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Development of novel auxetic structures based on braided composites

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ABSTRACT

Auxetic materials are a class of materials that expand transversely when stretched longitudinally. Recently, auxetic materials are gaining special interest in the technical sectors mainly due to their attractive mechanical behavior. This paper reports, for the first time, the development of auxetic structures from composite materials and the characterization of their auxetic as well as mechanical properties. Five different auxetic structures were developed varying their structural angle using core reinforced braided composite rods, containing glass fibers for axial reinforcement, polyester filaments for braided structure and epoxy resin as the matrix. Auxetic behavior of these structures was studied in a tensile testing machine using an image-based tracking method. Additionally, an analytical model was used to calculate Poisson's ratio of these structures. According to experimental and analytical results, auxetic behavior and tensile characteristics of these structures were strongly dependant on their initial geometric configuration (i.e. structural angle). These novel auxetic structures exhibited Poisson's ratio in the range of −0.30 to −5.20.

1. Introduction

Poisson's ratio of any material is defined as the negative ratio of transverse strain to axial strain in the direction of loading (longitudinal strain) [1]. In general, materials have positive Poisson's ratio i.e. stretching in one direction (axial) results in reduced dimension in the other direction (transverse); but in auxetic materials the phenomena is just the opposite i.e. stretching in one direction results in widening in another direction (Fig. 1). Therefore, auxetic materials possess negative Poisson's ratio [2,3–7]. Till now, wide varieties of auxetic materials and structures have been discovered and manufactured both at micro and macroscales. For anisotropic materials, the values of Poisson's ratio can vary in wider range as compared to those of isotropic materials. The variation in the Poisson's ratio clearly depicts that the negative Poisson's ratios or auxetic effects are theoretically permissible [2].

Auxetic materials are of particular interest due to their counter-intuitive behavior under strain as well as improved properties such as enhanced strength, better acoustic behavior, improved fracture toughness, superior energy absorption, damping improvement, and indentation resistance [3,7–10]. Auxetic materials can be used in wide range of applications in apparel textiles (auxetic fibers, threads, functional fabrics, etc.), technical textiles (air filter, gasket, fishnet, fastener, shock absorber, sound absorber, etc.), aerospace industry (curved body parts, wing panel, and aircraft nose-cones), materials for protection (crash helmet, projectile-resistant materials, shin pad, glove, protective clothing, car bumpers, etc.), bio-medical industry (bandage, wound pressure pad, dental floss, artificial blood vessel, drug release devices, etc.), furniture and also in sensors and actuators (hydrophone, piezoelectric devices, miniaturized sensors) [1,2,11]. Different types of auxetic materials include auxetic bio-materials, auxetic foams, auxetic honeycombs, auxetic microporous polymers, auxetic structures, auxetic composites (fiber reinforced plastics or FRPs), etc. Auxetic composites can find potential applications in aerospace and automotive industry as well as in materials for protection, where non-auxetic composites with high specific strength and stiffness are currently used [1]. Presently, there exist two main approaches for producing auxetic composites: (1) angle ply method i.e. through stacking of composite laminates at specific angles and (2) fabrication of composites in which one or more phases are auxetic. In the angle ply approach, unidirectional carbon fiber/epoxy laminates are stacked in a certain sequence resulting in negative Poisson's ratio either in in-plane or through-thickness direction. Poisson's ratio achieved using this method lies in the range of −0.21 to −0.37. The angle of laminates in these composites is kept between ±15° and ±30°

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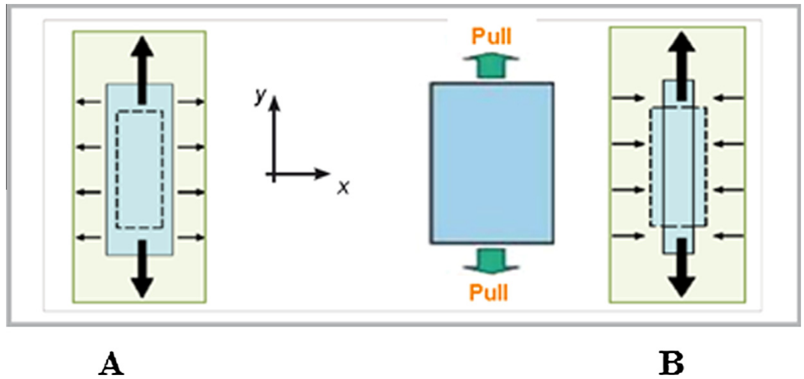

Fig. 1. Negative (auxetic) (A) and positive Poisson's ratio (B) behavior [3].

[9]. In the other approach, auxetic composites are manufactured using double helix yarns (DHY) [8,12,13]. Helical yarns are used to produce auxetic composites in two different ways. In one method, carbon double helix yarns are used to reinforce polyester matrix uni-directionally to produce composites with relatively high stiffness (4 GPa) and negative Poisson's ratio of −6.8 at 30% fiber volume fraction [8]. In the second method, helical yarns are woven in to a fabric and silicone rubber is used as the matrix to produce flexible composites with Poisson's ratio of −0.1 and low elastic modulus (5.8 MPa) [12].

Besides composites, the auxetic property can also be achieved with certain structural designs. In last few decades, dissimilar geometric structures and models exhibiting auxetic behavior have been proposed, studied and tested for their mechanical properties. The main auxetic structures reported are two dimensional (2D) and three dimensional (3D) re-entrant structures, rotating rigid/semi-rigid units, chiral structures, hard molecules, liquid crystalline polymers and microporous polymers. Some of these auxetic structures are presented in Fig. 2 [2,5,14–16].

Fiber reinforced composites have been applied widely in civil engineering applications because of their improved properties as compared to traditional materials (concrete and steel) or ceramic based composites [17–20]. These properties include high tenacity, low density, higher stiffness and strength, and easy handling. Composites are introduced into structural elements to improve their flexural resistance, shear strength, confinement, bending property, etc. [17]. Nowadays, research is being carried out to utilize composite materials in structural elements to improve their resistance against earthquake, blast or impact loads caused by explosions [21]. Capacity to absorb energy is one of the primary requirements for these applications and, in this sense, auxetic composites and structures may prove to be excellent materials. In this perspective, the present study reports the development of a novel auxetic structure made with braided composite rods (BCRs) for use as the strengthening element of civil engineering structures. The auxetic structural design considered in this research is "missing rib" (Fig. 2e) due to its simple design and ease of manufacturing using braided structures. According to the authoŕs knowledge, this type of auxetic structures has been developed for the first time at macro-scale using composite materials, based on the auxetic structural design previously reported. BCRs have been used in these structures as they offer several advantages over the other types of FRP rods such as simple and economical manufacturing process, tailorable mechanical properties and good bonding behavior with cementitious matrices [22–24]. These structures were subjected to tensile loading in a Universal Testing Machine and auxetic behavior (Poisson's ratio) was characterized by means of an image-based tracking method [25,26]. The influence of the structural angle on Poissońs ratio and tensile properties was thoroughly investigated. An analysis of the auxetic behavior was performed

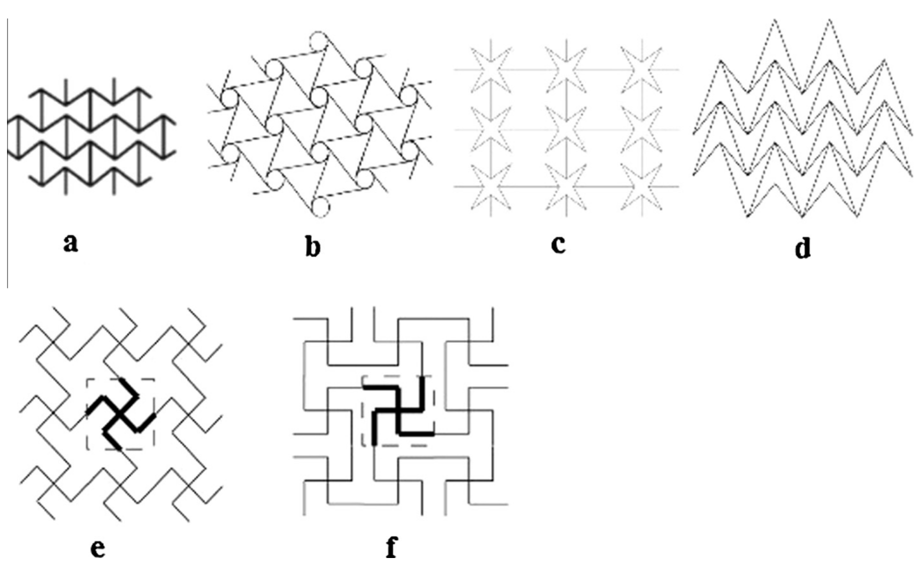

Fig. 2. Auxetic structures: (a) re-entrant honeycomb, (b) chiral honeycomb, (c) star-shaped honeycomb topology, (d) double arrow head honeycomb topology, and (e and f) missing rib [2,5,14–16].