Self-diagnosing braided composite rod

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ABSTRACT: This paper presents the development of a braided reinforced composite rod (BCR) able to both reinforce and monitor the stress state of concrete structures. Carbon fibers have been used as sensing and reinforcing materials along with glass fiber. Various composites rods have been produced using an author patented technique based on a modified conventional braiding machine. The materials investigated were prepared with different carbon fiber content as follows: BCR_2 (77% glass/23% carbon fiber), BCR_3 (53% glass/47% carbon fiber), BCR_4 (100% carbon fiber). BCRs have been tested under bending while the variation of the electrical resistance was simultaneously monitored. The correlations obtained between deformation and electrical resistance show the suitability of the rods to be used as sensors. The fractional resistance change versus strain plots show that the gage factor increases with decreasing carbon fiber content.

1 INTRODUCTION

External dynamic loading and severe environmental conditions are the major cause of deterioration in reinforced concrete structures. This deterioration may cause serious structural damages. The corrosion of steel reinforcing rebar is the dominant cause of concrete structure degradation. The most effective way to prevent corrosion of steel rebar is the use of a corrosion resistant reinforcing material, such as fiber-reinforced-polymer (FRP) composites. The types of fiber-reinforced-polymer composites best suited for the reinforcement of concrete are those providing high strength, high stiffness, and environmental compatibility with concrete. Most commercial FRPs are rod-like elements that are pultruded, shaped, and treated so that surface texture provide mechanical adherence with concrete.

Nevertheless, the interest in the safety of concrete structures has increased and monitoring and maintaining their safety has become a main goal. To achieve this main goal monitoring systems that can be applied to the reinforced concrete elements are required. The damage sensing is conventionally performed by attached or embedded damage sensors, such as optical fibers, acoustic sensors, etc. however these sensors have limited application because of high cost, low durability, and limited sensing volume and spatial resolution. One solution is that the materials themselves can possess a self-diagnosing function for fracture; thus, strong and heavy design, complex and expensive equipment and numerous sensors becomes unnecessary, the so called self-diagnosing structural materials (Muto, 2001), (Chung, 1997).

Structural materials have evolved from materials that are mechanically strong (such as steel) to materials that are both strong and lightweight (such as composite materials) and most recently to materials that are both strong and self-monitoring (Muto, 2001). By definition, a self-monitoring material is one which can sense its own strain and damage. It can be considered a smart material. However, in contrast to smart materials such as optical fibers, piezoelectric sensors, etc., the self-monitoring materials are themselves structural materials. Thus, in contrast to structures rendered smart by embedded or attached sensors, self-diagnosing structural materials

are intrinsically smart, so there is no need of embedded or attached sensors. For example, the basic principle of the carbonaceous smart structural material to detect strain or damage lies in the electrical conductivity of the carbon fibers, as already known from the literature (Chung, 1997). As the carbon fibres are electrically conductive, the composite itself can exhibit electrical properties, which will depend upon strain, damage and temperature. The self-diagnosing structural material will, in this way, provide determination of the strain or damage by measuring the change in the electrical resistance during real time loading (Bakis, 2001).

Several investigations carried on this subject are as follow: hybrid, carbon fibre (CF) and glass fibre (GF) reinforced composite rods were tested for sensing performance. It was reported that the memorizing ability of the material resulted from the increased residual resistance of the composites after loading-unloading cycles, which was in dependence with the previously applied maximum strain. Under pre-stressed condition the composite gave remarkable memorizing ability with lower detectable strains. A main drawback raised by this study is related to damage detection: damage cannot be detected in the early stages, unless the carbon fibres are replaced with carbon particles (Okuhara, 2005). In the later case, on the other hand, massive production is more expensive and demanding.

Another study using a glass fibre reinforced composite rod incorporating carbon particles dispersed in the resin reported that the material can be used as an autonomous sensor, as it can monitor strain without external pre-stress condition (Okuhara, 2007).

In a hybrid composite, the carbon fibre type and the relative percentage of carbon fiber and glass fiber are factors that determine the variations of the electrical resistance upon stress and/or strain. As mentioned before, the main drawback of hybrid CF-GF reinforced polymer composites is the lack of sensitivity at lower strains, which can be improved by pre-stressing (Nanni, 2007).

Nevertheless, by modifying fibre reinforced polymer composites (FRP) concentration formulations and geometry (e.g., carbon fibres core and glass fibres insulating outer layer components), the electrical response of the composites can be tailored to a desired value (Nanni, 2006)

In this work the monitoring capabilities of braided reinforced composite rods (BCRs) and the differences in the sensing behavior related to the different carbon fiber content are investigated.

2 MATERIALS AND METHODS

Three types of braided composite rods with different carbon fiber content (23%, 77% and 100%) were prepared by the single step process of braiding and simultaneous resin impregnation. Braided reinforced composite rods have been produced on a vertical braiding machine with an incorporated impregnation system (Gonilho Pereira, 2008). Table 1 shows the BCR composition while Figure 1 shows the correspondent BCR cross-sections. A total number of 14 samples were prepared and evaluated.

Table 1. BCR compositions.

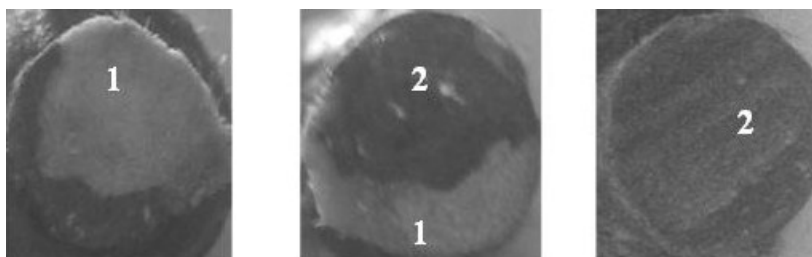| Type	Fiber composition	Fiber %	N° of rovings	Linear mass (tex)
BCR_2	E-glass/Carbon	77/23	18/3	1600/900
BCR_3	E-glass/Carbon	53/47	53/47	900
BCR_4	Carbon	100	12	900

Figure 1. BCR cross-sections for BCR_2, BCR_3 and BCR_4. 1 – Glass fiber   2 – Carbon fiber.

The testing procedure carried on the BCR is based on the electrical resistance measurement during simultaneous application of a deformation in a cyclic three-point bending test (Figure 2). The testing parameters are shown in Table 2. Cyclic three-point bending tests (Table 3) were carried on a Universal Testing Machine – Autograph IS (Shimadzu) 500N. The electrical resistance measurement was carried on a digital multi-meter (Agilent, 84401A). The electrical signal was acquired through golden wires attached to the cross section of the samples with silver paint.
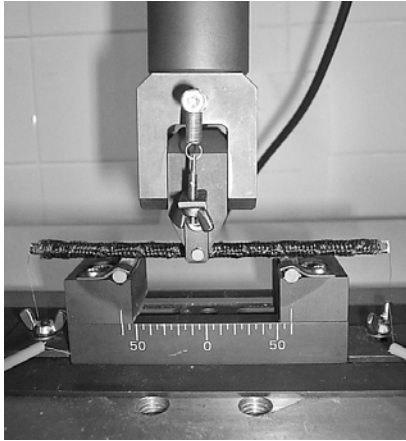

Figure 2. Sample set-up during testing.

Table 2. Dimensional characteristics of the BCR s.

BCR type	Diameter (mm)	Linear mass (g/m)
BCR_2 (glass 77%, carbon 23%)	5,66	36,16
BCR_3 (glass 53%, carbon 47%)	5,80	39,89
BCR_4 (carbon 100%)	6,40	40,47

Table 3. Testing parameters.

Parameter	Settings
Nº of cycles	4
Load cell	500 N
Span	6 cm
Displacement limit	0,5 mm
Cross-head speed	0,3 mm/min
Sampling interval	500 ms

3 EXPERIMENTAL RESULTS AND DISCUSSION

Representative examples of the two types of behavior obtained for the mechanical and electrical results from the cyclic loading three-point bending tests and the simultaneous electrical resistance measurements are presented in Figures 3 and 4 for the BCR samples tested.

Figure 3 presents the increase in the electrical resistance with increasing displacement. Figure 4 shows curves showing the decrease of the electrical resistance with increasing deformation. In general, the electrical resistance during loading and unloading increases linearly at lower displacement values and nonlinearly at higher ones. In the case of the inverse response, during decrease of the electrical resistance and deformation increase, the nonlinearity is less evident. Whether it was a reverse or inverse response in both cases the tested sample showed the change of the electrical resistance in proper compliance with the change of its deformation. The main factors influencing the type of response of each sample was the relative position of the fibers and the resin inside the rods, or more precisely the carbon fiber placement along the length of the rods.
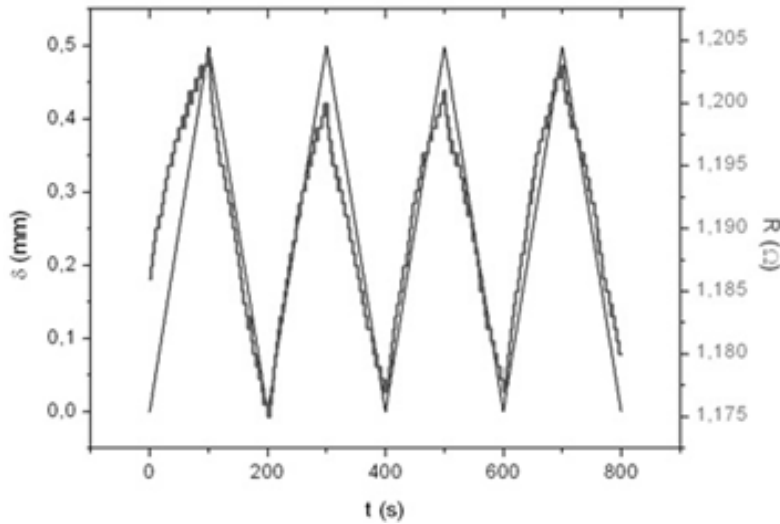
Figure 3. Displacement, resistance change and time dependence for type BCR_4 (100% of carbon); Positive response of tested samples.
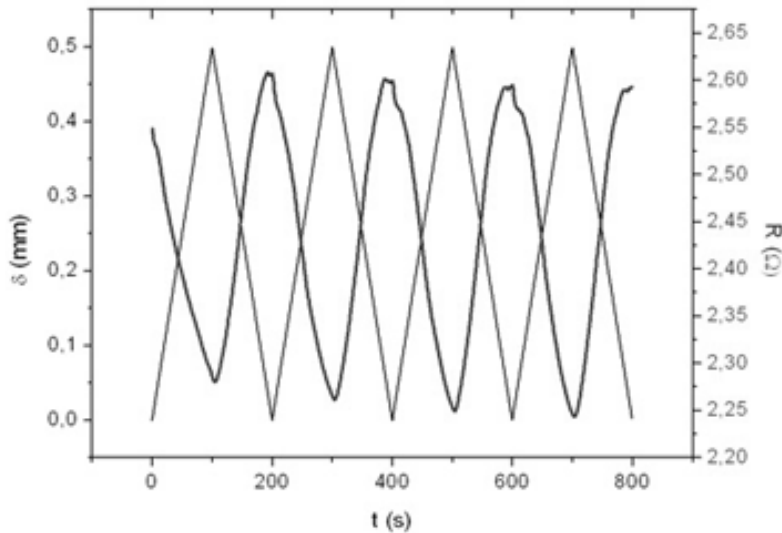

Figure 4. Displacement, resistance change and time dependence for type BCR_2 (77% of glass, 23% of carbon); Negative response of tested samples.

As shown in Figure 1, from the images of the samples cross-sections, there are variations in the carbon fiber placement. The fibers are not placed uniformly on one side of the cross-section and, more important, the distribution is not the same on both cross-sections of a rod sample. In this situation, increasing of the resistance with increasing deformation occurred when the carbon fibers are placed on the tensile side and the opposite behavior when their placement is on the compression side of the bending rod. This issue indicates the relevance of controlling carbon placement uniformly along the length of the rod. This is a difficult step on the production process, which sometimes results in non-uniformity along the length of the rods as the braiding process rotates the fibers [8].

On the other hand, for each rod, the cycles are reproducible, confirming the reliable sensing property of the rods. The difference between the peak values in each of the cycles is around 0,01 Ω to 0,02 Ω.

The range of the initial electrical resistance for the first typeBCR_2 (77% glass, 23% carbon), vary from 1,46 Ω to 3,92 Ω, for the second type BCR_3 (53% glass, 47% carbon) from 1,11 Ω to 1,50 Ω and for the third BCR_4 (100% carbon) from 0,80 Ω to 1,37 Ω.

Furthermore, for the comparison of the sensing behavior differentiation due to carbon fiber content, the strain ε ($\times 10^{-2}$) and the fractional resistance change $\Delta R/R_0$ of the three types of BCR are presented in Table 3. The strain is calculated from the displacement and the fractional resistance change is calculated from the electrical resistance change, the values from the two parameters are presented over time of 100, 300, 500 and 700 seconds.

Table 4. Strain and fractional resistance change of the BCR (mean values).

	Cycle No. t (s)	1 100		2 300		3 500		4 700	
Type	Sample No.	ε $\times 10^{-2}$	$\Delta R/R_0$	ε $\times 10^{-2}$	$\Delta R/R_0$	ε $\times 10^{-2}$	$\Delta R/R_0$	ε $\times 10^{-2}$	$\Delta R/R_0$
	Xm								
BCR_2	1, 2, 3	0,48	-0,10	0,48	-0,11	0,48	-0,12	0,48	-0,12
	12, 13, 14	0,47	0,08	0,47	0,07	0,47	0,07	0,47	0,06
BCR_3	3, 7, 12	0,48	0,04	0,48	0,02	0,48	0,01	0,48	0,01
	6, 10, 13	0,48	-0,06	0,48	-0,07	0,48	-0,07	0,48	-0,07
BCR_4	5, 7, 12	0,55	0,02	0,55	0,01	0,55	0,01	0,55	0,01

Figure 5 shows the correlation between the fractional resistance change ($\Delta R/R_0$) and the flexural deformation (ε) for of all the three rod types BCR_2 (77% glass, 23% carbon), BCR_3 (53% glass, 47% carbon), BCR_4 (100% carbon) in the time range (0-100sec; 200-300sec; 400-500sec; 600-700sec) – first half of the cycle (loading sequence), or (100-200sec; 300-400sec; 500-600; 700-800sec) – second half of the cycle (unloading sequence).

Figures 5 A1 and 5 A2 represent the positive type of response. Figures 5 B1 and B2 represent the negative type of response. The numbers 1 and 2, respectively, represent the loading and unloading sequence of the cycles. Furthermore the trend lines are presented for each of the plotted curves showing the linear accordance between the fractional resistance change and the deformation.
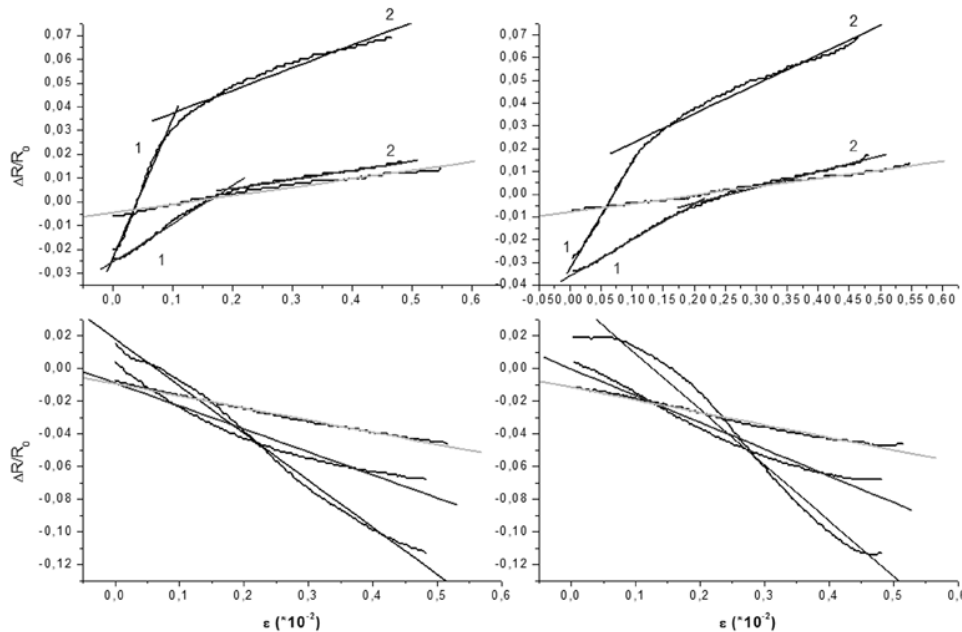

Figure 5. Fractional resistance change dependence on deformation. Comparison between the three types of tested samples: BCR_2, BCR_3, BCR_4.

1 – loading	A – positive response	——	BCR_2 (77% of glass, 23% of carbon)
2 – unloading	B – negative response	——	BCR_3 (53% of glass, 47% of carbon)
		——	BCR_4 (100% of carbon)

In the case of the positive response of types BCR$_2$ (77% glass, 23% carbon) and BCR$_3$ (53% glass, 47% carbon) the plotted curves were divided into two parts, presented by two trend lines (1 and 2) for each curve. The reason for this division is the sharp slope of the curves in the interval from 0 to 0,1 for type BCR$_2$ (77% glass, 23% carbon) and 0 to 0,2 for type BCR$_3$ (53% glass, 47% carbon) as a function of the strain (ε). The corresponding trend equations established in this study are further shown in Table 4, as well as the resulting squared regression values and gage factors in Table 5.

The fractional resistance change was expressed from the linear trend equations as a function of the strain for each of the three types of the BCR rods, for the loading and unloading part of the cycle (1 and 2) for both types of responses.

The overall linear relationships of the two parameters obtained in the work showed a high satisfactory level of BCR sensing capability.

As can be seen in Table 5, the gage factor for type BCR$_2$ (77% glass, 23% carbon) is almost five times higher than that for the type BCR$_3$ (53% glass, 47% carbon) and BCR$_4$ (100% carbon). The gage factor of type BCR$_3$ (53% glass, 47% carbon) is slightly higher.

Table 5. Gage factors (GF) and squared regression values (R^2) of established trend equations.

Type	GF		Xm	R^2		Response
	1*	2*		1	2	
BCR$_2$	0,58100	0,46312	0,52206	0,98965	0,99602	Positive
	0,09554	0,12951	0,11253	0,95651	0,97279	
	-0,28869	-0,34058	-0,31464	0,99218	0,97288	Negative
BCR$_3$	0,16095	0,15806	0,15951	0,98918	0,99668	Positive
	0,03847	0,07018	0,05433	0,98339	0,98172	
	-0,14084	-0,16380	-0,15232	0,93925	0,96892	Negative
BCR$_4$	0,03581	0,03702	0,03415	0,97118	0,99305	Positive
	-0,07451	-0,07684	-0,07568	0,99448	0,98699	Negative

The gage factor, known as the strain-sensing factor, shows the sensing behavior of the BCR samples. It increases with the decreasing of the carbon fiber percentage. This means that type BCR$_2$ (77% glass, 23% carbon) has the most reliable monitoring behavior.

It is interesting to compare the resulted gage factors of the braided composite rods with other materials for the same applications. For example in a study of a carbon nanotube strain sensors, it was investigated that the range of the gage factor was between 1 and 5, depending on the percentage of the single walled carbon nanotube (SWCNT) polymer composites, and better sensitivity was established in the range of 3 to 10wt% of the SWCNT in the polymer (Kang, 2006).

Another study, investigating a multi walled carbon nanotube (MWCNT) films used as strain sensing material, reported that the calculated gage factors were 2, 3,09 and 3,76, respectively, for 3 types of samples (Li, 2008).

Taking these examples into comparison with the investigated samples in this study, it is evident that the gage factors calculated for the BCRs are all less than 1, much smaller than the example studies set forth above. The reason for these small values of the gage factors would be, as mentioned, the higher percentage of the carbon component. On the other hand, the main advantage of the present materials is the superior reinforcing capabilities and therefore the combination of reinforcing and sensing capabilities.

4 CONCLUSION

This work represents a contribution to develop monitoring systems for civil engineering structures in order to improve their sustainability. The final goal of this study is to develop such on–line monitoring system, by the application of braided reinforced composite rods (BCR) in concrete structures.

This paper reported on the influence of carbon fiber amount in the sensing proformance of braided reinforced rods using glass and carbon. It was proven that all three types of BCR used can stand as a self-sensing material. The electrical contact set-up was effective in the purpose

of resistance stabilization and measurent.Two types of responces were obtained by the BCR. Positive GF, in the case of the carbon fibreplaced inthe area subjected to tensile and negative GF, in the case of the carbon fibre placed in the compressive side of the rod. Furthermore, the GF increased with decreasing carbon fiber content. The most reliable monitoring behavior was given by type BCR_2 (77% glass, 23% carbon) with the smallest carbon fiber content.

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