STRAIN AND DAMAGE SENSING BEHAVIOUR OF CORE REINFORCED BRAIDED COMPOSITE RODS

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Abstract

In the present research, we have investigated the possibility of using core reinforced braided composite rods (BCRs) for self monitoring of deformation and damage. The BCRs were produced by braiding polyester fibres around a resin (unsaturated polyester) impregnated core, composed of glass and carbon fibre mixture, using a simple, single-step and low cost braiding process. The sensing behaviour was characterized by monitoring the change in electrical resistance with deformation using two terminal dc method. According to the experimental results, the composition with less amount of carbon fibre in the core showed the best strain sensing behaviour.

1 Introduction

Light weight combined with very good mechanical properties has opened up the possibility of using fibre reinforced plastics (FRPs) in several high end applications including concrete structures. The main disadvantage of the steel bars commonly used for concrete reinforcements is the corrosion problem. The use of FRPs in civil structures as replacements of steel is gaining popularity due to their light weight and very good corrosion resistance. Moreover, the FRPs offer huge flexibility in tailoring their properties by selecting different fibre/matrix systems and composite structures. Therefore, it is possible to introduce different functions to FRPs so that they can serve many purposes simultaneously.

Health monitoring of civil structures is very much essential in order to avoid accidents from sudden fractures. The approach of inserting various types of sensor in to the structures for health monitoring is usually complex, expensive and requires highly skilled personnel for their application and use. These problems can be overcome by designing concrete structures with the self-sensing capability of damage and deformation. FRPs are the ideal reinforcements for designing such concrete structures due to the possibility of imparting multi functionality to them by tailoring their composition or structure. Efforts have been directed towards designing FRPs with self sensing capability by including in to their structure a conductive component such as carbon fibre, which can change their electrical resistance with deformation and damage. Use of hybrid composites containing a combination of conductive reinforcement with other reinforcements such as glass, aramid etc. proved helpful to introduce pseudo-ductility in order to detect damage well before the structural collapse [1-3]. Several hybrid composite systems with different structures and compositions of glass fibre and carbon fibre or powder have been investigated in order to develop either continuous monitoring system [3-5] or discontinuous warning system for structural health monitoring [6, 7]. A few researchers succeeded to develop hybrid CF/CF composites which are able to provide alarm signal well before the composite collapse [7]. However, a very small change in resistance at low strain level makes these hybrid composites unsuitable for designing continuous monitoring system [5]. Combinations of glass fibre with carbon particle instead of continuous carbon fibre were found to improve the strain sensitivity at low strain level [8, 9]. Recently attempts have also been made to develop hybrid composites with good sensitivity using carbon nanotubes (CNTs) [10]. Design of continuous monitoring system can also be based on the measurement of residual resistance caused due to deformation. However, it was observed that good sensitivity at low strain in terms of residual resistance is obtained only at the pre-stressed conditions [5]. Although pre-stressing of composites is a suitable condition for civil engineering structures but may present problems in other applications.

Braiding process is gaining lot of importance in recent times for manufacturing of composite preforms with complex structures due to its simplicity and low cost [11]. Core-reinforced braided composite rods, which are comprised of unidirectional core fibres surrounded by a braided cover, have already been proposed for applications like concrete rebars and medical implants due to their very good mechanical performance [12]. A simple and cost-effective process for continuous single step production of core-reinforced braided rods has been patented by authors [13]. Superior adhesion of these braided rods with concrete as well as their applicability for concrete internal reinforcement as replacement of steel rebars has also been demonstrated by them [14].

The present research demonstrates the strain sensing capability of braided composite rods (BCRs) reinforced with a hybrid core made of carbon fibre and glass fibres. The main aim of this research work is to design a simple and cost-effective strain sensing composite system which will overcome the problems associated with existing hybrid and CNT based systems. In order to find out the best composition in terms of sensing capability, the effect of carbon fibre/glass fibre weight ratio on strain sensitivity was thoroughly investigated.

2 Materials and methods

2.1 Production of BCR

BCRs were produced using polyester fibres for braided structure and a combination of glass fibre and carbon fibre as the core reinforcement. The braiding of polyester fibres and impregnation of core fibres with polyester resin/hardener mixture were done simultaneously in a single process using a vertical braiding machine with an incorporated impregnation system. The take up speed was kept at 0.01 m/s, which leads to a breading angle of 23-24°. The composite rods were then cured at environmental temperature and moisture conditions (20 ± 2ºC and 50 ± 5%). The properties of E-glass and carbon fibres used for core reinforcement is provided in Table 1 and the composition of different composites is listed in Table 2.

Fibre Type	Manufacturer	Strength [GPa]	Modulus [GPa]	Elongation [%]
Carbon	TohoTenax	4.3	240	1.8
Glass	Saint Gobain Vetrotex	3.5	73.5	4.8

Table 1. Properties of carbon and glass fibres

Type	Fibre Weight Fraction	Diameter[mm]	Core Fibres	Core Composition
BCR1	0.35	5.27	E-glass/carbon	77/23
BCR2	0.32	5.75	E-glass/carbon	53/47
BCR3	0.33	6.40	Carbon	100

Table 2. Composition of different braided composites

The surface texture and cross-sections of the braded rods have been illustrated in Figure 1. The ribbed surface texture leads to superior adhesion of these composite rods with concrete. It can be noticed that in the hybrid rods, the carbon fibres are present in one side of the cross-section and the other side is comprised of glass fibres. The placement of the fibres within the cross-section of the braided rods was controlled while feeding them in the braiding machine. However, the core fibres were not put under any tension during feeding. As a result, they lost their straightness to some extent due to the braiding of polyester fibres around them and took a misaligned arrangement decided by the braiding process parameters such as braiding angle, take up speed and pre-tensioning.

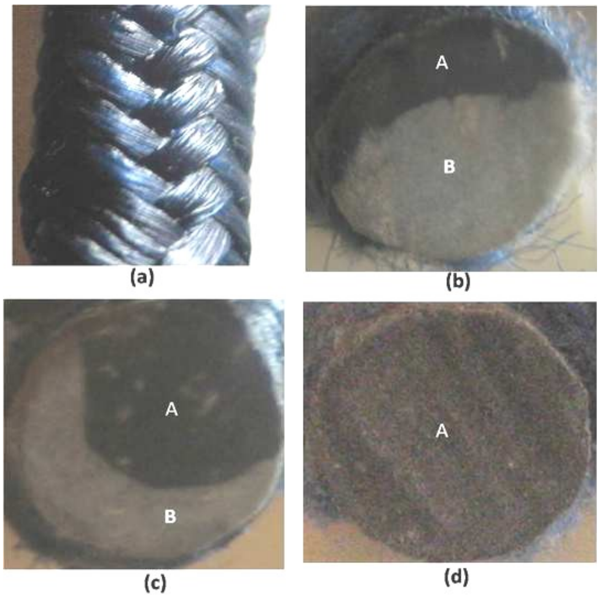


Figure 1. Surface texture of BCR (a) and distribution of carbon fibre (A) and glass fibre (B) within BCR1 (b), BCR2 (c) and BCR3 (d)

2.2 Characterization

The strain sensing behaviour of the BCRs was characterized by measuring the change in electrical resistance between the sample ends using two terminal dc method. Cyclic tests were performed at low strain range (up to 0.55%) in order to investigate the performance of the BCRs in sensing very low deformation in continuous manner. The experimental setup for the characterization of piezoresistive behaviour is shown in Figure 2. The electrical resistance of the samples was continuously measured during the flexural test by making electrical connections between the two probes of a digital multi-meter (Agilent 84401A) and sample ends through gold wires fixed to the samples using silver paste. The strain sensing capability of the composites was evaluated in terms of gauge factor (GF), which is defined as follows:

$$GF = \frac{(\frac{\Delta R}{R})}{\varepsilon}$$

where, ΔR is the change in electrical resistance, R is the initial resistance, ΔR/R is the fractional change in resistance and Є is the flexural strain at the outer surface of specimen at midspan.

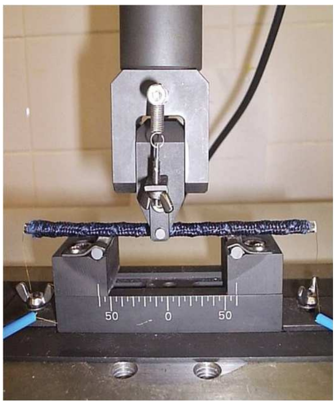


Figure 2. Measurement setup for piezoresistive characterization

3 Results and Discussion

The BCRs showed two types of piezoresistive behaviour under flexural loading depending on the position of carbon fibres in the cross-section of braided composites. In positive response, electrical resistance increases with deformation, whereas resistance decreases with deformation in case of negative response. Figure 3 shows the type of response observed with BCR1 depending on the placement of carbon fibres.

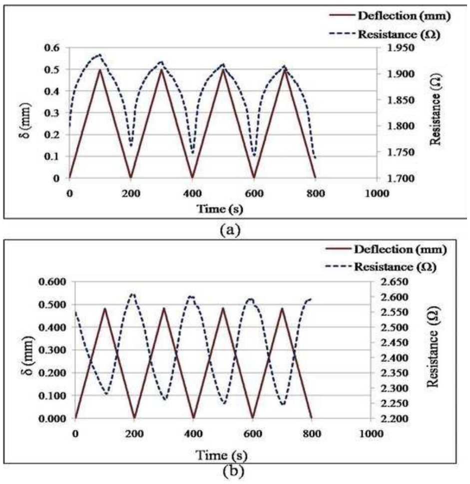


Figure 3. Change of deflection and resistance with time for BCR 1 in (a) positive response and (b) negative response

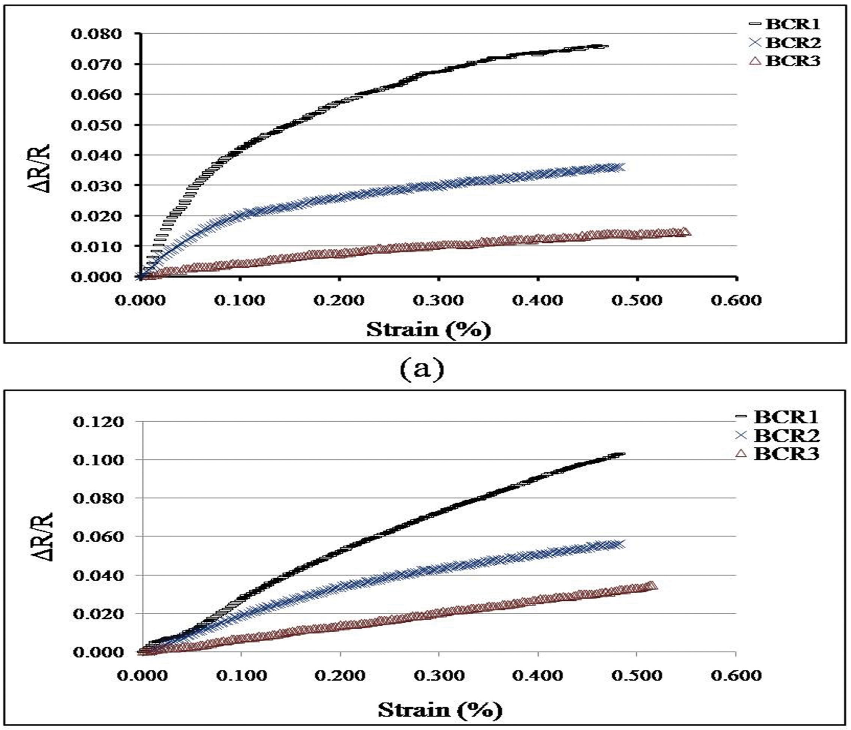
It can be seen that the resistance change with deformation is quite reversible. The other braided composites (BCR2 and BCR3) also showed similar positive and negative responses. However, the extent of resistance change with deformation was different for different BCRs. The fractional change in resistance in different cycles and the average gauge factors for different BCRs are listed in Table 3.

Cycle No.		**1**		**2**		**3**		**4**		
BCR type	**Response**	**ε $(* 10^{-2})$**	**$\Delta R/ R$**	**ε $(* 10^{-2})$**	**$\Delta R/ R$**	**ε $(* 10^{-2})$**	**$\Delta R/ R$**	**ε $(* 10^{-2})$**	**$\Delta R/ R$**	**Average GF**
BCR1	Positive	0.48	0.10	0.48	0.11	0.48	0.12	0.48	0.12	23.4
	Negative	0.47	0.08	0.47	0.07	0.47	0.07	0.47	0.06	14.9
BCR2	Positive	0.48	0.04	0.48	0.02	0.48	0.01	0.48	0.01	4.2
	Negative	0.48	0.06	0.48	0.07	0.48	0.07	0.48	0.07	14.1
BCR3	Positive	0.55	0.02	0.55	0.01	0.55	0.01	0.55	0.01	2.3
	Negative	0.52	0.04	0.52	0.04	0.52	0.05	0.52	0.05	8.6

Table 3. Fractional resistance change and average gauge factor of BCRs

As reported previously [7], the zero-frequency resistance change of carbon fibre composites may be due to (a) dimensional change as a result of elastic deformation of fibres, (b) change of resistivity resulting from change in inter fibre contacts due to strain or change in fibre arrangements and (d) fibre breakage. Since, the composites were subjected to a low strain level in the present study and the piezoresistive behaviour was quite reversible, the effect of dimensional change and fibre breakage was expected to be negligible. The role of inter fiber contacts was believed to be the dominating factor for resistance change in the studied braided composites. The change of electrical contact points is expected to be more with misaligned fibre arrangements due to the possibility of fibre alignment upon deformation. The misaligned arrangement of conductive carbon fibres, therefore, resulted in very good strain sensitivity of the studied BCRs.

It can be noticed that the highest piezoresistive behaviour is obtained with BCR1 and the strain sensibility decreases with increase in the carbon fibre %. In the composites with higher amount of carbon fibres, there will be less change in electrical contacts during deformation due to more touching of fibres leading to a large number of electrical contact points throughout the composites. Moreover, with higher amount of carbon fibres it was not possible to restrain the position of carbon fibres only in one half of the cross-section and therefore the carbon fibres experience both tensile and compressive stresses. As a result, the overall strain sensitivity decreases due to cancelling effect of positive and negative responses. The trend of fractional resistance change with strain in the first cycle has been presented in Figure 4.



(a)

(b)

Figure 4. Change of fractional resistance with strain for different BCRs in (a) positive response and (b) negative response

It is interesting to note that the curve for BCR1 presents more non-linearity than the other BCRs. The fractional resistance change sharply and linearly up to 0.1% strain and then more gradually at higher strains due to saturation in the electrical contacts.

4 Conclusions

This paper reported the potential of core-reinforced hybrid carbon fibre/glass fibre braided rods for continuous monitoring of very low flexural strain. It was observed that the braided composites with low volume fraction of carbon fibres (23%) led to best strain sensitivity. The change of resistance in the braided composites was mainly attributed to the resistivity change due to strain dependant change in the electrical contacts. The braided composites showed both positive and negative responses under flexural strain depending on the placement of carbon fibres in the cross-section. The much higher gauge factors obtained with the best composition at low strain level (23.4 for positive response and 14.9 for negative response at strain up to 0.55%) as compared to previously reported hybrid composites was due to the misaligned arrangement of carbon fibres caused by the braiding process. Therefore, the core-reinforced hybrid braided composites developed in this research can be used in civil engineering and other applications as replacements for steel bars and conventional FRPs for mechanical reinforcement as well as for continuous health monitoring.

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