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Self-sensing CF-GFRP rods as mechanical reinforcement and sensors of concrete beams

F Nanni[1], F Auricchio[2], F Sarchi[2], G Forte[1] and G Gusmano[1]

[1] Department of Sciences and Chemical Technologies, University of Rome 'Tor Vergata', Italy
[2] Department of Structural Mechanics, University of Pavia, Italy

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Abstract
In this paper testing carried out on concrete beams reinforced with self-sensing composite rods is presented. Such concrete beams, whose peculiarity is to be reinforced by self-sensing materials able to generate an alarm signal when fixed loads are reached, were designed, manufactured and tested. The reinforcing rods were manufactured by pultrusion and consisted of self-sensing hybrid composites containing both glass and carbon fibres in an epoxy resin. The experimentation was carried out by performing simultaneously mechanical tests on the reinforced beams and electrical measurements on the composite rods. The results showed that the developed system reached the target proposed, giving an alarm signal.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, the use of composite materials in concrete structures in the form of rods, bars and laminates has increased dramatically due to their good mechanical and physical properties [1]. Composite reinforcements, in fact, can offer interesting mechanical properties but, at the same time, do not suffer corrosion attack that, as widely known, can cause large damage and high maintenance costs [2]. On the other hand, the lack of ductility of FRP components was initially considered a strong limitation to their use in the field of constructions, since it involves the problem of structure safety. In fact, the opportunity of having good plastic deformation in concrete reinforcing materials, such as that offered by steel elements, is an highly appreciated quality since it allows us to prevent sudden and fatal fractures. Incipient dangerous deformations and cracks, in fact, can be observed long before they become critical, bringing about structure collapse. Generally speaking, FRPs offer lower values of ultimate strain than that of more traditional metallic reinforcing elements, and this aspect has limited, till now, their applications to concrete structures. To overcome this problem two parallel approaches were applied: the first one consisting of working on material composition in order to improve their mechanical properties; the second one consists of promoting and optimizing the use of health monitoring systems to check structures during their working life.

The first approach brought about identification of hybrid composites as the most suitable for concrete applications [3] in order to guarantee good strength and, most important, to reach some degree of ductility (usually called pseudo-ductility). Such hybrid FRPs are made of a small number of low-elongation–high-strength fibres surrounded by high-elongation–low-strength fibres, as in the case of carbon/glass hybrid composites [4]. In the case of hybrid FRPs, in fact, a so-called 'positive hybrid effect' was observed [5, 6] by which an ultimate strain higher than that reached by using only stiff carbon fibres was recorded. It seems, in fact, that after the carbon fibre failure the surrounding glass fibres can bear the load and transfer it back to the isolated broken carbon fibres. By this mechanism an overall increase in the component ductility is observed.

The second approach concerns a more accurate and increased use of efficient health monitoring systems applied to the structures. Together with the traditional NDTs [7, 8], innovative systems were proposed [9–11], that involve the use of new sensors and techniques, as in the case of fibre optics [12, 13] or piezoelectrics. Such solutions were successfully applied but had shown severe limitations due to different factors. First of all, in most cases, these techniques can be considered too invasive since, to be effective, they require the insertion of sensors near important structural positions and, moreover, the assistance of highly skilled personnel to be involved in their manipulation. The overall costs increase a lot.

More recently, a new trend occurred in the field of health monitoring that suggests realization of new materials, the so-called 'self-monitoring materials' [14], able to show contemporarily good mechanical characteristics and self-sensing properties. Recent studies, carried out on the applications of such materials in the field of construction engineering, had shown that it is possible to obtain either self-monitoring concrete or self-monitoring reinforcing elements to be inserted in concrete structures as replacement for steel rods [15]. In this direction some solutions have recently been proposed [15–18], among which some were presented by the present authors [19–21].

The experimentation carried out in the present paper acts in this scenario since it involves the use of hybrid composite rods made of carbon fibre–glass fibre reinforced polymer (CF-GFRP) as reinforcing self-monitoring elements in concrete beams. The idea is to realize a self-diagnostic structural composite able to offer both good mechanical and self-sensing properties. The designed material consists of a hybrid composite rod made by an internal carbon core, that insures the self-sensing characteristics, externally covered by glass fibres to reach the necessary load-bearing abilities. The monitoring is performed by measuring the electrical resistance variation of the carbon fibres during their working condition. With this study the authors wished to realize a flexible system that can be designed every time to suit specific applications, in accordance with peculiar builders' needs.

In the material proposed, in fact, the carbon fibres are used as 'guard sensors': this means that they are required to break, giving an alarm signal (electrical resistance to infinity) when a fixed value of stress, that depends on the particular application, is reached. In any case, the proposed CF-GFRP rods are designed so that, after the carbon failure, the glass part can still bear mechanical load, before collapsing.

In the present study the results obtained by experimental tests carried out on concrete beams reinforced by self-sensing CF-GFRP rods are reported.

2. Materials and methods

2.1. Specimen preparation

The proposed self-sensing CF-GFRP rods consist of an internal conductive core made of carbon fibres coated by an external coaxial GFRP skin, as shown in figure 1. The internal carbon core consists of a pultruded rod, 1000 mm long and with a diameter of 0.5 mm, made of unidirectional carbon fibres (RC-30). Electrical contacts were provided at each end of the carbon rod by bonding metallic wires with silver adhesives.

The external coaxial skin is made of unidirectional glass fibres (RV-18/F—2400tex), consisting of a bunch of ten glass fibre bundles. In all cases a Renlam M-1 epoxy resin, with HY956 hardener, was used as matrix. Table 1 summarizes the main characteristics of the realized CF-GFRP reinforcing rods. In the described material, the relative number of carbon fibers versus glass fibers is a very important parameter to obtain the desired behaviour. Carbon fibres are, in fact, much stiffer than glass fibres, and they have a shorter ultimate elongation. When the composite is initially loaded, both reinforcements can bear the applied load. With increasing applied load, carbon fibres first fracture, because their ultimate elongation is reached, while glass fibres can bear the applied load. When carbon fibres fracture, the whole load is born by glass fibres. This behaviour guarantees the self-diagnosing ability of the composite.

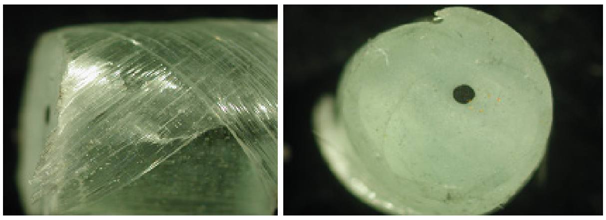

Figure 1. A CF-GFRP rod made of an internal unidirectional carbon fibre rod inserted in a glass fibre bundle: (a) transverse sight, (b) section.

Table 1. Main characteristics of CF-GFRP reinforcing rods.

	CF-GFRP rods
∅ pultruded internal carbon rod (mm)	0.5
Overall diameter (mm)	6
Global length (mm)	1000
Number of glass fibre bundles	10
Initial electrical resistance (Ω)	≈60

To insure good bond and mechanical interlocking to concrete, the composite rods were externally wrapped with two crossed glass tows. Finally, the obtained composite rods were inserted into concrete beams.

The beams, $1000 \times 200 \times 100$ mm^3, had two reinforcing CF-GFRP rods placed in section at 5 cm from the beam external surfaces, at 10 cm from each other and at 2.5 cm from the bottom (figures 2 and 3). In the following the CF-GFRP elements will be indicated as rod 1 and rod 2. Additional tests (EN 10080) were carried out on analogous beams reinforced with conventional S 500 Φ6 steel rods. In all cases C50/60 concrete was employed.

2.2. Testing

The reinforced beams were mechanically tested by performing three-point bending tests with 80 cm span in static conditions.

Electrical measurements were performed by imposing, during the mechanical tests, a constant current and evaluating the voltage decay. An NI Field Point SG104 system was used to collect the electrical data. The electrical scheme of the measurements is that of the Wheatstone bridge, in which a bridge leg is the specimen and another leg is provided by a completion resistor necessary to obtain the exact bridge balancing.

3. Results and discussion

The results of the bending tests carried out on both steel and FRP reinforced concrete beams showed that the structures

Table 2. Results of the bending tests.

	Fracture load (kg)	Load at which rod 1 activated (%)	Load at which rod 2 activated (%)	Max electrical resistance variation of rod 1(%)	Max electrical resistance variation of rod 2(%)
Steel reinf. beam	1600	—	—	—	—
CF-GFRP reinf. beam 1	1200	—	83	6.8	∞
CF-GFRP reinf. beam 2	1110	46	85.6	∞	∞
CF-GFRP reinf. beam 3	1220	97	86	∞	∞

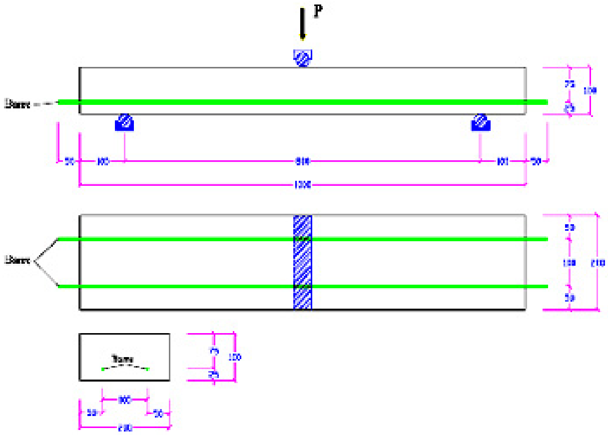

Figure 2. Beam design containing two reinforcing rods.

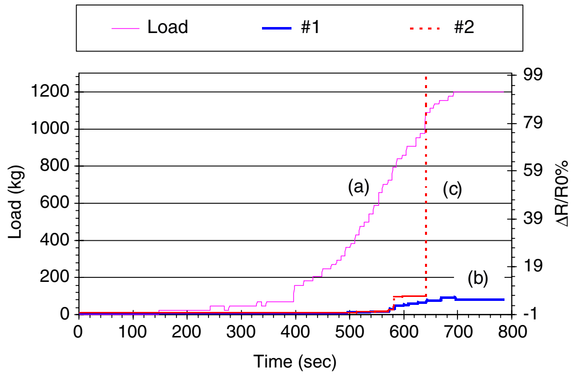

Figure 4. Mechanical and electrical results on beam 1: (a) load/ time curve; (b) $\Delta R/R_0\%$/ time curve of self-sensing rod 1 and (c) $\Delta R/R_0\%$/ time curve of self-sensing composite rod 2.

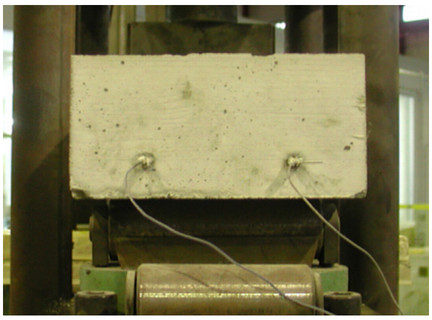

Figure 3. A picture of the section of a self-sensing CF-GFRP rods reinforced beam.

collapsed due to the reinforcing element fracture. In the case of the steel reinforced beam failure occurred at about 1600 kg, while in the case of CF-GFRP reinforced concrete the maximum load was about 1200 kg, showing that, even in this case, good mechanical performance is guaranteed. Interesting results were also obtained from electrical measurements. Table 2 summarizes the results of the tests performed on all types of beams.

Rod 2 of beam1 (figure 4) correctly acted as a guard, since it broke at 83% ultimate strength, before the fracture of the beam occurred. It has to be remarked that the signal is too close to the beam final fracture to be considered an effective alarm signal; nevertheless, it has to be considered that this parameter can be tailored to the desired value, by modifying the hybrid composite formulation. Rod 1, instead, did not break, even after the beam breakdown. Its electrical resistance, in fact, does not go to infinity. Moreover, it is interesting to note that, besides the guard behaviour, the system proposed presents an electrical resistance variation able to describe the mechanical history of the beam.

Such behaviour is recorded starting from about 150 kg of load, when an increase of both CF-GFRP rods' electrical resistance variation is recorded. This performance is most probably due to the progressive breakdown of some of the carbon fibres of the rods. In the case of rod 1 such increase is continuous until the end of the test, showing that not all the carbon fibres broke. In the case of rod 2, instead, such continuous increase of electrical resistance is interrupted in correspondence with the sensitive element failure (electrical resistance to infinity). Nevertheless, in both rods, the recorded global change of the electrical resistance prior to failure is pretty small (6–7%) to employ the system as a sensor that punctually follows the mechanical history of the beam.

On the beam bottom surface, during the tests, some cracks started to appear in correspondence to the central axis (figure 5) in accordance to the beam design and loading conditions. As always occurs when reinforcing with composite elements, some cracks started to be visible immediately after load application (figure 5(a)); successively, the crack expands in the concrete, reaching the situation reported in figure 5(b), taken after CF-GFRP rod 2 activation. Figure 5(c) reports the collapsed beam.

The results of the tests carried out on beam 2 (figure 6) show that in this case the electrical resistance of both the composite reinforcing elements goes to infinity at ≈85% of the beam ultimate load, which corresponds to severe beam damage, as indicated by the steep increase of the load/time curve. The beam is not completely broken, but continues

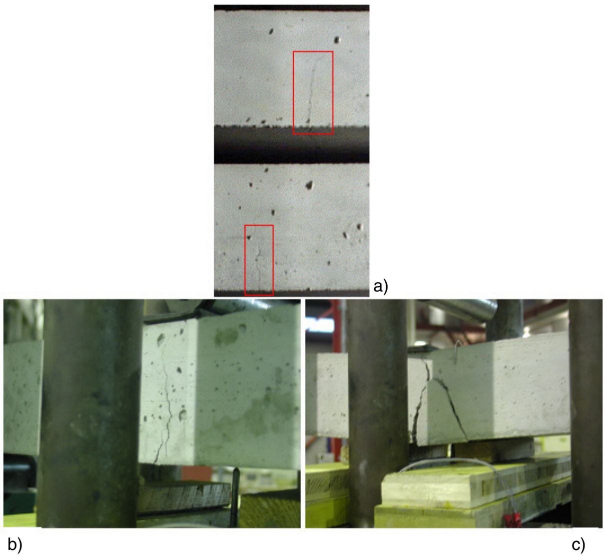

Figure 5. (a) Some cracks appearing on beam1 immediately after load application; (b) beam 1 after rod 2 failure and (c) beam 1 at failure.

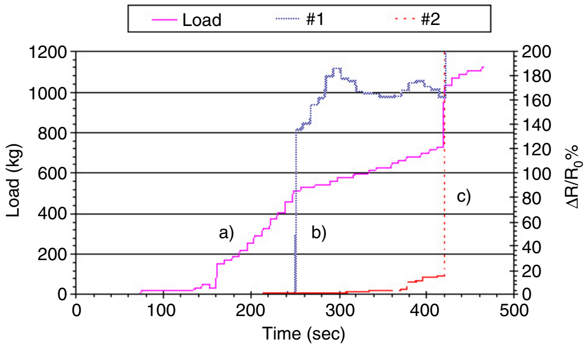

Figure 6. Mechanical and electrical results on beam 2: (a) load/time curve; (b) $\Delta R/R_0$%/ time curve of self-sensing rod 1 and (c) $\Delta R/R_0$%/ time curve of self-sensing rod 2.

to bear some load, about 100 kg, before final fracture. As previously noted, even in this case the electrical response is too close to the beam failure to be considered a useful warning system, yet this aspect can be successfully changed by adding more glass to the composite rod. Nevertheless, even after the carbon sensing parts of the rods were broken, their glass portion correctly continued to bear the load until the beam final fracture.

In this test, though, the two CF-GFRP reinforcing bars showed two different electrical behaviours. In the case of rod 1, in fact, a considerable electrical resistance variation of about 130% was recorded at 46% of the ultimate strength. It corresponds to a discontinuity of the beam load/time curve, due to partial damage occurring to the beam itself. The composite rod, however, continued to bear the load until its final fracture.

Such behaviour indicated that in the case of rod 1 the alarm signal can be considered the first sudden increase of electrical resistance, even if it does not correspond to a value of electrical resistance equal to infinity. This occurrence brought us to state that the alarm signal should be considered a sufficiently

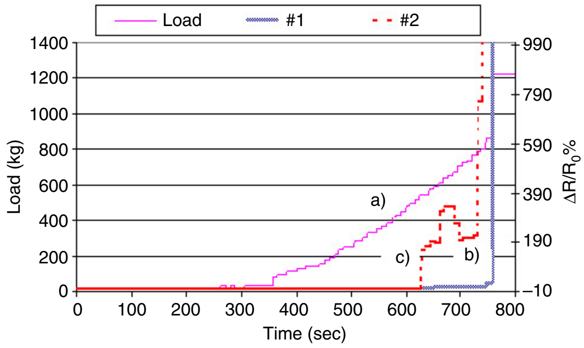

Figure 7. Mechanical and electrical results on beam 3: (a) load/time curve; (b) $\Delta R/R_0$%/ time curve of self-sensing rod 1 and (c) $\Delta R/R_0$%/ time curve of self-sensing rod 2.

high variation of electrical resistance (as an example >50%) even if it does not correspond to the complete carbon core rupture. Rod 2, instead, showed a more classic trend, since its electrical response is characterized by an initial negligible variation of electrical resistance, followed (at about 750 kg) by its continuous increase, up to the value of 19%, before going to infinity at the sensitive element rupture.

In the case of beam 3 (figure 7), rod 2 (curve (c) in figure 8) activated the guard behaviour and presented an intermediate very high electrical resistance variation of 190% at 45% of the ultimate load, and, in the end, went to infinity at about 86% of the ultimate load. The other rod (curve (b) in figure 7), instead, did not present any electrical resistance variation until final fracture, corresponding to the whole beam failure. The reported results had shown that in all three cases at least one of the two FRP rods placed inside the beams broke, giving an alarm signal at about 85–90% of the ultimate beam strength. Between the two FRP rods reinforcing each beam, the one that activates first depends, in turn, on the beam internal stress distribution, defects, etc. Only in the case of test 2 did both the rods of the beam activate, corresponding to two different moments of the test, always when beam damage occurred, as evident by the slope variations of the load/time beam curve. Moreover, this aspect is remarkable since it can help to localize the damage. As an example, from the graph of figure 6, it is possible to observe that the damage occurring to the beam at about 500 kg and after about 250 s was most probably localized near beam 1, since it presented a very high electrical resistance variation.

All the obtained results seem to suggest the consideration that a discussion on the meaning of 'sensor activation' has to be expressed. In fact, in two tests (2 and 3) one of the two sensors showed an important electrical resistance variation, which does not correspond to the whole sensor conductive core rupture, but which testifies that more or less severe damage occurred. Such signals, which are due to the fracture of a small number of carbon fibres inside the conductive core, are extremely interesting and cannot be ignored during the sensor data analysis. It is therefore necessary to state an electrical resistance variation above which the signal received has to be considered a message of damage, but which does not mean that the total fracture is reached, since the conductive element can still offer a finite, even if high, electrical resistance. More detailed experiments need to be carried out in order to establish a meaningful value, but, from the results shown here, it seems that it should be placed between 50 and 100% of electrical resistance variation.

4. Conclusions

In this paper hybrid glass/carbon self-sensing FRP rods were manufactured and inserted into concrete beams as sensing reinforcement. Such elements, in fact, can act contemporarily as structural reinforce and as sensor of the beam structural state. The proposed rods present a 'guard' behaviour, which gives an alarm signal when a fixed load is reached, depending on the composite formulation.

The performed tests showed interesting results since it was possible to obtain alarm signals from the electrical measurements carried out on the CF-GFRP rod reinforced beams. In all tests, in fact, at least one of the two sensitive elements breaks, giving an electrical resistance equal to infinity. Nevertheless, such breakdowns always occurred at high values of the ultimate loads, too close to the beam final fracture, demonstrating that the system needs to be improved by varying the hybrid composite formulation. Moreover, another interesting phenomenon was observed from the electrical measurements: one of the sensors showed an important electrical resistance variation which does not correspond to the sensor rupture, but which testifies that a more or less severe damage occurred and that this can be somehow considered an alarm signal. This aspect needs to be further investigated.

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