Three-dimensional textile structural composites with negative Poisson's ratio

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Abstract

In this study, two types of 3D auxetic textile structural composites, Composite A and Composite B, were developed for energy absorption. Both of them were made by dip-coating 3D auxetic textile reinforcements consisting of three yarn systems with silicone based polymer. The difference of two composites comes from the arrangement of the warp yarns in their reinforcement structure which leads to different deformation and mechanical responses. The quasi-static compressive tests were conducted to study their mechanical properties and deformation mechanism. Results show that Composite B exhibits higher initial stiffness due to the close contact of warp yarns between each layer, while the composite A shows higher values of negative Poisson's ratio owing to the easy bending of weft yarns and early contraction of the whole structure. Results also show that Composite B needs lower compressive force to absorb the same energy absorption than Composite A, hence it is better suitable for applying as protective materials.

1. Introduction

Composites with negative Poison's ratio (NPR) have been receiving more attention in recent decades. Known as auxetic composites, this type of composites has high application potentials in different areas due to their unique features and unusual properties [1]. Researches proved that the introduction of NPR could evidently enhance the mechanical properties of conventional materials like compression [2], shear resistance [3,4], indentation hardness [2,5] and fracture toughness [3,6]. And the enhancement of these properties will lead to the improvement of materials' energy absorption [7-10].

There are two approaches that have been reported to fabricate auxetic composites [11]. The first one is to produce the fiber-reinforced laminates using non-auxetic materials [11-14]. The second approach is to use auxetics as reinforcements [15,16]. Herein, the second method was adopted. 3D auxetic composites were made by dip-coating two types of textile structures with silicone based polymer [17]. Their mechanical properties under quasi-static compression including NPR effect and energy absorption capacities were studied and compared. The produced composites could be used as packaging and protective materials or served as the core parts of sandwich materials for energy absorption. The multi-voids structures make the composites to hold good air permeability in use.

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2. Experimental

2.1 Samples

Both of the composite materials were made by dip-coating 3D auxetic textile structural reinforcements which had been developed in our previous studies [18,19] with silicone based polymer [17]. The reinforcements were fabricated with 13-layer 3D auxetic textile structures consisting of warp yarns, weft yarns and stitch yarns. They were firstly dispersed into isopropanol at ambient temperature, and then dip-coated with the polymer liquid and dried at 60℃ for hours to get the composite samples. The difference of two composites comes from the arrangement of the warp yarns in their reinforcement structures, where a half-yarn spacing shift of the warp yarns exists between even layers and odd layers in composite A (Fig. 1 (a)), and in composite B, the warp yarns is arranged in a vertical form (Fig. 1 (b)). In both of the structures, three groups of yarns are orthogonal to each other and the stitch yarns serve as the binding yarns to increase the structural stability and avoid delamination. Polyamide braided yarn, cotton braided yarn and polyester filaments were selected as the materials of warp yarns, weft yarns and stitch yarns, respectively. Among them, polyester yarn is the thinnest and lightest then it will not increase the weight of composites too much. And in comparison to polyamide braided yarn, cotton braided yarn is thinner and has lower bending stiffness as well smaller Young's modulus. All of the three materials have low tensile deformation. So they will not be stretched to a big strain under load.

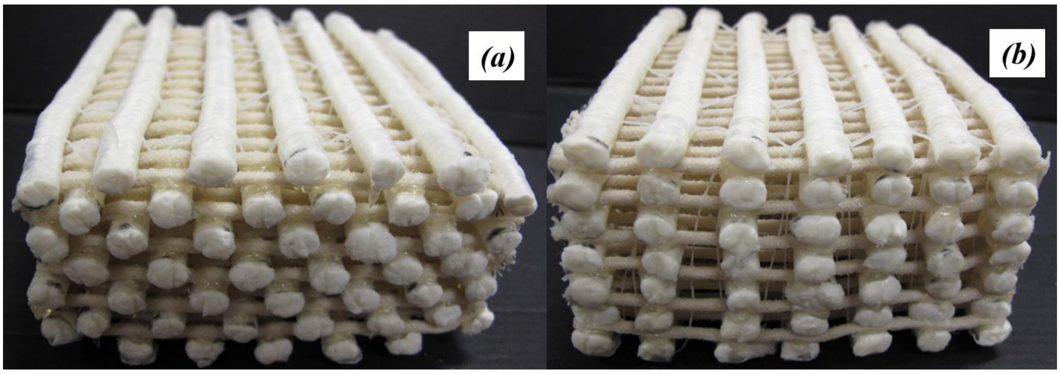

Figure 1. Pictures of samples: (a) Composite A; (b) Composite B.

2.2 Quasi-static compression test

To assess the NPR effect and mechanical behavior of the auxetic composites produced, the quasi-static compressive tests were performed using an Instron 5566 testing machine installed with two 150 mm compression circular plates. The tests were carried out at laboratory temperature (25±3 ℃) and relative humidity (60±5%). The specimen dimensions and densities of Composite A and B were 102.8mm×100.2mm×52.0mm and 102.0mm×98.4mm×53.6mm, 374.5 kg/m^3 and 391.5 kg/m^3, respectively. The compression rate was 5 mm/min. To measure the Poisson's ratio of specimens, a camera with a timer shot function placed at a distance of 50 cm from the specimens was used to synchronously record the lateral and vertical displacement of the specimen. Four points were marked with black color at top, bottom, left and right position of each sample to facilitate recording deformation information during compression tests. The initial distance in vertical and horizontal direction was first measured before compression. During the compression test, photos were taken for each specimen with a time interval of 10 seconds. The distances of the marks in the photos were measured by a screen ruler to calculate the strain of composites in the vertical and lateral directions. Three samples were tested for each composite and the mean value was used to calculate the compressive strain and lateral strain. After the compressive strain ε_z and lateral strain ε_x were obtained, the Poisson's ratio of the tested sample ν was calculated from Eq. (1).

$$\nu = -\varepsilon_x / \varepsilon_z \quad (1)$$

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3. Results and discussion

3.1 Auxetic effect

As shown in Fig. 2, evident NPR effect was found for both composites under quasi-compression. During the compression process, Composite A shows higher NPR value than Composite B from the beginning of compression. And its peak NPR value reaches -0.186, a little higher than that of Composite B, which is -0.166. Even though both composites exhibit NPR effect, their mechanisms of producing NPR are different owing to the difference of yarn arrangement in the 3D textile structure. When compressed, Composite A contracts in the lateral direction due to the half-yarn spacing shift arrangement of warp yarns and the easy bending of weft yarns (Fig. 3(a)). And it will shrink further till the total compaction of the whole material. While the warp yarns in Composite B bear most of the load because they are aligned in a vertical line and the sample gradually buckles towards left or right side till the final densification (Fig. 3(b)). Therefore, both composites shrink in the horizontal direction under compression to have NPR, but the reasons to cause the NPR effect are different. And the compaction phenomenon will help composites to better resist the impact load.

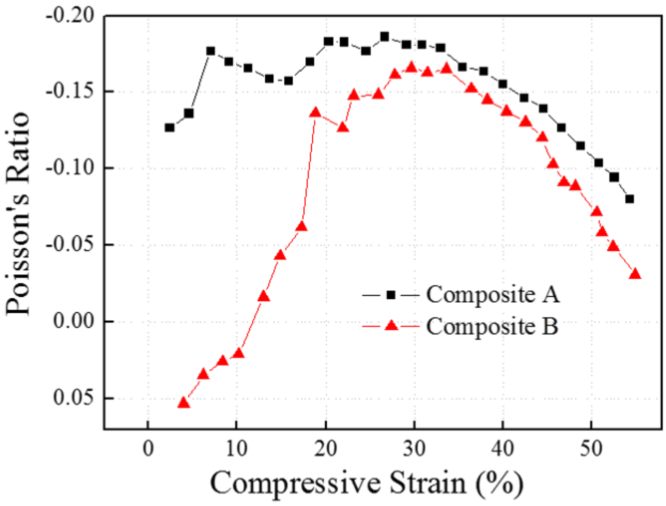

Figure 2. Poisson’s ratio-compressive strain curves of composites.

Figure 3. The final states of composites after compression: (a) Composite A; (b) Composite B.

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3.2 The compressive force versus displacement curves

As shown in Fig. 4, similar variation trends of the compressive force versus displacement curves could be observed for Composite A and Composite B. Both of the compressive forces climb slowly before the displacement of 15 mm. After that, the compressive forces increase quickly to the maximum values. The difference is that Composite B has higher initial stiffness and compressive force than Composite A at the first compression stage in the displacement range of 0 to 22 mm. But in the second stage afterwards, the compressive force of Composite B becomes lower. The reason is still caused by the difference of reinforcement structures and deformation mechanisms. The half-yarn spacing shift arrangement leaves multiple void spaces in Composite A, so the weft yarns will firstly bend and deform under the compressive load due to their lower bending stiffness. Thus the initial stiffness of Composite A is smaller. Also Composite A starts to shrink firstly and it will arrive at densification earlier than Composite B so that the Composite A shows higher compressive force in the latter part. Meanwhile, both composites show the strain hardening effects because of the decreasing of reinforcement gaps and the compaction of whole structures.

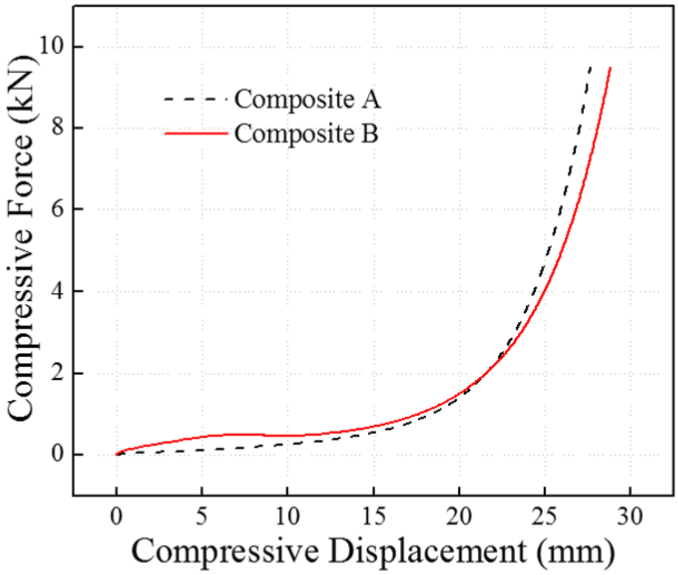

Figure 4. Compressive force-displacement curves of composites.

3.3 The compressive force versus energy absorbed curves

As shown in Fig. 5, Composite B can absorb more energy than Composite A when the compression forces are the same. Or in other words, Composite B needs lower compressive force to absorb the same energy absorption except the initial small region of curves. When using as protection materials, the contact force is a key factor under concern and the maximum tolerance load of the protected items should be considered. Too high contact force will cause the damage of goods in packaging. In this regard, Composite B is better suitable for applying as impact protectors and energy absorbers.

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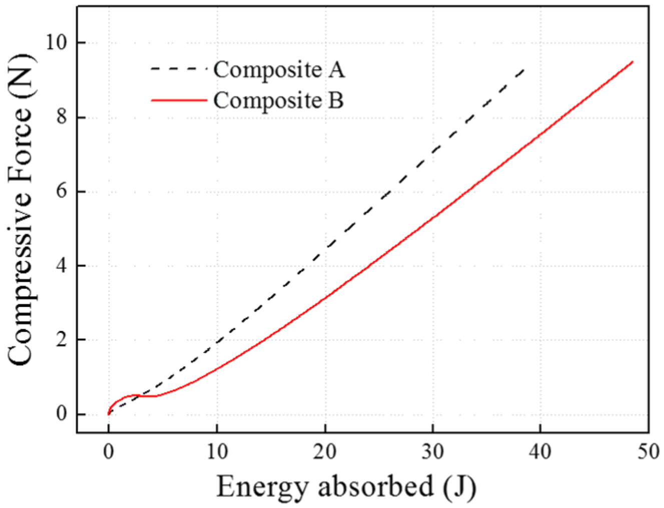

Figure 5. Compressive force-energy absorbed curves of composites.

4. Conclusions

Two types of auxetic composites were fabricated by dip-coating 3D textile structural reinforcements with silicone based polymer. Their compressive behaviors and NPR effect under quasi-static compression were analyzed and compared. Results show that two composites have similar variation trends in the compressive force versus displacement curves, but distinct NPR effect under quasi-compression. The NPR effect and final compaction phenomenon of composites will help them to better resist the impact load. And Composite B needs lower compressive force to absorb the same energy absorption than Composite A, hence it is better suitable for applying as protective materials.

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References:

[1] YP Liu, H Hu. A review on auxetic structures and polymeric materials. *Scientific Research and Essays*, 5 (10):1052-1063, 2010.
[2] KL Alderson, AF Fitzgerald, KE Evans. The strain dependent indentation resilience of auxetic microporous polyethylene. *Journal of Materials Science*, 35(16):4039-4047, 2000.
[3] JB Choi, RS Lakes. Nonlinear properties of polymer cellular materials with a negative Poisson's ratio, *Journal of Materials Science*, 27(19):4678-4684, 1992.
[4] V Salit, T Weller. On the feasibility of introducing auxetic behavior into thin-walled structures. *Acta Materialia*, 57 (1):125-135, 2009.
[5] KL Alderson, AP Pickles, PJ Neale, KE Evans. Auxetic polyethylene: the effect of a negative Poisson's ratio on hardness. *Acta Metallurgica et Materialia*, 42(7):2261-6, 1994.
[6] JB Choi, RS Lakes. Fracture toughness of re-entrant foam materials with a negative Poisson's ratio: experiment and analysis. *International Journal of Fracture*, 80(1):73-83, 1996.
[7] F Scarpa, P Pastorino, A Garelli, S Patsias, M Ruzzene. Auxetic compliant flexible PU foams: static and dynamic properties. *Physica Status Solidi (b)*, 242(3):681-694, 2005.
[8] F Scarpa, JA Giacomin, A Bezazi, WA Bullough. Dynamic behavior and damping capacity of

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auxetic foam pads. *Proceedings of SPIE, San Diego CA, USA,* Februrary 26 2006.
[9] F Scarpa, LG Ciffo, JR Yates. Dynamic properties of high structural integrity auxetic open cell foam. *Smart Materials and Structures,* 13(1):49-56, 2003.
[10] A Bezazi, F Scarpa. Mechanical behaviour of conventional and negative Poisson’s ratio thermoplastic polyurethane foams under compressive cyclic loading. *International Journal of Fatigue,* 29(5):922-930, 2007.
[11] KL Alderson, VR Simkins, VL Coenen, PJ Davies, A Alderson, KE Evans. How to make auxetic fibre reinforced composites. *Physica Status Solidi (b),* 242(3):509-518, 2005.
[12] CT Herakovich. Composite laminates with negative through-the-thickness Poisson's ratios. *Journal of Composite Materials*, 18(5):447-455,1984.
[13] HL Yeh, HY Yeh, RG Zhang. A Study of negative Poisson's ratio in randomly oriented quasi-Isotropic composite laminates. *Journal of Composite Materials,* 33(19):1843-1857, 1999.
[14] KE Evans, JP Donoghue, KL Alderson. The design, matching and manufacture of auxetic carbon fibre laminates. *Journal of Composite Materials,* 38(2):95-106, 2004.
[15] KL Alderson, RS Webber, AP Kettle, KE Evans. A Novel fabrication route for auxetic polyethylene. Part 1. Processing and microstructure. *Polymer Engineering and Science,* 46(5):568-78, 2005.
[16] W Miller, PB Hook, CW Smith. The manufacture and characterisation of a novel, low modulus, negative Poisson’s ratio composite. *Composites Science and Technology,* 69(5): 651-655, 2009.
[17] K Xu, Y Tan, JH Xin, A novel impact hardening polymer with negative Poisson’s ratio for impact protection. *Materials today communications,* 5:50-59, 2015.
[18] ZY Ge, H Hu, Innovative three-dimensional fabric structure with negative Poisson’s ratio for composite reinforcement. *Textile Research Journal*, 83: 543-550, 2013.
[19] LL Jiang, BH Gu, H Hu, Auxetic composite made with multilayer orthogonal structural reinforcement. *Composite structures,* 135: 23-29, 2016.

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