Fibres: Future Materials for Advanced Emerging Applications

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Abstract

Fibrous materials are finding widespread applications in diversified areas, starting from clothing sector to medical fields, various structural and infrastructural applications of civil engineering, aerospace industries and even for energy harvesting and storage applications. In this paper, the results of various research activities conducted by the Fibrous Materials Research Group (FMRG), University of Minho to explore fibrous materials in several advanced and emerging applications have been presented and discussed.

Keywords: Fibrous materials, engineering, advanced applications

1. Introduction

Application of fibrous materials is now not limited to merely fulfill the basic needs of human beings (clothing); they also proved as a potential material to improve other aspects and quality of human life. Huge flexibility in terms of material selection, dimensions (micro or nano), structure and properties made it possible to employ fibrous materials in many advanced areas like aerospace industries, civil engineering, transportation, architecture, sports, medical field and even for energy harvesting and storage.

The most common form in which fibrous materials have been explored in several high end applications is their combination with various matrices as fibre reinforced composites (FRCs). FRCs are being extensively used to design light weight, high strength and durable structures. The main advantage which FRCs offer is the possibility to achieve desired properties by combining different materials or designing different structures. Multi-scale FRCs [1], which can be fabricated by combining nanomaterials (such as nanotube or nanofiber) with conventional composites, is a new generation of multi-functional composites (light weight, high strength, tough, good thermal stability, thermally and electrically conducting, etc.) and, is a potential candidate for aerospace industries.

Civil engineering is one of the major areas, where FRCs find widespread applications for building constructions, reinforcing concrete as replacement of steel rebars and for retrofitting or reinforcing civil structures to improve their resistance under severe conditions (blast, earth quake, etc.) [2]. The dream of developing smart and durable civil structures, capable of sensing their own damage with subsequent automatic repairing, is appearing to be true with the advent of self-sensing FRCs.

The application of fibrous materials also extended to the medical fields starting from health care garments to implantable devices. It became possible to design sutures, artificial ligaments, tendons, skin, cartilage, bone or joints, artery and heart valves using fibrous structures. Moreover, fibrous materials and structures are one of the extensively used scaffolds for tissue engineering applications.

The development of highly flexible energy storage and harvesting devices seems to be possible thorough the use of fibrous structures. The possibility of developing fibrous structure based super capacitors, electrolytes, thin-film batteries and organic solar cells have already been explored and this will lead to new directions towards energy harvesting and storage.

Recently, the interest on nano dimensional fibres (nanofibres) is rapidly growing. Nanofibres are finding potential applications in diversified areas such as filtration, medical and biomedical (prostheses, wound dressing, tissue engineering, drug delivery, etc.), sensors, electrical conductors, etc. Moreover, the use of natural plant fibres (sisal, jute, flax, hemp, etc. or natural nanofibres such as cellulose, chitin, chitosan, etc.) is being highly promoted to address the sustainability and environmental issues.

In this context, the present paper presents a brief overview of various research studies carried out by the Fibrous Materials Research

Group (University of Minho) on engineering and designing novel fibrous materials for high end applications.

2. Braided Fibrous Materials

Axially reinforced braided fibrous materials have been developed through braiding of a number of synthetic or natural yarns around a core of high performance yarns such as glass or carbon. The process has been shown in Fig. 1.

Fig. 1 – Braiding process

Fig. 2– Surface of braided structure

The produced fibrous structures present several advantages such as characteristic ribbed surface texture (Fig. 2) leading to improved interfacial interactions with polymeric or cementitious matrices, good and tailorable mechanical properties based on the type of axial fibres, possibility to introduce pseudo-ductility through hybridization of core fibres and strain or damage sensing capability using conducting core fibres.

2.1 Strengthening of masonry structures

Braided fibrous structures have been applied for strengthening of masonry infill walls as an alternative to commonly used fibre reinforced polymers (FRPs). Studies have been conducted incorporating these braided fibrous structures on to the surface of masonry wall using mortar plaster and characterizing and comparing their performance with commonly used glass/epoxy laminates. These strengthening systems were incorporated in the form of grids as shown in Fig. 3 and tested in flexural mode using 3 point bending configuration.

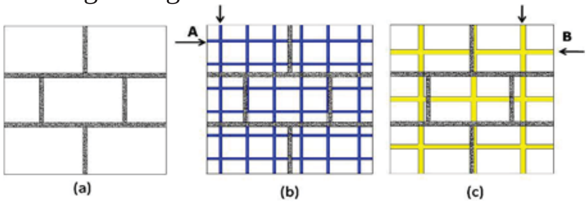

Fig. 3 - Configuration of masonry walls specimens: (a) unreinforced, (b) reinforced with braided structures and (c) reinforced with glass laminates

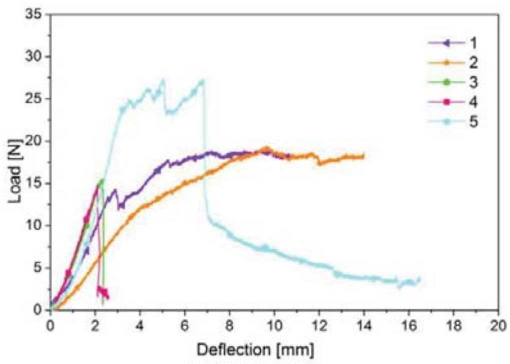

Fig. 4 - Load-deflection curves of masonry walls: (1) reinforced by braided structure with carbon core, (2) reinforced by braided structure with glass core, (3) reinforced by simple braided structure, (4) unreinforced and (5) reinforced by glass laminate

According to the results as shown in Fig. 4, the walls with braided material containing carbon fibre core exhibited much better ductile behaviour than the glass/epoxy laminates.

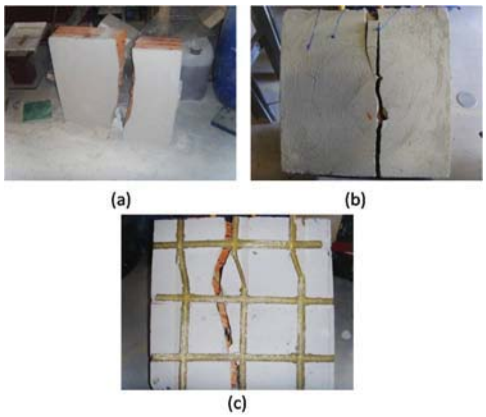

Fig. 5 - Masonry walls after flexural test: (a) unreinforced, (b) reinforced by braided structure with carbon core and (c) reinforced by glass laminate

Moreover, braided structure prevented complete splitting of the walls as seen in case of unreinforced walls (Fig. 5) and also showed no delamination from the cement mortar as found in case of glass epoxy laminates. Therefore, these innovative materials may prove better strengthening systems for masonry structures than the existing solutions.

2.2 Artificial ligaments

Recently, a great deal of research attention is being paid to develop artificial grafts using fibrous materials. Research studies carried out by FMRG revealed that a special type of braided fibrous material can mimic the structure as well as the mechanical behaviour of native anterior cruciate ligaments (ACL) of knee. These structures were developed using polyamide 6.6 yarns having similar mechanical properties as the biodegradable polyglycolic acid fibre, so that in future these structures can be developed using biodegradable yarns for better integration with the surrounding tissues.

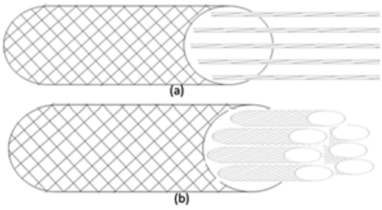

Fig. 6 – Braided structure with axial yarn (a) and axial braid (b)

Table 1 - Various braided structures and their codes

Type of Braided Structure	Number of axially introduced inner braids or yarns		Type and liner density of braiding yarns (dtex)	Sample Codes
axially reinforcing yarns	5 filaments		Polyamide 160	Core PA 160_5F
			Polyamide 90	Core PA 78_5F
	10 filaments		Polyamide 160	Core PA 160_10F
			Polyamide 90	Core PA 90_10F
	15 filaments		Polyamide 160	Core PA 160_15F
			Polyamide 90	Core PA 90_15F
	20 filaments		Polyamide 160	Core PA 160_20F
			Polyamide 90	Core PA 90_20F
axially reinforcing braid	3 Braided	4yarns	Polyamide 160	Core_4Y_3B
		5yarns		Core_5Y_3B
		6yarns		Core_6Y_3B
	5 Braided	4yarns		Core_4Y_5B
		5yarns		Core_5Y_5B
		6yarns		Core_6Y_4B
	7 Braided	4yarns		Core_4Y_7B
		5yarns		Core_5Y_7B
		6yarns		Core_6Y_7B

Two different types of braided structures were produced using a vertical braiding machine namely, circular braids with axially reinforcing yarns and circular braids with axially reinforcing braids. Their structure is illustrated in Fig. 6. The influence of various parameters such as the type and linear density of braiding yarns, number of axial yarns or axial braids and number of yarns used to produce the axial braids on the mechanical behaviour was thoroughly investigated. The types of structure produced are listed in Table 1.

The experimental results revealed that the fibrous structures with axial braids mimic the mechanical behaviour of native ACL in a better way as shown in Fig. 7, 8 and 9. It was observed that the braided fibrous structures with axial braids showed similar elongation as native ACL and have much smaller diameter (0.6 mm as compared to 11 mm of native ACL) and the number of axial yarns or braids and the number

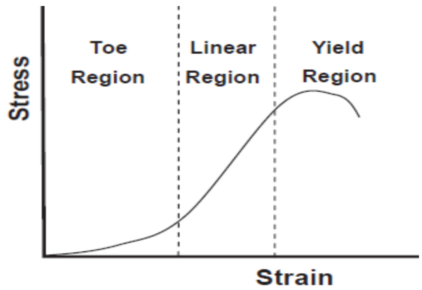

Fig. 7 – Mechanical behaviour of native ACL

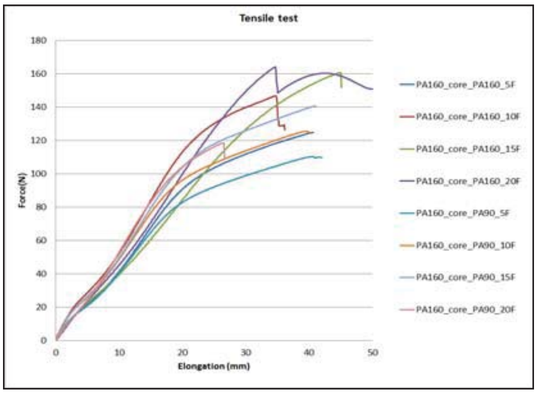

Fig. 8 – Mechanical behaviour of braids with axially reinforcing yarns

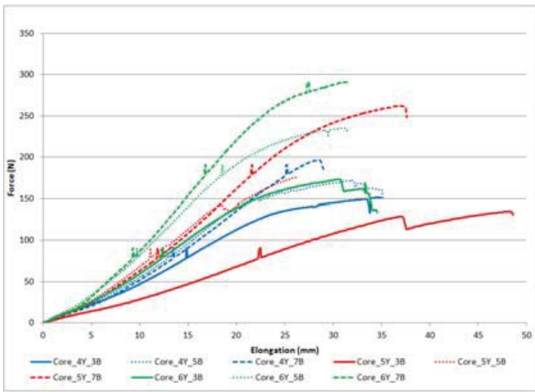

Fig. 9 – Mechanical behaviour of braids with axially reinforcing braids

of yarns in the axial braids can be increased to obtain a linear increase in stiffness and strength, allowing possibility to reach the mechanical properties of natural ACL. Therefore, there exists a huge possibility to develop artificial ACL using these novel fibrous structures, replacing polyamide fibres with biodegradable polyglycolic acid fibres.

3. Braided Composite Rods

Braided composite rods (BCRs) have been developed using a single step braiding process [3] (patented by FMRG), which involves simultaneous braiding of surface fibres and feeding of resin impregnated core fibres. The schematic diagram of the BCR production process is shown in Fig. 10. The influence of various structural (type of surface and core fibres, braiding angle) and process parameters (take up speed, tension) were thoroughly investigated and observed that it is possible to tailor the surface characteristics as well as mechanical properties of BCR by adjusting these parameters.

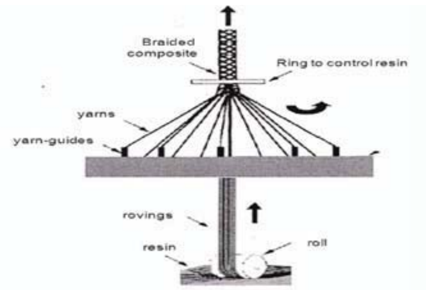

Fig. 10 – BCR production process

3.1 Internal reinforcement of concrete

The possibility of using BCRs for internal reinforcement of concrete has been investigated [4]. Table 2 shows the examples of some BCRs and their mechanical properties are listed and compared with steel rebars in Table 3

Table 2 – Various types of BCR with their compositions

Rod type	Core reinforcement fibres (%)		
	E-Glass	Carbon	HT polyethylene
1	100	-	-
2	77	23	-
3	53	47	-
4	-	100	-
5	50	45	5
6	52	45	3
7	75	22	3

It can be observed that these BCRs have different mechanical properties depending on their composition and most of these rods have higher tensile strength as compared to steel rebars, although their modulus is much lower. Research is presently going on to further improve the properties of BCRs through optimization of production process as well as their structure and composition,

Table 3 – Mechanical properties of BCR and comparison with steel rebars

Rod Type	Tensile strength [MPa]	Elastic modulus (GPa)
1	485,35	55,36
2	766,70	78,52
3	740,41	74,48
4	747,77	96,29
5	679,45	83,92
6	652,77	81,09
7	690,99	73,20
A 235 NL	360	210
A 400 NR/ER	460	210
A 500 NR/ER	550	210

3.2 Strain Sensing

The use of conductive core such as carbon fibres led to the development of BCR with strain sensing capability [5]. A hybrid core containing glass and carbon fibre has been used to obtain pseudo-ductility as well as piezoresistivity. The influence of carbon/glass fibre weight ratio on the piezoresistive behaviour has been investigate and the BCR containing lower % of carbon fibre was found better in terms of both strength and sensing behaviour, however, at the cost of modulus. Fig. 11 shows the change of electrical resistance of BCR with very low flexural strain in cyclic test.

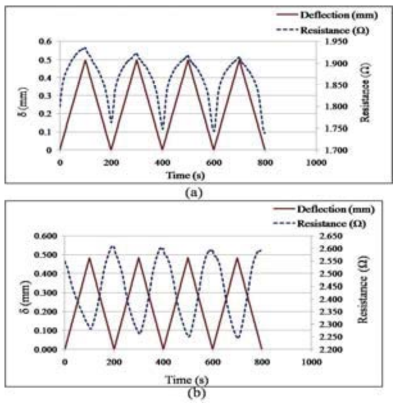

Fig. 11 – Piezoresistive behaviour of BCR: (a) positive response and (b) negative response

It can be noticed that the piezoresistive behaviour is quite reversible at this low strain level (0.5%) and two types of behaviour namely positive (increase in resistance with deformation) and negative (decrease in resistance with deformation) responses are obtained depending on the position of carbon fibres in the cross-section.

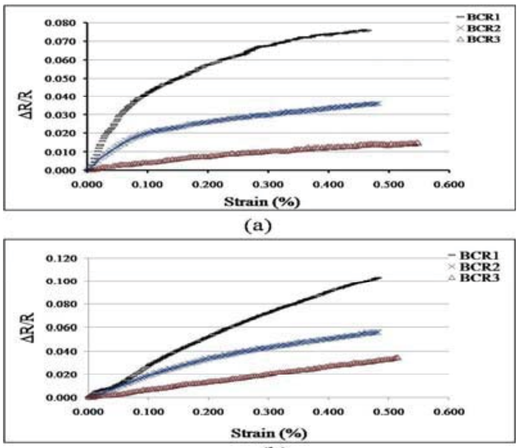

Fig. 12 – Fractional change in resistance with strain% of BCR1 (23% carbon), BCR2 (47% carbon) and BCR3 (100% carbon) in (a) positive response and (b) negative response

From Fig. 12, it can be noticed that the electrical resistance changes significantly at this low strain level and can be monitored for structural health diagnosis. Efforts are presently being directed towards improving the strain sensitivity further by dispersing carbon nanotubes (CNTs) within the matrix of BCR.

4. Multi-scale Composites

Carbon nanofibres (CNFs) and CNTs have been homogeneously dispersed within the matrix of carbon fabric reinforced epoxy composites to develop multi-scale composite materials [6, 7]. These composites were found to possess multi-functional properties such as improved mechanical behaviour, fracture toughness, electrical conductivity, thermal stability and conductivity. As the dispersion of CNF and CNT within matrix is the main challenge in developing these composites, the dispersion process has been optimized and an efficient dispersion route (combination of ultrasonication and high speed mechanical stirring) was used, in order to achieve property enhancement at very low nanomaterial concentration (up to 1wt%). The improvement in mechanical properties and conductivity using CNT is shown in Fig. 12 and Table 4 respectively.

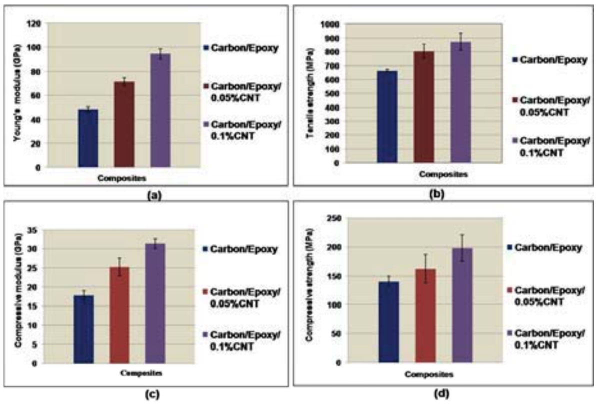

Fig. 13 – Comparison of mechanical properties of CNT based multi-scale and neat carbon epoxy composites: (a) elastic modulus, (b) tensile strength, (c) compressive modulus and (d) compressive strength

Table 4 – Electrical and thermal conductivity of neat carbon/epoxy and multi-scale composites

Composites	Electrical conductivity (S.m^{-1})	Thermal conductivity (W.m^{-1}.K^{-1} × 10^{-3})	Thermal resistance (W^{-1}.K.m^{2} × 10^{-3})
Carbon/epoxy	0.034	193 ± 5	7.9 ± 0.2
Carbon/epoxy/0.1% CNT	0.202	343 ± 20	4.3 ± 0.3

The strong improvement in mechanical properties was mainly attributed to the formation very strong interface in case of multi-scale composites, as shown in Fig. 14.

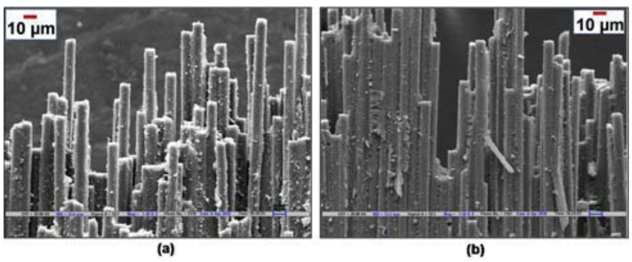

Fig. 14 – Fracture surface of neat carbon/epoxy composite (a) and multi-scale composite (b)

5. Energy Harvesting and Storage

To address the growing need to search for alternative source of energy, FMRG has been trying to develop fibre based flexible dye sensitized solar cells (DSCs). One of the main components of DSC is an electrolyte. A textile based solid polymer electrolyte with excellent conductivity and mechanical stability, known as Silk-Ion Jelly has been developed. This novel ion conducting textile (Silk-Ion Jelly), was developed through application of an ionic liquid based conducting material (Ion Jelly) on to a thin and porous silk fabric. Different strategies to improve the conductivity of Silk-Ion Jelly has been investigated and observed that the best Silk-Ion Jelly electrolyte showed room temperature ionic conductivity as high as 2.9×10^{-3}, which is almost similar to pure ionic liquid or Ion Jelly and much higher than the Ion Jelly treated commercial membrane, Celgard 3401. Fig. 15 shows the conductivity spectra of Silk-Ion Jelly electrolytes and their mechanical stability and flexibility are illustrated in Fig. 15.

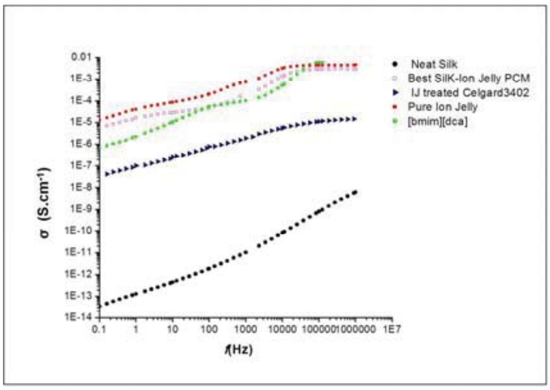

Fig. 15 – Conductivity of silk-ion jelly electrolyte and comparison of its conductivity with neat silk, ionic liquid, ion jelly and ion jelly treated commercial membrane

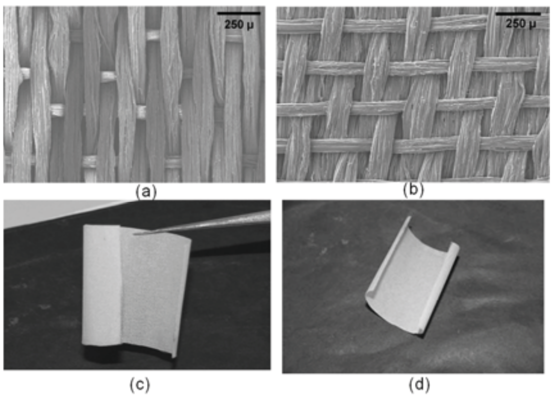

Fig. 16 – Surface morphology of neat silk (a), silk-ion jelly (b) and mechanical stability and flexibility of silk-ion jelly (c and d)

Research studies are also carried out to develop thin film batteries (TFBs) using these novel solid electrolytes, in order to develop power sources for wearable electronics.

6. Sustainable Fibrous Materials

A great deal of research activities being conducted by FMRG has been directed towards utilizing natural plant fibres (sisal, jute, hemp, flax, banana, etc.) which are the low cost, light-weight, non hazardous, eco-friendly and sustainable raw materials for many advanced applications. Natural fibre based braided structures and composites have been developed and investigated for several applications such as masonry strengthening, concrete and soil reinforcement, etc. Natural fibres have been treated with various chemical (alkali) and physical treatments (plasma) to improve their mechanical properties and surface morphology for better interaction with polymeric or cementitious matrices. The improvement of mechanical properties of banana fibres through atmospheric plasma treatment with different dosages is presented in Table 5.

Table 5 – Effect of atmospheric plasma treatment on the tensile properties of banana fibres

Samples	Tensile strength (MPa)	Elastic modulus (GPa)	Breaking elongation (%)
Untreated	102.7	3.3	2.5
$0.5 kW.min.m^{-2}$	221.9	5.6	2.3
$1.5 kW.min.m^{-2}$	298.0	5.6	2.2
$3.0 kW.min.m^{-2}$	338.0	5.0	2.2

6. Conclusions

The applications of fibrous materials is increasing rapidly in many diversified areas including civil engineering, aerospace industries, medial sectors and even for energy harvesting and storage applications. Researchers and scientists from both academics and industry are continuously working to engineer novel fibrous materials and structures in order to meet the demands for these advanced areas. Tremendous interest is also being paid on using fibres from natural and renewable resources, in order to reduce environmental problems and to address sustainability. In conclusion, due to their versatile nature and numerous benefits, fibrous materials will be the materials of choice for many existing and future advanced applications.

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