DEVELOPMENT OF NOVEL AUXETIC STRUCTURES FROM BRAIDED COMPOSITE RODS FOR STRUCTURAL APPLICATIONS

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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 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. The auxetic structures were developed by varying their geometry using core reinforced braided composite rods containing glass fibres for axial reinforcement, polyester filaments for braided structure and epoxy resin as matrix. The auxetic behavior of the structures was studied in a tensile testing machine using an image-based tracking method. The auxetic behavior and the tensile characteristics of the structure depends strongly on the initial geometric configuration of the structures. The Poisson's ratio measured from the structures tested are in the range of -0.30 to -5.15.

1. Introduction

The Poisson's ratio of any material is defined as the negative ratio of the 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 opposite i.e. stretching in one direction results in widening in another direction (Figure 1). Therefore, auxetic materials possess negative Poisson's ratio [2–4]. Till now, wide varieties of auxetic materials and structures have been discovered and manufactured both at micro and macro scales [2].

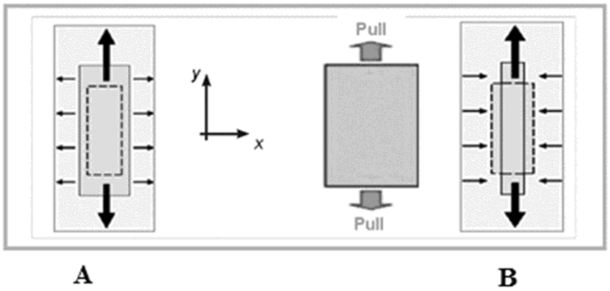

Figure 1. Negative (Auxetic) (A) and positive Poisson's ratio (B) behaviour [3]

Auxetic materials are of interest due to their counterintuitive behaviour under strain and improved properties such as enhanced strength, better acoustic behaviour, improved fracture toughness, superior energy absorption, damping improvement, and indentation resistance [3]. Auxetic materials can be used in wide range of applications like textiles, industry (air filters, gasket, fishnet, etc.), aerospace industry, protection (crash helmet, projectile-resistant, etc.), bio-medical (bandage, wound pressure pad, etc.), and in sensors and actuators [1, 2]. There are two major types of auxetic materials such as auxetic structures and auxetic composites. 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.

The auxetic property can also be achieved with certain structural designs. In last few decades, dissimilar geometric structures and models exhibiting auxetic behaviour 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 Figure 2 [2].

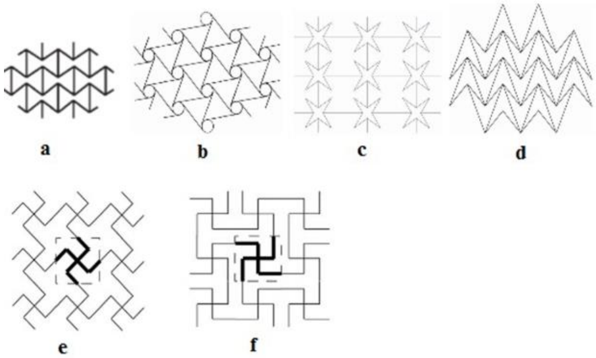

Figure 2. Auxetic structures: (a) re-entrant honeycomb, (b) chiral honeycomb, (c) star-shaped honeycomb topology, (d) double arrow head honeycomb topology, and (e & f) missing rib [2,4]

Fiber reinforced composites have been considered widely in civil engineering applications because of their improvised properties as compared to traditional materials (concrete and steel) or ceramic based composites [5]. 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. [5]. 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 [6]. 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 structure considered here is "missing rib" (Figure 2e) due to its simple design and ease of manufacturing using braided structures. According to the author´s knowledge, this type of auxetic structures has been developed for the first time in the 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 other types of FRP rods such as simple and economical manufacturing process, tailorable mechanical properties and good bonding behaviour with cementitious matrices [7-9]. These structures were subjected to tensile loading in a Universal Testing Machine and auxetic behaviour (Poisson's ratio) was characterized by means of an image-based tracking method [10, 11]. The influence of structural angle on Poisson´s ratio and tensile properties was thoroughly investigated.

2. Materials and methods

2.1. Fabrication of braided composite rods and auxetic structures

Braided structure was produced in a vertical braiding machine, using polyester multi-filament yarns (with linear density of 110 tex) in the sheath and glass multifilament rovings (with linear density of 4800 tex) as the core material. During the braiding process, sixteen polyester filament bobbins were used to supply the sheath yarns, which were braided around the glass fibre core to produce the braided structures [7-9].

In these braided structures, the cover or sheath influences the adhesion properties, whereas the axial reinforcement is responsible for their mechanical performance. Produced braided structures were then used to develop the auxetic structures in the following steps: (1) the auxetic structural design (Figure 3) was drawn on a white chart paper; (2) the chart paper was placed on a board and the braided structures were placed over the drawn design firmly with help of adhesive tape; (3) the cross-over points were tied by polyester filaments and epoxy resin was applied over the structures using a brush; (4) after curing, the structures were removed from the board. Five different auxetic structures were prepared by changing their structural angles ϕ and angle ζ (Figure 4). The weight percentage of the glass fiber in each of these rods was around 53.5%. The dimension of these structures was kept constant for all specimens i.e. 20 cm in width and 40 cm in length, with additional length for clamping during testing. In this study only the effect of angle (ϕ,ζ) in the structures was addressed. The five different types of auxetic structures produced in this study are shown in Figure 5 and their structural angles are provided in Table 1. Four specimens were produced and tested for each type of auxetic structure.

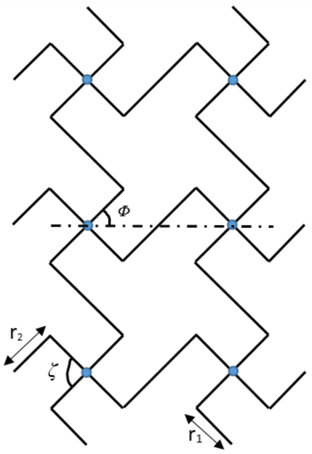

Figure 3. Auxetic structural design used in the present study showing the structural angles (r_1 – longitudinal rod rib length and r_2 – transversional rod rib length)

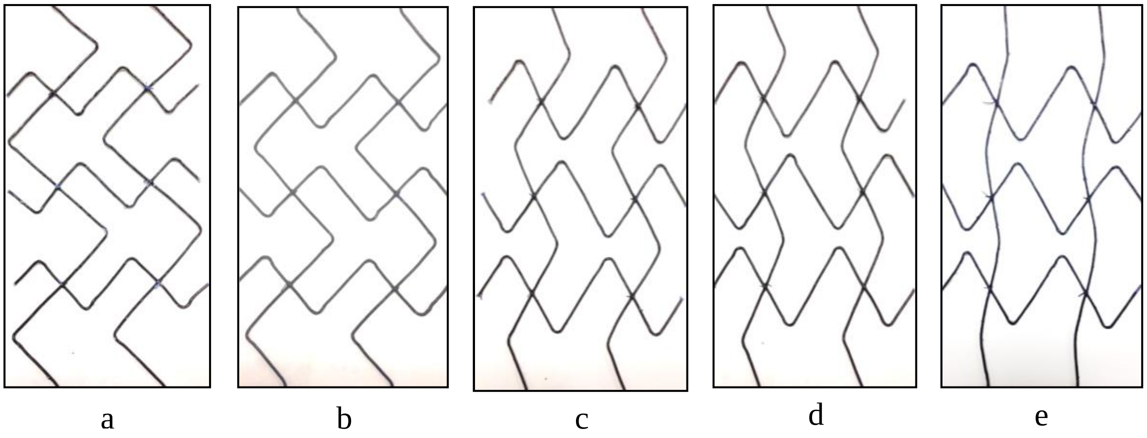

Figure 4. Developed auxetic structures: a) structure 1, b) structure 2, c) structure 3, d) structure 4, and e) structure 5

Structure	Angle	Value (degrees)	Rib	Value (cm)
1	ϕ	45	r_1	7.0
	ζ	91	r_2	3.5
2	ϕ	52	r_1	6.3
	ζ	102	r_2	4.0
3	ϕ	64	r_1	5.6
	ζ	122	r_2	4.6
4	ϕ	68	r_1	5.4
	ζ	127	r_2	4.6
5	ϕ	79	r_1	5.1
	ζ	138	r_2	4.6

Table 1. Values of the structural angles and rib length

2.2. Evaluation of auxetic and tensile behaviours of the structures

The auxetic and tensile behaviours of the structures were evaluated simultaneously using tensile testing machine. For the purpose of observing dimensional changes of the structures using feature tracking method during tensile loading, white marks were painted on the structures at the nodes (e.g. see Figure 5) [10]. A camera-lens optical system was used for image grabbing. A charge-coupled device (CCD) 8-bit Baumer Optronic FWX20 camera (resolution of 1624 × 1236 pixels, pixel size of 4.4 μm and sensor format of 1/1.8'') was coupled with a Nikon AF Micro-Nikkon 200 mm *f*/4D IF-ED lens. The working distance was set to 2755 mm and the focal length to about 50 mm. Images were recorded with an acquisition frequency of 0.4 Hz using a shutter time of 14 ms. The cross head speed of the tensile testing machine was kept at 25 mm/min. The recorded images of the structures were analysed by image processing. The centroid of target objects in the images were tracked during image sequence. The relative distance variation among the selected marks allowed to evaluating the strain on the structures. In each case, 4 samples were tested and Poisson's ratio values were measured using equation 1. Each sample was tested till to the breaking point of the structures.

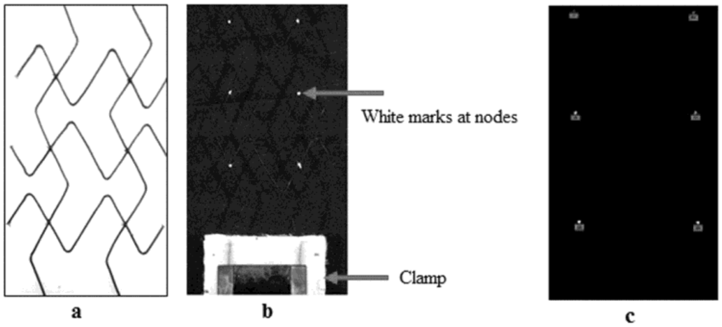

Figure 5. Auxetic Structure during testing. (a) Structure before testing; (b) structures with white marks painted at designated places; (c) binary image resulting from the post-processing using an image-based tracking algorithm.

3. Results and discussion

3.1. Auxetic behavior of the structures

Poisson's ratio of the structures was calculated by strain components obtained from the image-based tracking method and presented in Figure 6. In the Figure 6 each one structure is considered from the different structures and depicted. The results showed that the auxetic structures have Poisson's ratio in the range of -0.30 to -5.20. Poisson's ratio increases with the increase in initial angle ϕ. The absolute value of the Poisson's ratio decreases with the increase in the longitudinal strain level. In these structures, the longitudinal and transversal rods contain undulation and are arranged in a special configuration. As the cross-over points or nodes are tied by filaments, when tensile load is applied in the longitudinal direction, the load is transmitted to the transverse direction through these nodes. The undulation in the longitudinal rods continues to straighten under loads, leading to the increase in specimen's width due to straightening of the transverse rods.

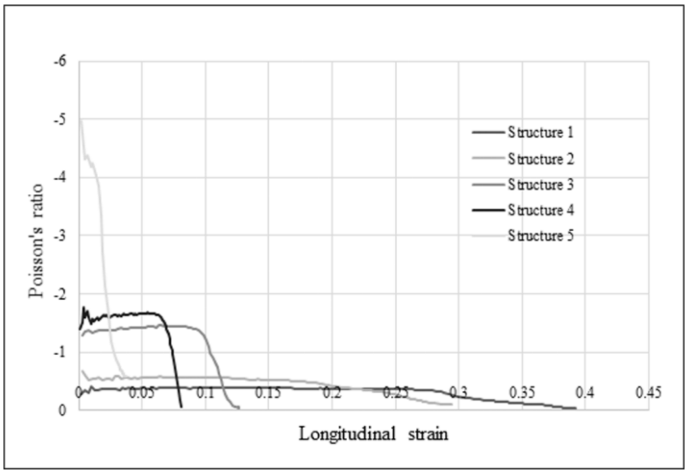

Figure 6. Change of Poisson's ratio with longitudinal strain for the auxetic structures

3.2. Tensile behavior of the structures

The tensile test results of the auxetic structures are provided in Table 2.

Structure No.	Tensile Strength (MPa)	Elongation at break (%)
1	46 (0.3)	38.8 (3.5)
2	60 (1.1)	25.8 (2.5)
3	94 (0.7)	11.3 (8.5)
4	121 (0.5)	8.4 (10.4)
5	184 (0.4)	4.74 (10.9)

Note – In the table values in the brackets are CV%

Table 2. Tensile test results of the structures

Figure 7 shows the tensile behaviour of developed structures. Tensile behaviour of these structures varies according their initial angle ϕ. The lower is the value of initial angle ϕ, the lower is the maximum tensile load, which increases with the increase in initial angle ϕ of the structures. Structure 5 shows the maximum tensile load (initial angle ϕ – 79^{o}) among all structures, and unlike other structures, exhibits good tensile load bearing capacity even at lower strain level.

Due to a less undulation of the longitudinal rods in Structure 5, the rods become straight quickly and therefore, exhibits higher strain range before failure. However, in other structures, the undulation of the longitudinal rods high and thus taking more time to become straight, also they exhibit less strain range before failure. Higher undulation of longitudinal rods in structures 1 to 4 causes development weakest points and stress concentration at the bending locations, and therefore, failure occurs suddenly at these weakest points.

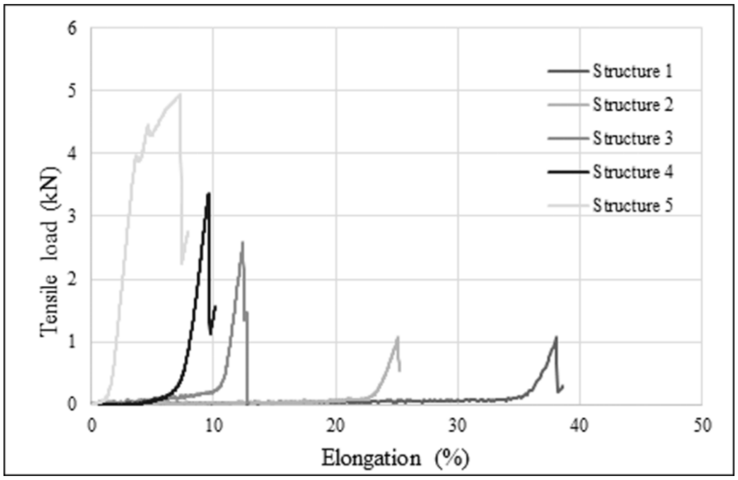

Figure 7. Tensile behaviour of developed auxetic structures

On the other hand, less undulation of longitudinal rods in structure 5 does not create weakest points at the bending locations and therefore, failure does not preferably occur at these locations. As a result, the structure 5 can show its complete tensile behaviour, i.e., a linear elastic behaviour due to elongation of core fibres and subsequent plastic behaviour probably due to matrix deformation and load transfer to the sheath polyester fibres.

3.3. Work of rupture of the structures

Work of rupture i.e. work done or energy required to break the structures has been calculated using load-elongation curve of the structures. The area under the curve has been calculated using Origin 8.0 software. Work of rupture (J) of the auxetic structures, calculated through this approach, are provided in the Table 3.

Structure No.	Average work of rupture (J)	CV%
1	13.83	20.9
2	12.09	18.3
3	14.39	8.0
4	19.73	22.5
5	57.09	50.5

Table 3. Work of rupture of the auxetic structures

Work of rupture for the auxetic structure 5 is three to four times higher than the other structures. So, the auxetic structure 5 is capable to absorb more energy and therefore, proposed for the civil engineering applications, where superior energy absorption is required.

4. Summary and conclusion

In this research, auxetic structures were developed from glass fiber reinforced composite rods and their auxetic and tensile behaviours were studied. Image-based tracking method was used to measure the strain components of the structure during tensile testing. Poisson’s ratio was calculated by using strain components (from both longitudinal and transverse) obtained through an image-based tracking method. All structures exhibited negative Poisson's ratio and Poisson's ratio value was dependent on the initial value of structural angle (ϕ). Poisson's ratio found to increase with increase in the initial angle (ϕ). Tensile behaviour was also observed to depend mainly on the initial angle (ϕ), and the structure with maximum initial angle (ϕ) showed highest maximum tensile load. Tensile behavior of structure 5 i.e. structure with highest initial ϕ *angle* was totally different from others and it exhibited highest strength with ductile deformation, which was not observed in case of structures 1 to 4. This was mainly due to higher initial ϕ *angle* i.e. less degree of undulation in the longitudinal rods. Work of rupture was also highest for structure 5 i.e. this structure requires higher energy to break as compared to other structures and therefore mostly suitable for civil engineering application demanding high energy absorption capacity. This work confirmed that development of auxetic structure at macro scale is possible from braided composite rods.

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