Health monitoring performances of FRP self-sensing composites rods in concrete beams

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ABSTRACT: In this paper the monitoring performance of two different self-monitoring reinforcing composite rods in concrete beams were measured and compared. Both types, consisting of hybrid composite materials containing glass fibres and a carbon phase, make use of the presence of conductive carbon to perform electrical measurements. The carbon phase is either in form of unidirectional carbon fibres (CFs) or in form of carbon nanoparticles (CnPs). The manufactured self-sensing rods were mechanically tested and inserted into concrete beams. The results showed that both type of materials present self-sensing properties, even if with different monitoring behaviors: CnP-GFRPs are able to perform a reliable continuous monitoring, while CF-GFRP rods are more suitable for non-continuous monitoring. The effect of glass content in self-monitoring performance was evaluated too.

1 INTRODUCTION

Recently the use of composite rods as alternative reinforcing element of concrete beams is becoming always more attractive, due to their good corrosion resistance. Nevertheless, their mechanical behavior, which is linear elastic to failure, is a big concern to insure structures safety. To overcome such drawback, many different approaches have been proposed, among which the use of self-monitoring materials. Two solutions are possible to achieve a self-monitoring material: the first one concerns the introduction of various types of sophisticated sensors into the material (usually these are complex and expensive solutions, not suitable for civil applications), the other approach involves the realization of bi-functional hybrid polymer composites, able to behave contemporarily as sensor and structural reinforce of concrete. Such monitoring system is easy to produce, low cost and involves simple measurements. Composite materials are often chosen because of their increasing use in concrete technology and because of their intrinsic versatility and possibility to include separate phases within the matrix. Usually, the self-monitoring task is performed by controlling the variations of a physical property (electrical resistance) of an electrically conductive element (usually carbon) embedded into the matrix. The conductive element can be in form of long fibres, as in the case of CF-GFRPs (Carbon Fibre Glass fibre Reinforced Plastic) or in form of particles or nanoparticles CnP-GFRPs (Carbon Particles Glass Fibre Reinforced Plastic). In the first case the electrical resistance variation is due to a number of fractures occurring in carbon fibres, nevertheless the sensitivity of the system is limited since a number of bridge contacts between neighbouring broken carbon fibres can always ensure the current flow. In the case of CnP-GFRP (Carbon Particles Glass Fibre Reinforced Plastic), instead, the electrical conductivity is due to the formation of a percolation network among conductive particles dispersed in an insulating media. As a consequence, higher sensitivity can be achieved, since a progressive reduction of current flow paths occurs at increasing strain, corresponding to the physical separation of the particles.

In this paper both hybrid CF-GFRP and CnP-GFRP rods were manufactured and tested by performing laboratory monotonic tensile tests. Glass fibres were used as structural part of the com-
posite, while carbon was inserted for the monitoring task. Successively the self-monitoring rods were inserted in concrete beams and tested by performing four points bending. Electrical measurements, i.e. electrical resistance variation, were carried out during mechanical tests, in order to evaluate the self-monitoring behaviour. The effect of glass content, i.e. glass/carbon ratio, on self-monitoring performance was evaluated too.

2 MATERIAL AND METHODS

2.1 CF- GFRPs

In these samples an internal CFRP rod ($\phi=0.5$ mm) was surrounded by external glass fibres (COFITECH 475 W 2400 TEX) by an handmade pultrusion process. In both cases epoxy resin (RENLAM M-1) was used. Samples with different number of external glass fibres, respectively 5, 10 and 15 bundles, were prepared as laboratory samples. Longer samples, with 10 external glass boundless were prepared for concrete testing. Table 1 reports the CF-GFRP samples major characteristics.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample for Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Sensitive element diameter [mm]</td>
<td>0.5</td>
</tr>
<tr>
<td>Overall diameter [mm]</td>
<td>3</td>
</tr>
<tr>
<td>Global length [mm]</td>
<td>200</td>
</tr>
<tr>
<td>N. Glass fibre bundle [#]</td>
<td>5</td>
</tr>
</tbody>
</table>

2.2 CnP-GFRPs

Samples with sensitive elements made of carbon nanoparticles (DEGUSSA XE 2B and epoxy resin RENLAM M-1) were prepared too. The nanoparticles were added to the epoxy resin and the mixture was mechanically stirred for 1 hour at 500 rpm, successively the hardener was added stirring for 20 minutes at 500 rpm. A glass bundle was embedded with this mixture to prepare the conductive core. The external reinforcement was again made of glass fibres (COFITECH 475 W 2400 TEX). Samples with different number of external glass fibre were prepared in order to find a correlation between self sensing properties and glass content. Table 2 reports the CnP-GFRP samples major properties.

<table>
<thead>
<tr>
<th>Sample Type A'</th>
<th>Sample for Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Type B'</td>
<td>Sample Type C'</td>
</tr>
<tr>
<td>Sensitive element diameter [mm]</td>
<td>2</td>
</tr>
<tr>
<td>Overall diameter [mm]</td>
<td>2</td>
</tr>
<tr>
<td>Global length [mm]</td>
<td>200</td>
</tr>
<tr>
<td>N. Glass fibre bundle [#]</td>
<td>0</td>
</tr>
<tr>
<td>Carbon content [%wt]</td>
<td>5</td>
</tr>
</tbody>
</table>

2.3 Mechanical and electrical test

Mechanical laboratory tests were carried out by performing monotonic tensile tests at a rate of 2 mm/min, with an Instron 5569J universal machine. During the tests, electrical measurements
were carried with a digital multimeter (2700 DMM KEITHLEY INSTRUMENTS) in order to evaluate the material self-sensing properties. In particular, electrical resistance variations of the sensitive carbon core was measured. Concrete beams reinforced with respectively type B and type C’ (both containing 10 external glass bundles) self-monitoring rods were cast and tested in bending condition. Electrical measurements were simultaneously carried out.

3 RESULTS AND DISCUSSION

3.1 CF-GFRPs

Picture followed shows the results of monotonic tensile tests carried out on CF_GFRPs, samples containing respectively 5, 10 and 15 glass bundles around on the sensor. The presented graphs report average results, being the standard deviations 8.86 for sample type A, 18 for sample type B and 31.1 for sample type C.

In all cases self-monitoring properties were found, in the sense that an electrical resistance variation is always recorded when the mechanical load is increased. Nevertheless, the maximum CF electrical resistance variation recorded prior to carbon failure is too small to be considered as a reliable continuous monitoring system. On the contrary, such a system can be usefully employed as “guard sensor”. In this perspective, the versatility, typical of composite materials, can be exploited to design and realise components which generate the alarm at specific levels of the component $\sigma_{\text{ultimate}}$. Such goal can be achieved by varying the CF/GF ratio. In fact, CFs breakage occurs at lower component $\%\sigma_{\text{ultimate}}$ as the CF/GF ratio decreases.

![Figure 1](image1.png)

Figure 1: Monotonic tensile test for CF-GFRPs specimens: Stress/time curve (continuous line) and $\Delta R/R_0/\%$ time curve (dotted line)

Figure 2 reports the results of CF_GFRP rods reinforced concrete beams tests. The carbon rod shows little sensitivity at low strains, nevertheless clear signals were recorded at beam damage.
Figure 2: Self-Sensing properties of CF-GFRP in concrete beam under bending conditions. Stress/time curve (continuous line) and $\Delta R/R_0$%/time curve (dotted line)

In fact, a severe crack occurred in concrete after about 250 sec as testified by the change in slope of the beam mechanical curve. At the same time the electrical resistance variation presented a steep increase, which has in turn to be related to a severe damage in the CF-GFRP, i.e. a large number of broken carbon fibres. Nevertheless the presence of electrical signal allows to think that the composite rod is still working, until final fracture that occurred at about 420 sec were electrical resistance goes to infinite in correspondence to concrete beam failure.

3.2 CnP_GFRPs

Figure 3 reports the results of monotonic tensile tests carried out on CnP-GFRP laboratory samples with respectively 0, 5 and 10 glass fibre bundles around on the sensor.

Figure 3: Monotonic tensile test for CnP-GFRPs specimens: Stress/time curve (continuous line) and $\Delta R/R_0$%/time curve (dotted line)
Standard deviation for these specimens was evaluated: 5.57 for sample type A, 13.45 for sample type B and 19.1 for sample C.

These results show that CnP_GFRPs always present good self-monitoring properties with high electrical resistance variation. Samples with different numbers of glass fibre show different sensitivity at low strain: this characteristic is inversely proportional to external glass quantity. Differently from the case of CF-GFRP, this system show to be suitable for continuous monitoring.

Tests on CnP-GFRP reinforced concrete beams confirmed the results found in the laboratory tests, in the sense that a continuous monitoring of the beam loading state can be reliably performed by using such reinforcement (fig. 4). In fact, in this case, a continuous increase of electrical resistance is always associated with the continuous increase of load in the concrete beam.

![Figure 4: Self-Sensing properties in Cn-GFRP reinforced concrete beam.](image)

4 CONCLUSION

In this work it was evidenced that both CF_GFRP and CnP_GFRP materials present self-sensing properties to evaluate the condition of strain and stress in concrete beam. Nevertheless the self-monitoring behaviour is different: CF_GFRP is more suitable for non-continuous monitoring, while CnP_GFRP can successfully perform continuous monitoring. Such result can be explained considering that when dealing with CF-GFRP the electrical resistance increase is due to sudden fibre fractures that cause the interruption of current flow, while in the case of CnP-GFRP a progressive separation of carbon particles or aggregates continuously occurs following the increasing strain, leading to higher sensitivity. Both behaviours of the two self-
monitoring systems were confirmed in concrete. Finally, the effect of external glass on the two self-monitoring materials was evaluated. In the case of CF-GRFRP it was found that glass quantity is a key parameter to use this material as “guard sensor”: higher glass/carbon ratios bring to early warnings, i.e. carbon fibres brake at lower strains generating electrical resistance to infinity. In the case of CnP-GRFRP, it was found the a lower amount of glass increases sample sensitivity at low strains. In the case of concrete reinforce, though, a certain quantity of glass must be employed to guarantee the necessary mechanical performance.

5 REFERENCES

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