and analyzed. Results show that both composites are strain rate sensitive under low-velocity impact and they exhibit totally different mechanical responses due to different deformation and damage mechanism. And the auxetic composite has better energy absorption performance in medium strain range.

Keywords: multilayer orthogonal, negative Poisson's ratio, low-velocity impact, energy absorption

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 are widely used as packaging cushions and damping sectors due to their superior energy absorption capability. However, easy deformation, plastic collapse and fracture can easily cause fatigue even failure of the polymeric foams. To increase the mechanical properties of polymeric foams, parameters such as polymer type, foam density, open/closed cell content, cell size and cell shape are usually adjusted [2,3]. Another approach is to fill chopped fibers [4] or nano-sized particles [5] into foams to increase their stiffness and plateau stress. But the continuous and integral structures are seldom used as reinforcements for mechanical enhancement in case the big increase of foam weight.

In this study, multilayered orthogonal structure with light-weight and high mechanical properties materials are designed as the reinforcements to enhance the polyurethane foam without decreasing the strength to weight ratio. Meanwhile, the negative Poisson's ratio (NPR) effect is achieved due to the unique structure arrangement of the reinforcement. It will further enhance the mechanical performance of foams under compression and impact [6]. The word "auxetic" comes from Greek and it means that materials will expand transversely when pulled longitudinally or contract transversely when compressed longitudinally [7]. Here, the term "auxetic" is used to refer NPR. With the combination of structural reinforcement and matrix foam as well as the special auxetic effect, the new material is named as auxetic composite. Non-auxetic composite with the same raw materials as auxetic composite but different reinforcement structure is also designed and fabricated for comparison. These multilayered orthogonal structural reinforced composites could be regarded as a kind of reinforced foam and used individually or 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 research covering the design [9,10], fabrication [11,12] and characterization [13,14] of auxetic materials has been conducted. Research showed that the auxetic effect could evidently help increasing the mechanical properties of materials including shear resistance [15], indentation resistance [16,17] and fracture toughness [15,18]. While the enhancement of compression [17], shear stiffness [15,19], impact resistance [20] and indentation hardness[17,21] of cellular foams can lead to the improvement of its energy absorption. Mechanical testing [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 foams and the 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 380m/s to 600m/s was identified and attributed to the local densification of materials due to the NPR effect. Scarpa et al. also studied the quasi-static compressive behaviors [23] and dynamic crushing [14,24] of auxetic PU foams and conventional non-auxetic foams. The comparative results also showed the distinctive improvement of mechanical characteristics for auxetic foams including energy absorption.

In our previous study [6], the quasi-static compression and energy absorption properties of the pure polyurethane foam, auxetic composite and non-auxetic composite were investigated and compared. 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 and composites to investigate their impact protection and energy absorption capability. The quasi-static compressive and dynamic impact properties of foams and foam-cored sandwich panels have been studied by many researchers using experimental and numerical methods [28-31]. The low velocity impact response of rigid polyurethane foam at velocities from 2 m/s to 4 m/s was studied by V.P.W. Shim [28]. During impact, quantities like the impactor deceleration, velocity and displacement, and the energy dissipated were measured. The effects of impact velocity and impactor geometry on the energy absorption were studied. In reference [29], the impact behavior of aluminum syntactic foams was investigated using an instrumented drop tower. The failure mechanisms of foams were interpreted from impact load versus displacement curves and examination of impacted aluminum syntactic foam plates. The properties of the aluminum syntactic foam were compared to that of conventional aluminum foam and steel syntactic foam. 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, Guoqi Zhang et al. [30] fabricated the polyurethane foam filled pyramidal lattice core sandwich panels and studied their quasi-static compression and low velocity impact properties. A synergistic effect that the foam filled sandwich panels have better load carrying capacity than the sum of the unfilled specimens and the filling polyurethane foam was found based on the compression results. During the impact tests, the contact time between the impactor and the sandwich panels is shorter and the impact peak force of foam filled specimens is a little higher than that of unfilled specimens. Herein, a mass dropper is used to test the samples of foam and composites with predefined impacting energy. The impact process is analyzed and the relationship between impact contact force and compressive displacement, energy absorption versus compression strain is studied. This research provides a new and simple method for energy absorbers design.

2. Experimental

2.1 Samples

The samples used for drop-weight impact tests in this paper include the auxetic composite, non-auxetic composite and polyurethane foam. They were developed and tested under quasi-static compressive loading in our previous study [6]. As shown in Fig. 1, both composites consist of two parts, namely the matrix and the reinforcement. The closed-cell polyurethane (PU) foam was adopted as the matrix material of composites and it was made by self-developed formulation [6]. The main feature of this PU foam is quasi-zero Poisson's ratio (ZPR) when compressed [32]. As one of the most widely used cushioning and packaging materials, PU foam with ZPR characteristics will help the composites to exhibit more evident NPR phenomenon. The reinforcement 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.

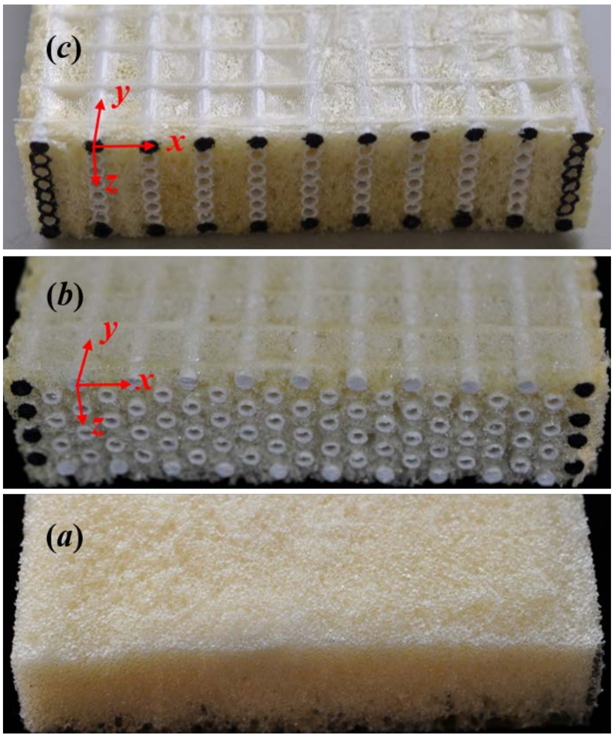


Figure 1 Samples: (a) pure polyurethane foam; (b) auxetic composite; (c) non-auxetic composite.

For auxetic composites, the polyester filaments are arranged in the same way in all layers. While the ABS tubes are arranged differently, a half-spacing shift exists between even layers and odd layers. When compressed, the PU foam will be easily deformed due to its very low compressive modulus (0.45 MPa). While the interface properties between the foam and reinforcements would directly influence how the filaments and tubes behave. Single polyester filament and single ABS tube pull-out tests from the foam block have been conducted as shown in Fig. 2 [33]. Results show that the shear modulus between the filaments and foam (47.29 MPa) plus the shear modulus between the tubes and foam (2.05 MPa) is higher than the compressive modulus of foam (0.45 MPa) and much lower than the tensile modulus of polyester filament (12.77GPa) and ABS tube (1.63 GPa). Hence, the polyester filaments with lower flexural rigidity (51.08 N·mm^2) than that of the ABS tubes (9.21×10^3 N·mm^2) will be firstly bent under the action of ABS tubes and they will not be stretched in the x direction due to very high elastic modulus. Therefore, the reinforcement will become contracted in the x direction during the deformation process of three materials and at the same time the NPR effect of the auxetic composite could be achieved. The Poisson's ratio (PR) curve and the deformed state of the auxetic composite under quasi-static compression is shown in Fig. 3. The maximum PR value for the auxetic composite is -0.105 at the compressive strain close to 50 %. For non-auxetic composites, the materials and volume fraction of reinforcements are the same with that of the auxetic composite. But the reinforcement structure is different. The filaments and the tubes which are separately arranged in their own layers are laid in the same parallel way and no shifting exists. Viewing from the z direction, ABS tubes are aligned in a vertical linear pattern and they will bear most of the compressive load. So buckling would easily occur and high initial stiffness could be observed for non-auxetic composite under compression.

The diameter of the ABS tube is 3 mm and the linear density of polyester filaments is 1670 dtex (456f). The density of pure foam is 0.10 g/cm^3, while the auxetic composite and non-auxetic composite have the same density of 0.27 g/cm^3. The dimension of the samples is 100 mm (length) × 98 mm (depth) × 28 mm (thickness).

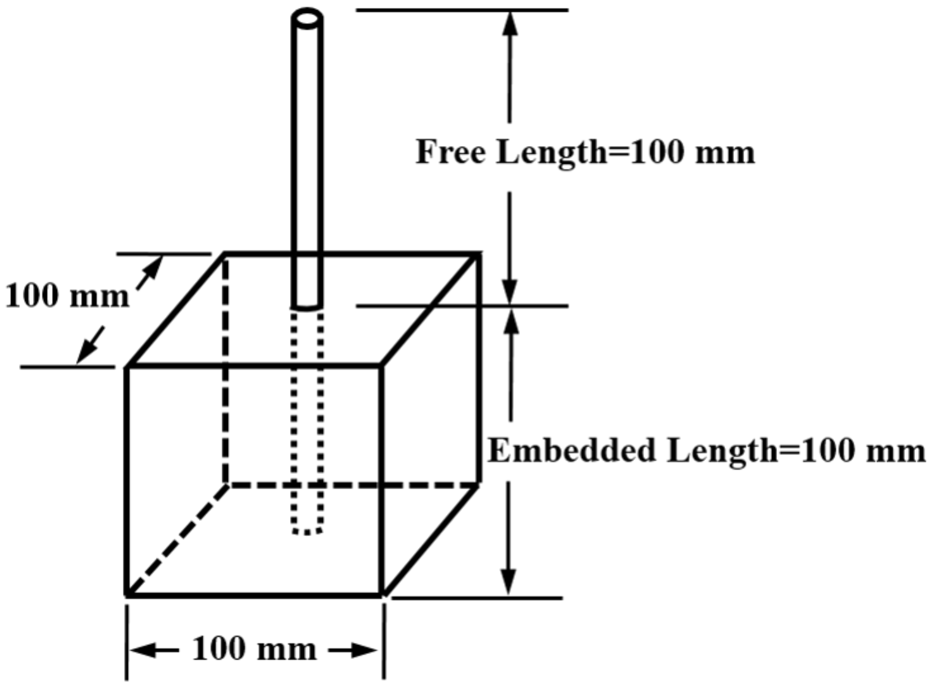


Figure 2 Schematic illustration for single filament and single tube pull-out tests from the foam block

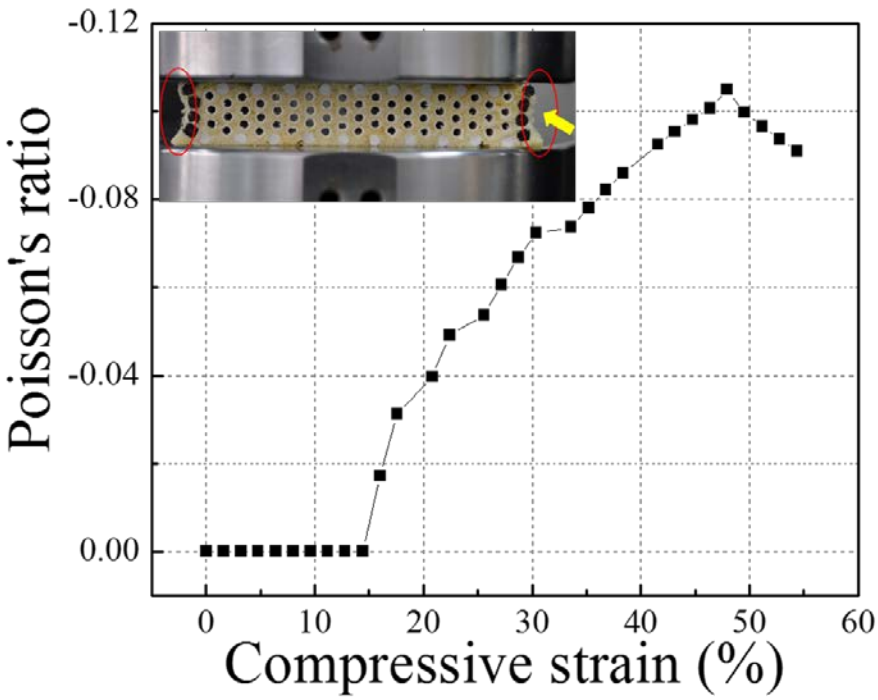


Figure 3 The Poisson's ratio curve and the deformed state of auxetic composite under

quasi-static compression

2.2 Low-velocity impact test

The dynamic compression tests were conducted on a drop-weight impact test system INSTRON 9250 (Instron® Worldwide Headquarters, Massachusetts, USA) in an environment of 25°C and 65% relative humidity. As shown in Fig. 4, the weighted tup was released and dropped vertically onto the sample which was fixed on the anvil during the impact. The force sensor installed above the impactor captured the signals and recorded the contact forces. The weight of the striker was 14.5 kg and the size of the impactor is 80 mm × 40 mm. Three specimens were tested and all the curves presented are the mean of three groups of testing results.

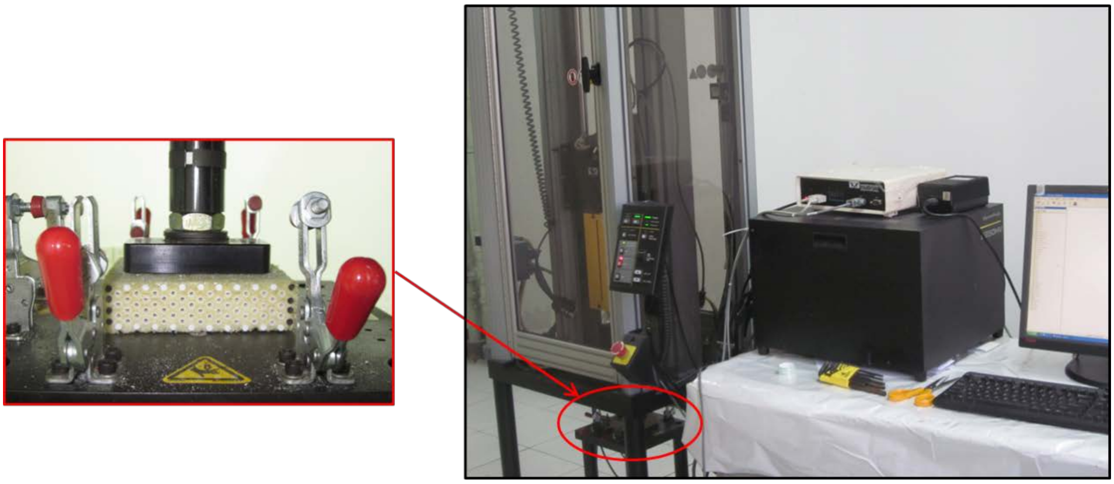
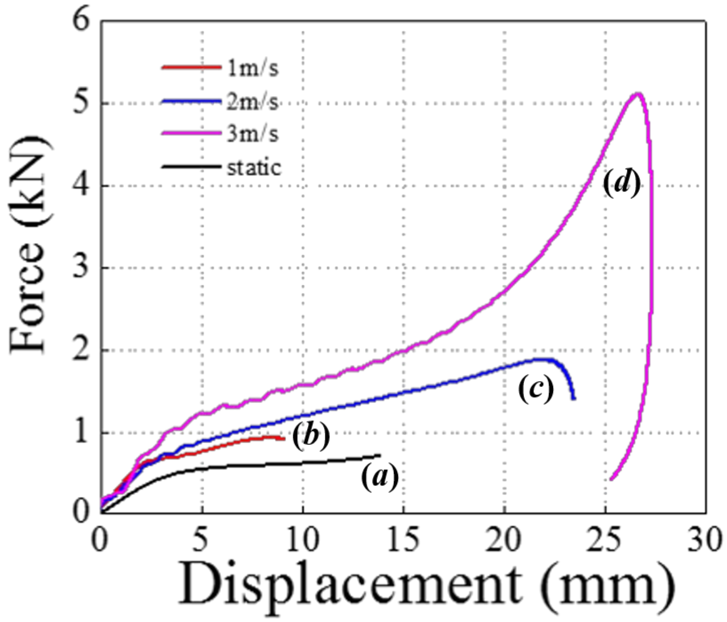


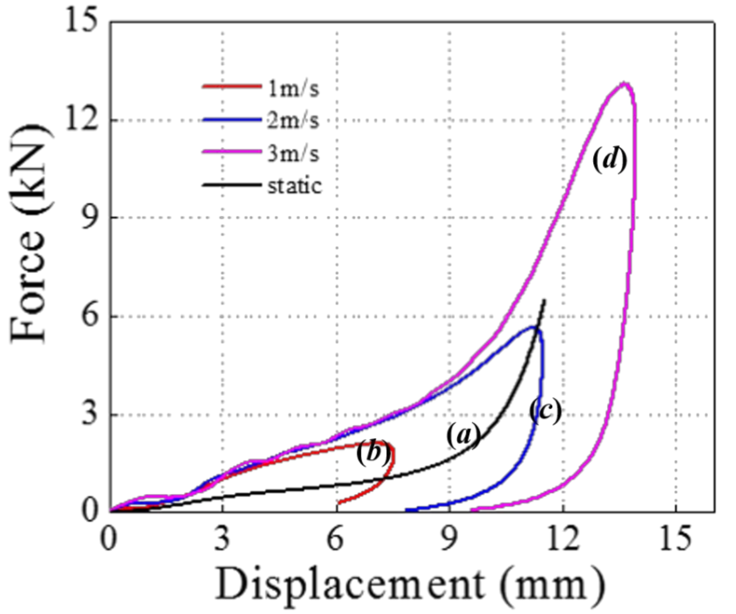
Figure 4 Picture of Instron® 9250 impact tester and samples fixed on the anvil

3. Results and discussion

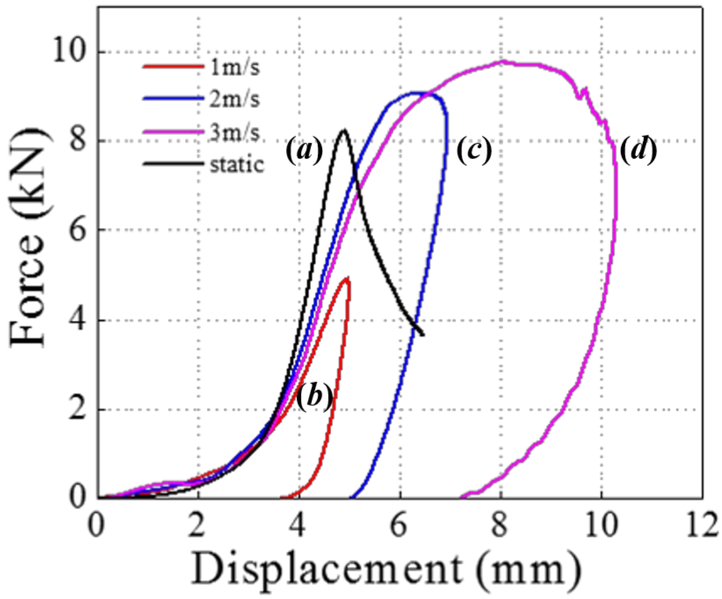
3.1 Force-displacement curves



(1) PU foam



(2) Auxetic Composite



(3) Non-auxetic Composite

Figure 5 Comparison of force-displacement curves for different materials: (1) PU foam, (2) Auxetic Composite, (3) Non-auxetic Composite under different compression velocities: (a) static, (b) 1 m/s, (c) 2 m/s, (d) 3 m/s

As shown in Fig. 5, the pure PU foam, auxetic composite and non-auxetic composite all have different mechanical responses under the quasi-static compression and low-velocity impact from 1 m/s, 2 m/s to 3 m/s. The values of impact energy according to three different impact velocities are 7.25 J, 29 J and 65.25 J, respectively. The values of peak contact force, maximum displacement and total energy absorbed during impact are listed in Table 1. The numbers in brackets are standard deviations for three groups of results. For PU foam, the initial stiffness is similar under the impact velocities from 1 m/s to 3 m/s but a little higher than that under quasi-static compression. The plateau-stage in the force versus displacement (F-D) curves under low-velocity impact is less obvious compared to the static compressive response. For auxetic composites, the F-D curves under low-velocity impact show much bigger stiffness and obvious rebounding process compared to the static situation. The contact force has similar rising trends with the increase of displacement under the velocity from 1 m/s to 3 m/s. The F-D curves of non-auxetic composites also have similar climbing trends under four different compression velocities. All the contact forces rise rapidly with the increment of displacement and pretty similar initial stiffness could be found in four F-D curves.

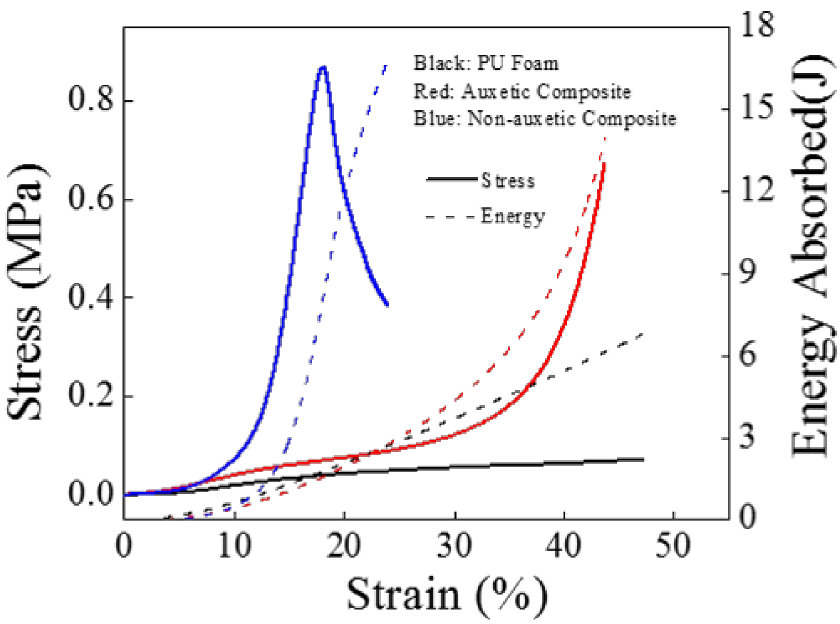
The corresponding strain rates of pure foam under the velocity of 1 m/s, 2 m/s and 3 m/s are measured to be 35.63 s^{-1}, 68.99 s^{-1} and 105.69 s^{-1}, respectively. The strain rates of auxetic composite are 43.31 s^{-1}, 76.57 s^{-1} and 111.48 s^{-1}. The strain rates of non-auxetic composite are 34.23 s^{-1}, 68.94 s^{-1} and 105.85 s^{-1}, accordingly. The difference of mechanical responses for PU foam, auxetic composite and non-auxetic composite under various impact velocities proves that they are all strain-rate sensitive materials in above strain rate range. The peak force, maximum displacement and energy absorption all have big difference under various strain rates.

Table. 1 Dynamic compressive results for foam and composites

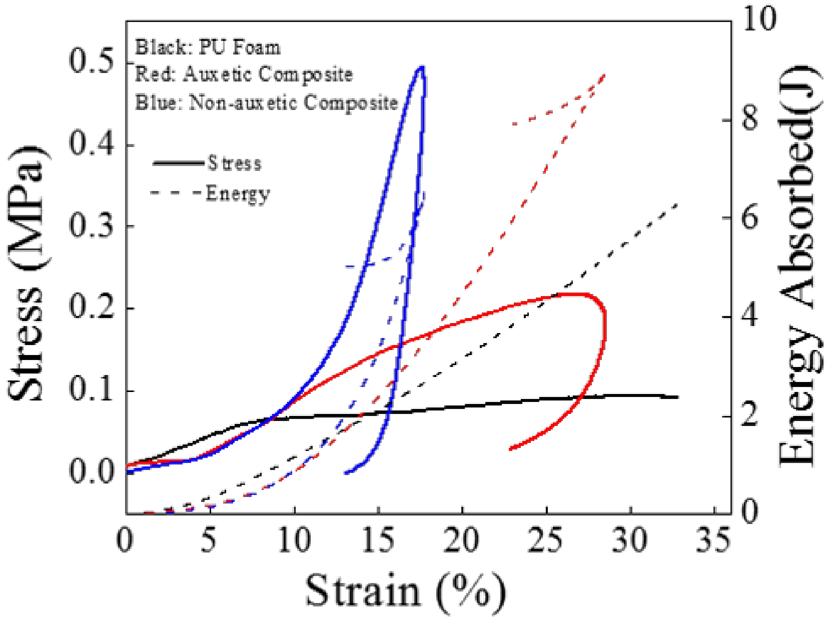
Material	Impact Velocity (m/s)	Peak Contact Force (kN)	Maximum Displacement (mm)	Total Energy Absorbed (J)
Foam	1	0.93(0.02)	9.09(0.44)	6.29(0.21)
	2	1.88(0.18)	23.49(2.08)	29.01(2.37)
	3	5.11(0.56)	27.37(1.87)	57.26(0.25)
Auxetic Composite	1	2.10(0.06)	7.53(0.22)	7.92(0.42)
	2	5.67(0.36)	11.48(0.64)	24.40(0.20)
	3	13.11(0.71)	13.94(0.75)	50.51(0.18)

	1	4.92(0.41)	5.01(0.30)	5.04(0.31)
Non-auxetic Composite	2	9.08(0.52)	6.96(0.42)	19.16(0.34)
	3	9.76(0.51)	10.33(0.44)	49.44(0.57)

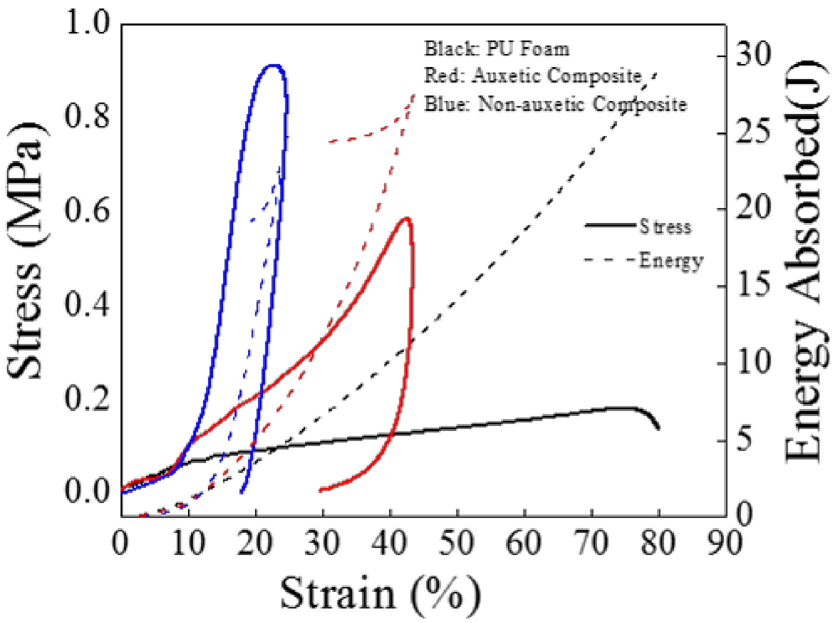
3.2 Stress-strain and energy absorption



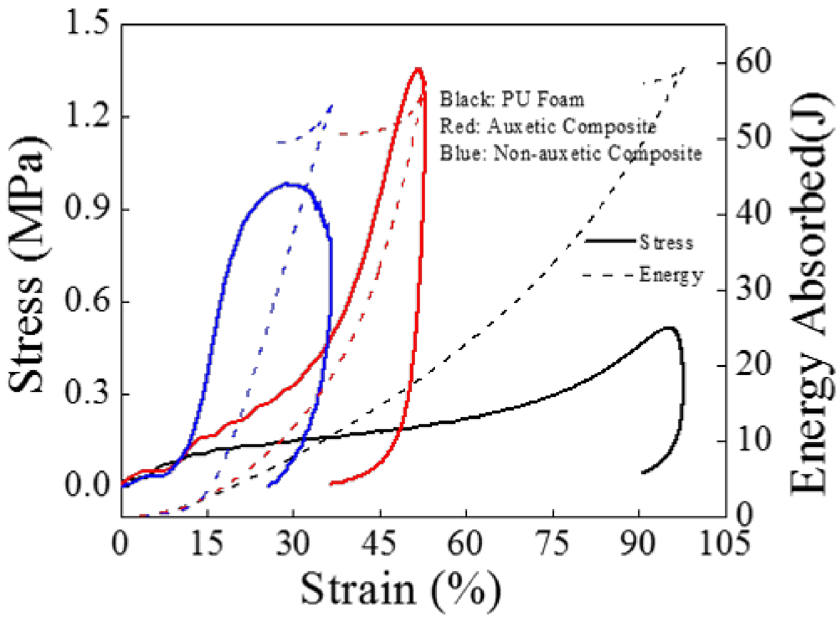
(1) Quasi-static


Black: PU Foam
Red: Auxetic Composite
Blue: Non-auxetic Composite
Stress
Energy
Stress (MPa)
Energy Absorbed(J)
Strain (%)

(2) 1m/s


Black: PU Foam
Red: Auxetic Composite
Blue: Non-auxetic Composite
Stress
Energy
Stress (MPa)
Energy Absorbed(J)
Strain (%)

(3) 2m/s



(4) 3m/s

Figure 6 Contact stress and energy absorbed versus compressive strain curves of three materials under different velocities: (1) Quasi-static, (2) 1 m/s, (3) 2 m/s, (4) 3 m/s

The compressive stress versus compressive strain curves and energy absorbed versus compressive strain curves for PU foam, auxetic composite and non-auxetic composite under different compressive velocities are shown in Fig. 6. The same trends of stress versus strain curves and energy absorption curves can be found for three kinds of materials. As shown in Fig. 6 (1), under static compression, the stress of non-auxetic composite rises sharply to 0.87 MPa till the final collapse of material occurs at the strain of 18 % and the corresponding energy absorbed is 8.08 J, but it will continue absorbing energy to the end of compression. Very different from the mechanical performance of the non-auxetic composite, the PU foam gradually absorbs 6.79 J energy from elastic to plateau region and then to densification stage. The mechanical properties of auxetic composite including initial modulus, strain range and failure stress locates between those of the PU foam and non-auxetic composite. The auxetic composite exhibits strain hardening effect and it gradually absorbs 14.03 J energy to the end of compression. So the auxetic composite behaves like functionally graded material. It is much stiffer than foam but softer than non-auxetic composite.

The compressive failure strength and the corresponding compressive strain of three materials could also be observed in Fig. 6. Under the velocity of 1m/s, the maximum compressive stress of the foam, auxetic composite and non-auxetic composite are 0.09 MPa, 0.22 MPa and 0.49 MPa with the corresponding strain of 29.91 %, 26.99 % and 17.21 % respectively. At velocity of 2 m/s, the compressive stress of PU foam increases slowly with increasing of strain due to the large deformation, the maximum stress is 0.18 MPa at the strain of 74.33 %. Different from the pure foam, the compressive stress of the non-auxetic composite rises rapidly with the increase of compressive strain, and the peak stress reaches 0.91 MPa with the small strain of 22.36 %. The stress-strain curve of the auxetic composite locates between that of two other materials. The maximum compressive stress of auxetic composite is 0.59 MPa at a compression strain of 42.52 %. Under velocity of 3 m/s, the non-auxetic composite is out of stability at the small strain of 28.56 % and its compressive stress reaches 0.98 MPa. While auxetic composite exhibits larger deformation with the maximum stress of 1.36 MPa at the strain of 51.54 %. The pure foam shows largest deformation among them with the strain of 95.35 % and its maximum stress is 0.52 MPa.

For energy absorption, three materials show totally different energy absorption properties under the same impact velocities. The pure PU foam exhibits a slow increase of energy absorption with the increase of compressive strain owing to its low stiffness and large deformation. The energy absorbed by the non-auxetic composite rises quickly with the increase of compression strain due to its high stiffness and early failure at small strain. The energy curves of the auxetic composite material locate between those of two others. From Fig. 6 (2) (3) (4), it can be found that the auxetic composite absorbs more energy than the pure foam in the region of strain 12.06 % to 28.56 % under 1 m/s impact, strain 11.73 % to 43.54 % under 2 m/s impact and strain 14.23 % to 52.86 % under 3 m/s impact, which indicates that the auxetic composite is better energy absorber than PU foam when used in medium strain range under low velocity impact. Compared with the foam and auxetic-composite, the non-auxetic composite absorbs more energy in a small strain range, but the contact stress is very high. While being used as packaging material, the peak stress is the primary concern and the maximum tolerance stress of the protected items should be considered. Too high peak stress or load will cause damage to goods in packaging. Therefore, the non-auxetic composite is less suitable for being applied as energy absorber.

3.3 Mechanism of deformation and damage

For PU foams under the static compression, the major mechanisms of deformation and damage include bending, buckling and crumpling [2]. The first stage of the stress-strain curve corresponds to the compression and bending of cell ribs and walls until they get buckled. In the second stage, the ribs and walls keep bent and there is a minor increase of compressive stress. In the third stage, the buckled ribs become crumpling and the compaction of foams happens. After the inspection of impacted foam samples, different failure modes could be identified for different impact velocities. It was found that the foam blocks almost completely recover to their original dimension and no pronounced defects were observed on the surface of the samples after the impact at the velocity of 1 m/s. However, after the impact under the velocity 2 m/s and 3 m/s, as shown in Fig. 7, fracture occurred in the foam along the edge of the impactor, which is caused by the tearing of cell walls. Although this failure crack would make the foam absorb more energy during this impact process, yet this destructive failure will prevent the samples from serving as multiply-impact protection materials.

For auxetic and non-auxetic composites, the deformation and damage mechanism under static compression have been recorded and analyzed in reference [6]. During compressing non-auxetic composites, the ABS tubes play a major role in bearing and transmitting load, which results in a high modulus and a sudden collapse of whole materials. So the non-auxetic composite gets permanent damage and absorbs less energy after the failure strength. The compression mechanism of auxetic composite is the combination of two other materials. The foam filling in between each layer of auxetic reinforcement firstly deforms before the ABS tubes contact with the polyester yarns. Then the composite gradually shrinks in horizontal direction due to the bending of polyester yarns under the compression of ABS tubes. When it moves to the densification stage, the ABS tubes start to form in a vertical line like the structure of non-auxetic reinforcement. The auxetic composite becomes stiff meanwhile the ABS tubes bear most of the compressive load. After the drop-weight impact under the velocity of 1 m/s to 3 m/s, both of the composite samples almost return to their original states without evident injury on the surface of the samples. This demonstrates the priority of integral structural reinforcement in avoiding the easy fracture of samples. Nevertheless, some internal damage must exist in the composites like the bending and collapsing of foam cells, debonding between the foam and reinforcement, the plastic deformation of ABS tubes and the breakage of polyester filaments. Further study will be focused on building meso-scale finite element models and simulating the impact process of different materials under various impact velocities. Then the deformation process and damage mechanism could be visualized and revealed.

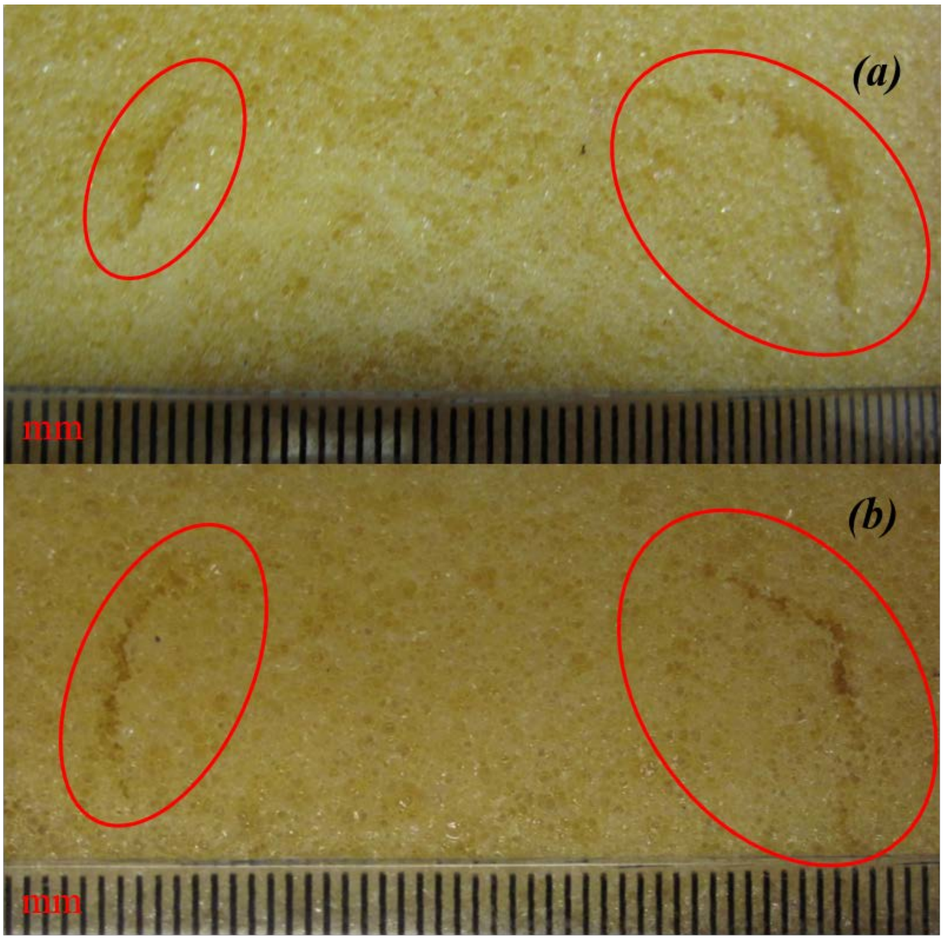


Figure 7 Fracture occurred in the PU foam after the impact velocity of: (a) 2 m/s, (b) 3 m/s

4. Conclusion

In this study, the dynamic impact compression tests of pure polyurethane foam, auxetic composite and non-auxetic composite under the impact energy of 7.25 J and 29 J to 65.25 J were conducted and analyzed. The relationship between impact contact force and compressive displacement, impact stress as well energy absorbed versus compression strain were studied. Results showed that all of the three materials are strain rate sensitive from 34.23 s^{-1} to 111.48 s^{-1}. But the trends for the same material exhibited under different compressive velocities are pretty similar. The PU foam behaves like flexible materials with low compressive modulus and plateau stress as well large deformation. The non-auxetic composite behaves like stiff material with high failure strength and small deformation. The auxetic composite behaves like functionally graded material with its mechanical properties including initial modulus, strain range and failure stress locating in between that of two others. The deformation and damage mechanism of foams and composites were also investigated. Evident fracture on the surface of foams could be observed when the impact energy is above 29 J. Plastic deformation and potential internal damage might occur in the auxetic and non-auxetic composites. This paper provides a simple way to produce light-weight and continuously reinforced energy absorber which could be used for impact protection. Details will be found by building meso-scale finite element models and simulating the impact process of materials under different load conditions in the future.

Acknowledgments

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