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Development and characterization of novel auxetic structures based on re-entrant hexagon design produced from braided composites

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ABSTRACT

This paper reports the first attempt of developing macro-scale auxetic structures based on re-entrant hexagon design from braided composite materials for civil engineering applications. Braided composite rods (BCRs) were produced and arranged as longitudinal and horizontal elements to produce three types of auxetic structures: (1) basic re-entrant hexagon structure, (2) basic structure modified by adding straight longitudinal elements and (3): structure-2 modified by changing structural angle. The influence of various material and structural parameters as well as structure type on Poisson's ratio and tensile properties was thoroughly investigated. The auxetic behaviour was found to strongly depend on the structural angle and straight elements, resulting in lower auxeticity with lower angles and in presence of straight elements. Material parameters influenced the auxetic behaviour to a lesser extent and a decrease in auxetic behaviour was noticed with increase in core fibre linear density and using stiffer fibres such as carbon. The reverse effect was observed in case of tensile strength and work of rupture. Among these structures, structure-3 exhibited good auxetic behaviour, balanced tensile properties, and high energy absorption capacity and their auxetic behaviour could be well predicted with the developed analytical model. Therefore, these novel structures present good potential for strengthening of civil structures.

1. Introduction

Advanced fibre reinforced polymer (FRP) composites find numerous applications in automobile, marine and aerospace industries due to their enhanced engineering properties such as low density, high specific strength and stiffness, high damping characteristics, high fatigue endurance and low thermal co-efficient (in fibre direction), etc. [1–4]. Recently, composites have been applied widely in civil engineering applications to replace conventional materials (concrete and steel) or ceramic based composites [1]. Composites are introduced into structural elements to improve their flexural resistance, shear strength, confinement, bending property, etc. [1]. Nowadays, research is being carried out to use composite materials in structural elements to improve their resistance against earthquake, blast or impact loads caused by explosions [5]. Capacity to absorb energy is one of the primary requirements for these applications and, therefore, designing strengthening materials possessing excellent energy absorption capability is highly demanding for these structural applications.

Braided composites rods (BCRs) have been introduced in the civil structural applications for the replacement of steel which presents serious corrosion problems. Braiding technology is a low cost and well established technology in which intertwining of three or more strands of yarns forms tubular fabric structures with different combinations of linear or twisted core (axial) materials. Impregnation of axial fibres with polymeric resin before introducing into the braided structure and subsequent curing forms composite materials with braided architecture or BCR. The load-deformation behaviour of braided structures of composites can be tailored by choosing suitable fibres for the sheath and core components. The most commonly used core fibres for civil applications are glass, basalt and carbon fibres. BCRs offer several advantages over the other types of FRP rods such as simple and economical manufacturing process, tailorable mechanical properties and good

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bonding behaviour with cementitious matrices [6–8]. BCRs have been already demonstrated to possess high potential for application in concrete reinforcement and monitoring [9,10], masonry wall strengthening [11] and reinforcement of soils for geotechnical applications [12]. BCRs were used in these applications in the form of meshes made of longitudinal and transverse elements and currently, efforts are directed towards arranging these elements in especial structural designs (such as auxetic), in order to greatly enhance the energy absorption capacity.

Auxetic materials are special kind of innovative materials which exhibit negative Poisson's ratio. Unlike conventional materials, auxetic materials expand in transverse direction in tension and shrink laterally in compression [13,14]. Auxetic materials are gaining considerable interest over the past three decades due to their superior physical properties such as improved strength, enhanced fracture resistance, superior energy absorption, superior acoustic behaviour, good indentation resistance, and improved damping [15–22]. Auxetic materials are available in different forms starting from micro to nano scale such as liquid crystalline polymers, microporous polymer, fibres, foams, honeycombs, biomaterials, nano composites, FRP composites, etc. Auxetic composites can find potential applications in automotive, protection and aerospace industry, where non-auxetic composites with high specific strength and stiffness are currently used [13]. The auxetic property can also be achieved with certain structural designs. In the last few decades, dissimilar geometric structures and models exhibiting auxetic behaviour like 2D and 3D re-entrant structures, rotating rigid/semi-rigid units, chiral structures, etc. have been proposed, studied and tested for their mechanical properties [14,17,23–26].

Among many auxetic structural designs, re-entrant hexagon or bow-tie or butterfly design [27] has been investigated frequently by several researchers. Re-entrant is the internal geometry of many structures, which are observed in macro, micro and nano forms [28]. As of now, re-entrant design was adopted to produce various auxetic materials such as foam cores of sandwich panel for aerospace and air filtration applications [24,29,30], flat and warp knitted fabrics [28,31], molecular auxetic, e.g. (n,m) - reflexyne [19,32], cellular tubes for angioplasty or Annuloplasty rings [33], honeycomb core from Kevlar/epoxy and recycled rubber for sandwich panels [34,35], etc.

Till date, development of auxetic structures at macro-scale and for strengthening of structural elements has been rarely reported. Recently, the authors developed, for the first time, auxetic structures from BCRs based on missing rib or lozenge grid and characterized their auxetic and tensile behaviours [36]. Although the developed structures exhibited negative Poisson's ratio, the structural parameter (opening between the meshes) and mechanical property (mainly stiffness at small strains) did not fit very well with the requirements of structural applications. Motivated by this initial study and in searching for a better structural design, attempt has been made in the present research to develop new types of auxetic structures from BCR based on re-entrant hexagon design. According to the author's knowledge, this type of auxetic structures has been developed for the first time in macro-scale and using braided composite materials. For the civil engineering applications, braided composites can be advantageous due to their especial textured surface providing excellent bonding characteristics with cementitious materials [11]. The developed auxetic structures were characterized for their auxetic and tensile behaviours and the influence of structure type and structural (angle) as well as material parameters (type of fibre and linear density) was thoroughly studied. In addition, analytical models have been developed and the experimental results have been compared with the analytical results.

2. Materials and methods

2.1. Materials

For the production of composite rods, glass fibre roving with linear density of 1200 tex and 4800 tex was purchased from Owens Corning, France. For the same purpose, basalt fibre roving with linear density of 4800 tex and carbon fibre roving with linear density of 1600 tex were purchased from Basaltex, Belgium and Toho Tenax, Germany, respectively. The epoxy resin used to coat the structures was supplied by Sika, Germany, in two components: Biresin CR83 Resin and Biresin CH-83-2 Hardener. The resin and hardener components were mixed in a weight ratio of 100:30 prior to application. The important characteristics of fibre and resin system are listed in Table 1.

2.2. Fabrication of braided composite rods and auxetic structures

Triaxial braided structures were produced in a vertical braiding machine using polyester multi-filament yarns (with linear density of 110 tex) in the sheath and glass/basalt/carbon multi-filament rovings as the core material. During the braiding process, sixteen polyester filament bobbins were used to supply the sheath yarns, which were then braided around the core fibres [6–8]. Produced braided structures were next used to develop three types of auxetic structures, as shown in Fig. 1. The first structure (structure-1) was developed using the basic re-entrant honeycomb design. In structure-2, the basic design was modified with straight longitudinal rods. Structure-2 was further modified to improve the tensile behaviour using higher angle of longitudinal rods, resulting in structure-3. For each type, three samples were produced keeping the total length and width as 40 cm and 11 cm, respectively, with additional length for clamping during tensile testing. Following steps were performed to produce the auxetic structures: the auxetic structural design (Fig. 1) 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 joints 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. The braided structures after resin application and curing became circular composites termed as braided composite rods (BCR). The weight percentage of core fibre in each of these rods was around 51 ± 2%. Resin application was necessary to give sufficient mechanical stability to the braided materials in order to handle them easily and turn them in to auxetic structures. In absence of resin, there may be slippage between the core and sheath as well as between the core fibres causing poor mechanical properties.

2.3. Parameters of developed structures

In order to study the influence of different parameters, auxetic structures were produced using different types of core fibre having

Table 1
Physical properties of core fibres and resin.

S. No.	Properties	Basalt	Glass	Carbon	Epoxy
1	Density (g/cm^3)	2.63	2.62	1.77	1.15
2	Filament diameter (μm)	17	–	13	–
3	Tensile strength (MPa)	>4000	3100–3800	4400	122
4	Tensile modulus (GPa)	87	80–81	240	3.3
5	Elongation (%)	–	–	1.8	6.7