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TOWARDS HIGH PERFORMANCE AND MULTI-FUNCTIONAL STRUCTURAL MEMBRANES USING ADVANCED FIBROUS AND TEXTILE MATERIALS

R. FANGUEIRO* and S. RANA[†]

[*] Department of Civil Engineering
University of Minho
Campus de Azurem, 4800-058 Guimaraes, Portugal
e-mail: rfangueiro@civil.uminho.pt, web page: http://www.web.fibrenamics.com

[†] Fibrous Materials Research Group, School of Engineering
University of Minho
Campus de Azurem, 4800-058 Guimaraes, Portugal
Email: soheliitd2005@gmail.com, Web page: http://www.web.fibrenamics.com

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Summary. Scientific and technological advancements in the area of fibrous and textile materials have greatly enhanced their application potential in several high-end technical and industrial sectors including construction, transportation, medical, sports, aerospace engineering, electronics and so on. Excellent performance accompanied by light-weight, mechanical flexibility, tailor-ability, design flexibility, easy fabrication and relatively lower cost are the driving forces towards wide applications of these materials. Cost-effective fabrication of various advanced and functional materials for structural parts, medical devices, sensors, energy harvesting devices, capacitors, batteries, and many others has been possible using fibrous and textile materials.

Structural membranes are one of the innovative applications of textile structures and these novel building skins are becoming very popular due to flexible design aesthetics, durability, lightweight and cost benefits. Current demand on high performance and multi-functional materials in structural applications has motivated to go beyond the basic textile structures used for structural membranes and to use innovative textile materials. Structural membranes with self-cleaning, thermoregulation and energy harvesting capability (using solar cells) are examples of such recently developed multi-functional membranes. Besides these, there exist enormous opportunities to develop wide varieties of multi-functional membranes using functional textile materials. Additionally, it is also possible to further enhance the performance and functionalities of structural membranes using advanced fibrous architectures such as 2D, 3D, hybrid, multi-layer and so on. In this context, the present paper gives an overview of various advanced and functional fibrous and textile materials which have enormous application potential in structural membranes.

1 INTRODUCTION

Architectural membranes are becoming an important building material due to several advantages such as flexible design aesthetics, outstanding translucency, durability, lightweight and cost benefits. The global membrane market is estimated to grow at a compound annual growth rate of 9.43% from 2014 to 2019, reaching a value of $29.3 billion[1]. Over the last few years, the construction industry is looking for innovative materials which, besides serving their basic purpose, should also provide other smart functionalities such as thermo-regulation, self-sensing and self-healing, colour and shape changes, etc., in order to enhance the quality and safety of human life. For architectural membranes, until now, only basic textile structures are being used, except some efforts to develop membranes with self-cleaning and thermoregulation features[2, 3]. Dubai cricket stadium with self-cleaning property (using TiO_2) and energy harvesting membranes developed using solar cells by PowerFilm, Inc. and Konarka Technologies, Inc. are examples of such recent developments.

2 SELF-SENSING FIBROUS AND TEXTILE STRUCTURES

Self-sensing is an important characteristics of current materials used in structural applications. Online monitoring of stress/strain helps to take timely actions in order to ensure proper functioning or prevent chance of consequent damage, whereas sensing of damages at earlier stages helps to take preventive measures avoiding additional costs due to substantial maintenance or replacement of the materials. Use of self-sensing materials can greatly enhance the durability of structures, improving safety and reducing maintenance costs and use of non-renewable materials. This leads to significant reduction in the carbon footprint of structures. Recently, a variety of sensors such as fibre optic, piezoelectric, piezoresistive sensors etc. have been developed for strain and damage sensing in structures[4].

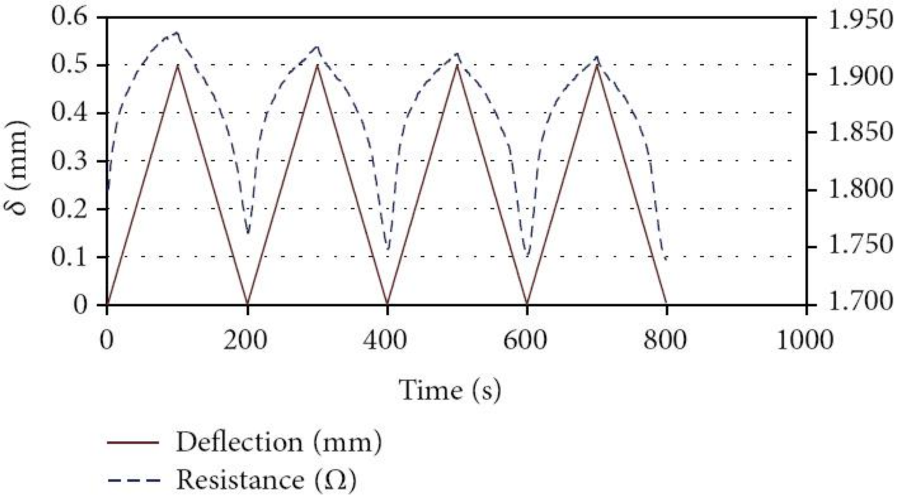

Figure 1: Strain sensing behaviour of recently developed braided textile composites

Among them, self-sensing composites have been considered to be highly advantageous due to their low cost as well as easy design and application possibilities. These composite materials contain an electrically conducting component (such as carbon fibre, powder, nanofibres or nanotubes, etc.) and exhibit change in their electrical resistance due to mechanical strain or damage. The sensing response from a recently developed self-sensing braided composite is presented in Figure 1.

Although a variety of techniques are available for the self-sensing purpose, there exists a strong need for a lightweight, strong and flexible sensing material which is well suited for applications in flexible materials such as architectural membranes. Recently, some piezoresistive coatings have been developed for fibrous materials to sense change in strain/stress state and damage through change in electrical resistivity[5]. These coatings are based on conducting polymers and advantageous as they can be applied using low cost and commercially available coating or printing technologies[6]. Moreover, when applied to a textile material, conducting polymers can impregnate the individual yarns and spaces within a fabric structure allowing the detection of local stress/strain or damages. Also, the coated textiles possess excellent flexibility just like the base materials[6]. Conducting polymers also possess other important characteristics such as generation of electrical voltage when heat is applied (thermoelectricity) or the opposite, i.e. generation of heat when voltage is applied[7]. Therefore, the generated heat can be used for various aesthetic purposes in architectural membranes, for example, color change using thermochromic pigments.

3 FIBROUS AND TEXTILE STRUCTURES FOR ENERGY HARVESTING

Fibrous and textile materials are being considered for several advanced applications as they possess some inherent beneficial characteristics such as lightweight, mechanical strength and flexibility, numerous design possibilities, easy processing and integration with flexible materials, etc. Producing energy using flexible textile materials is one of the remarkable innovations of the recent time. One example of this is the harvesting of energy from the wearable textiles due to body movements[8]. Production of energy through this technology can significantly reduce the usage of non-renewable energy sources and carbon footprint. Some research studies have demonstrated the feasibility of using polyvinylidene difluoride (PVDF) as the piezoelectric polymeric material for this purpose[9]. The use of PVDF films for continuous power generation in the order of 100 μW using wind energy at moderate wind speeds has also been demonstrated. Under certain conditions, PVDF films can produce more voltage and power from wind and rain as compared to ceramic based PZT[10]. Fibres and textiles made from PVDF are superior to PVDF films in terms of mechanical stability, flexibility and large scale production possibilities[10]. 2D and 3D textile fabrics (Figure 2) produced from PVDF fibres have been already designed and demonstrated for energy harvesting applications[11]. The developed 3D spacer piezoelectric fabrics exhibit a power density in the range of 1.10 mW cm^{-2} to 5.10 mW cm^{-2} at applied impact pressures of 0.02 MPa to 0.10 MPa, which is comparable to existing piezoelectric materials[11].

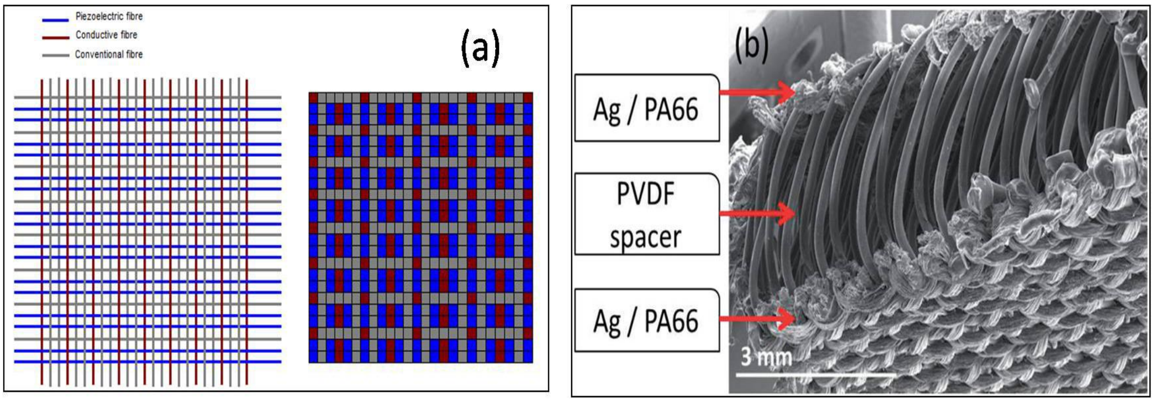

Figure 2: Design of 2D piezoelectric fabrics from PVDF fibres (a) and 3D piezoelectric textiles (b)

4 FIBROUS AND TEXTILE STRUCTURES FOR ENERGY STORAGE

Textile based flexible energy storage devices are also becoming very attractive for e-textile or other applications. These devices can be easily paired with fibre or textile based energy harvesting devices. Textile energy storage devices such as batteries, electric double layer capacitors (EDLCs) with good gravimetric performance have been already developed[12]. Well-established textile technologies such as knitting and screen-printing have been used to produce solid state ELDCs with capacitance as high as 0.51 F cm^{-2} per device at 10 mV s^{-1}, which is comparable to standard activated carbon film electrodes[13]. Lithium ion textile batteries with large areal mass loading and good performance have also been developed[14]. Proper functioning of these wearable textile batteries (Figure 3a) has been demonstrated by a research group from Korea Advanced Institute of Science and Technology (KAIST) and the possibility of powering these textile batteries through flexible solar cells has also been explored[15]**.** Textile batteries made from bio-based materials with good performance (cotton or silk fabric coated with eco-friendly conducting materials like Ion Jelly) have been developed, as shown in Figure 3b. For use in these flexible textile batteries, novel textile based solid electrolytes have also been developed[16-19]. Prepared from natural fibre based textiles (i.e. cotton, silk, etc.) using bio-based materials such as gelatin and water and a green solvent such as ionic liquid, these solid electrolytes are ecofriendly materials with very high ionic conductivity (similar to ionic liquid) and excellent electrochemical performance as well as possess excellent mechanical strength and flexibility. In addition, the process used to develop the electrolyte and battery is a low cost textile coating process, which is highly suitable for commercial production and applications. For the production of the electrolytes, gelation and ionic liquid are reacted in the presence of water to form a novel ion conducting material (Ion-Jelly), which is then coated on the textile fabrics. The textile batteries are then developed by depositing electrode layers (ion jelly containing electrode materials) on both sides of the textile electrolyte. Fig. 4 shows the solid electrolyte developed using silk fabrics and their ionic conductivity curves.

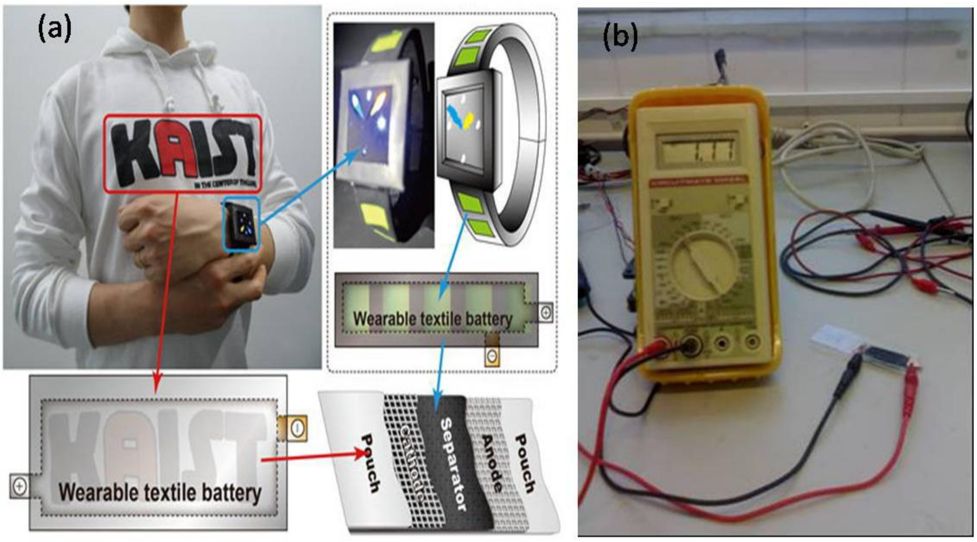

Figure 3: (a) Wearable textile battery (b) demonstration of thin film ion jelly battery

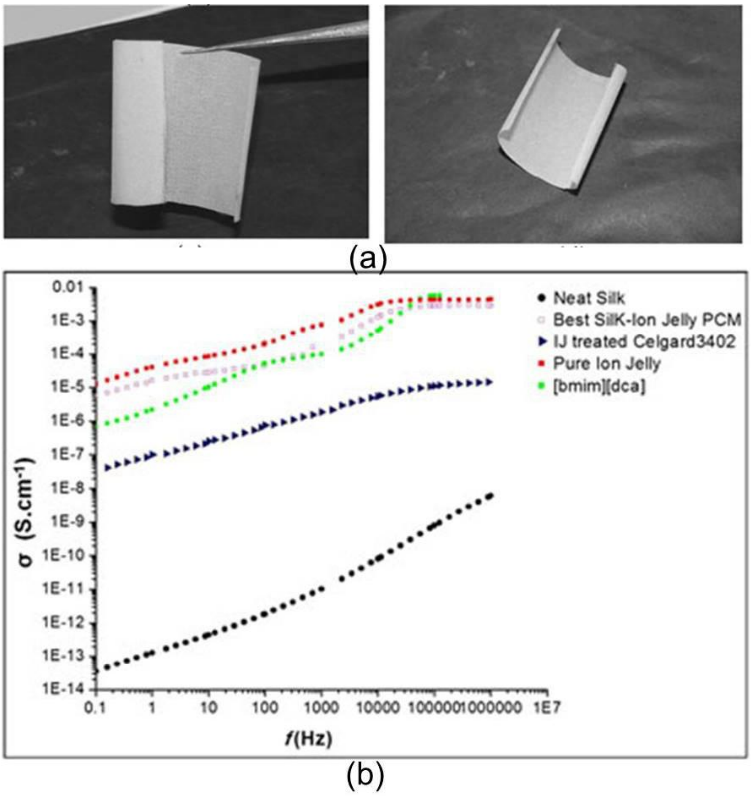

Figure 4: (a) Silk based textile electrolyte (b) comparison of Ionic conductivity of Silk electrolyte with neat silk, neat Ion Jelly, commercial membrane (Celgard3402) and pure ionic liquid ([bmim][dca]

5 ADVANCED TEXTILE ARCHITECTURES

Until now, structural membranes use only basic textile fabrics made of various fibres such as glass, aramids, acrylic, nylon, polyester, etc. coated with PVC, urethane, PTFE, silicone, etc. Innovation in textile technology has led to the development of a wide variety of advanced fibrous architectures such as directionally oriented structures (DOS), multi-axis, multi-layer, hybrid, etc. which can greatly reduce the weight and improve the performance of materials[20]. These advanced structures have been extensively used in advanced composite materials for various high end applications such as aerospace, construction, transport, medical, sports, and so on. Therefore, the use of these innovative fibrous architectures can greatly enhance the mechanical performance and functionalities of structural membranes. Figure 5 shows some examples of advanced fibrous architectures used for technical applications.

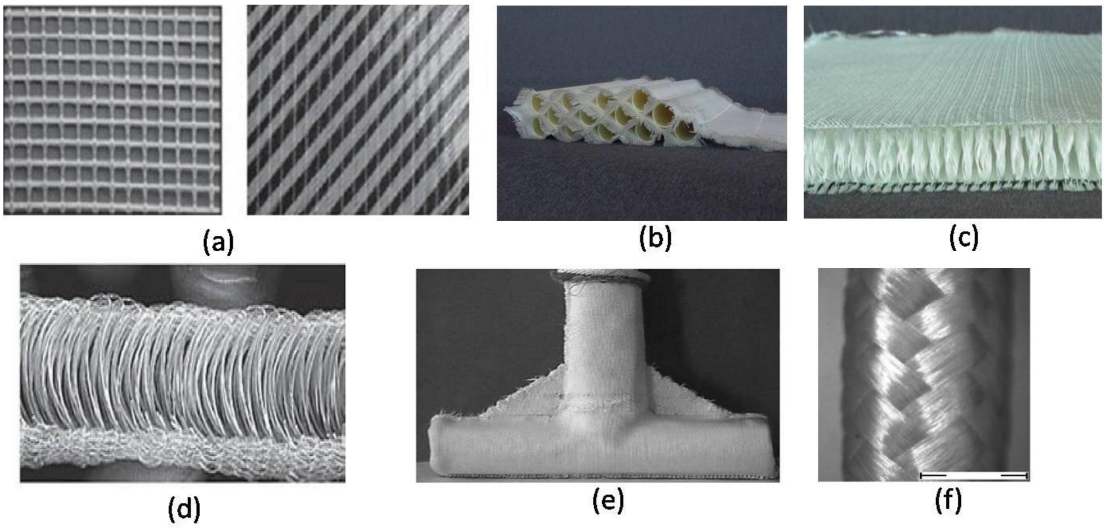

Fig. 5: Various advanced fibrous architectures: (a) DOS, (b) multi-layer, (c) 3D woven spacer, (c) 3D warp knitted spacer, (d) 3D weft knitted and (f) 2D braided structure

6 MULTI-FUNCTIONAL TEXTILES AND COMPOSITES

Recently, multi-functionality has been considered as an essential requirement of materials for application in advanced technical areas. Materials with high strength and stiffness, excellent electrical and thermal conductivity, self-sensing and self-healing capability, energy harvesting ability, etc. are highly suitable for applications requiring all/most of these properties. One of the easiest approaches to develop multi-functional materials is through nanotechnology by using various multi-functional nanomaterials. Nanomaterials can be easily incorporated within engineering materials to introduce multi-functionality, leading to a new generation of materials called "multi-scale composites"[21-27]. The incorporation of nanomaterials can be in the form of composite materials or coatings. The concept of multi-functional composites developed using nanotechnology is presented in Figure 6. However, designing of such materials and proper tuning of all these properties may be a challenging task. Recently, high performance and multi-functional composite materials using carbon and other nanomaterials have been developed to address the demand of many high end applications. Similar technology can also be utilized to develop flexible multi-functional materials for application in structural membranes. Alternatively, multi-functional coatings can also be applied to textile and fibrous structures to develop multi-functional architectural membranes.

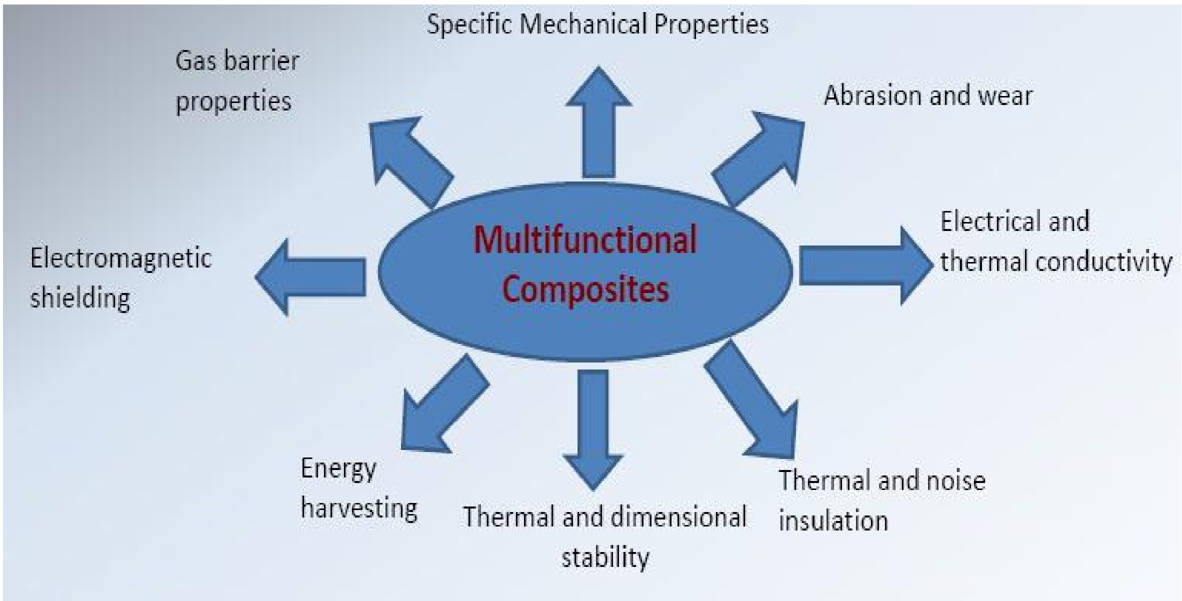

Figure 6: Concept of multi-scale composites

7 APPLICATION OF ADVANCED MULTI-FUNCTIONAL TEXTILE MEMBRANES

Advanced and multi-functional textile structures have been widely utilized for various applications in different industrial sectors including aerospace, transportation, medical, sports; civil engineering, etc.[28-31]. These advanced textile structures also can be used for different purposes in architectural membranes. The textile energy harvesters can be used to produce energy from vibrations due to wind, rain, snow or other sources. The produced energy can be stored in to textile based batteries and can be utilized for various purposes. So, these energy production-storage systems can reduce the energy requirements from other non-renewable sources. The textile piezoresistive sensors can be used to detect the tension level in the membrane and accordingly adjustments can be made ensuring proper functioning of the membranes. Moreover, in case of any damage, the sensors will show a sharp change in electrical resistance, thereby initiating damage detection and their timely maintenance. This will avoid excessive damage and major maintenance activities or their complete replacements. Consequently, the maintenance and material cost as well as environmental problems (due to production of these synthetic materials) can be significantly reduced. Multi-functional coatings with heat generation capability (for example, using conducting polymers) can help in thermo-regulation as well as can create different aesthetic colour effects if used with thermochromic pigments. The utilization of phase change materials (PCM) will further enhance the thermoregulation of spaces around the membranes, and self-cleaning materials will reduce the need for frequent washing and cleaning of membranes. Many other functionalities can be achieved based on the used functional materials. Further use of advanced textile architectures can greatly enhance the mechanical performance of the structural membranes. However, it is highly essential to conduct in-depth research and developments to optimize these various properties, in order to come up with multifunctional materials with properties matching with the requirements of targeting applications.

8 CONCLUSIONS

In conclusion, recent advancements in materials science and nanotechnology made possible to develop highly advanced fibrous and textile materials, which, besides being light-weight, flexible, strong and durable, can provide a combination of various features like self-sensing and healing, thermal and electrical conductivity, thermal regulation, self-cleaning, energy generation, and so on. These features not only enhance the performance and safety of the materials, but also make them more attractive to the users. Only a few of these features are currently available in the materials used for existing structural membranes. However, the concept and technology employed in developing multi-functional materials for other industrial domains can also be utilized for structural membrane sector to develop such advanced materials. Therefore, strong emphasis should be given on research and development in this sector to come up with advanced multi-functional materials which will improve the competitiveness and sustainability of this industrial domain.

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