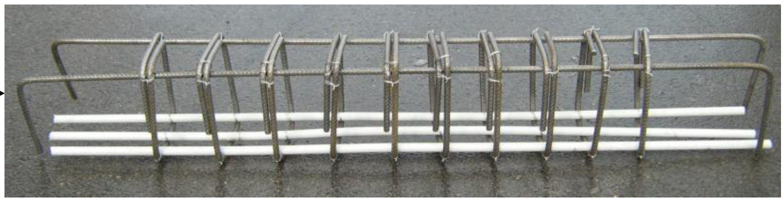
Innovative techniques for concrete reinforcement with polymers

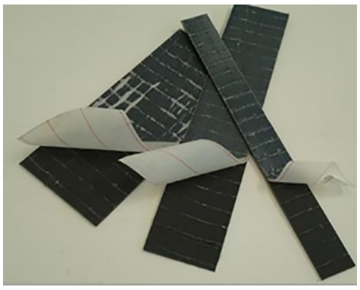
Graphical Abstract

PET bars



FRC

CFRP strips

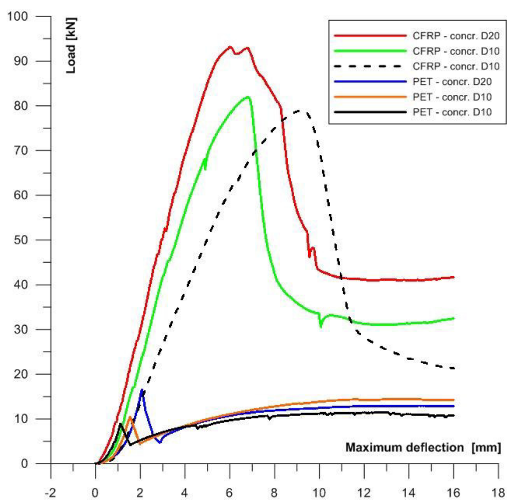


FRC

Specimens manufacturing

tests

bonding effect



increased ductility of FRC especially with CFRP strips

Future tests on lager samples:

1. concrete pavements
2. massive concrete elements
3. New Jersey barriers
4. etc…elements in aggressive environment and with the need of a high ductility

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3

INNOVATIVE TECHNIQUES FOR CONCRETE REINFORCEMENT WITH POLYMERS

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Abstract: In this work the results of a series of preliminary tests on concrete beam specimens reinforced with PET and CFRP are shown and discussed. The novelty in the tests lies in the use of a waste material with promising results. The reinforcement is made with PET and CFRP are arranged as continuous bars and strips, respectively. They are positioned inside the specimen, in the same position of the steel bars in a reinforced concrete element. For both cases it is noticed that they limit the presence of cracks and, especially, avoid and/or reduce the corrosion processes in reinforced concrete structural elements. In particular, the concrete-fibers adhesion and the global behavior of these fiber reinforced concretes is analyzed in order to evaluate the possibility of future investigation. However, the results of the tests showed a better behavior for specimens reinforced with CFRP strips.

Keywords: Fiber reinforced concrete, experimental tests, PET bars, CFRP strips, bending strength, concrete-reinforcement adherence.

1. INTRODUCTION

Concrete is a building material whose main drawback is its very low tensile strength, so low that it is often completely neglected in the calculus models. If concrete is today by far the most widely used building material in the world is thanks to reinforcement bars that make up for its poor tensile strength and brittle behavior. Steel reinforcement is often utilized but also reinforcement made with other materials are used [1-3]. Among these, polymeric materials are gaining success in recent decades. The use of such reinforcement has been also codified in a standard from FIB (Federation Internationale du Beton) [4]. National and international research is focusing, in particular, on the use and re-use of waste polymeric materials [5-16]. In this way it is possible to combine the advantages in terms of a better behavior of the mixture with those derived from the exploitation of large quantities of waste that would otherwise be used in landfill, incineration and recycling. The recycling of waste materials, in fact, is one of the most important problems nowadays and in the future that people must try to solve in every possible way.

The present study mainly concerns the use of polyethylene terephthalate (PET) and Carbon Fiber Reinforced Polymers (CFRP) in concrete. Tests have been performed utilizing them as reinforcement for concrete, showing for them good characteristics of adhesion with concrete. Previous pull-out tests confirmed this property for PET [17], while for CFRP most tests principally aimed to determine the adherence between the polymer and the bonding material utilized to externally stick the fiber reinforcement to the surface of the concrete element [18-19]. Modeling has been proposed for such confining effect of FRP [20]. Also investigation on the axial behavior of confined and unconfined concrete beams exposed to aggressive environment has been performed [21]. Some studies refer to the bonding produced by CFRP in beams damaged for corrosion of the steel bars [22-23]. Actually, they are analyzed on restored beams to get the level of confidence in using FRP for strengthening corroded beams.

In this paper, in accordance with the concept of environmental sustainability, the aim is to utilize CFRP strips and PET bars as reinforcement in substitution of steel in concrete elements subject to bending forces. The principal novelty of the present study is the use of a waste material such as PET with promising results. In this case the small steel long bars present in the reinforcement cage of the concrete element have a very low contribution to the strength capacity of the section, they are inserted with the aim of keeping the stirrups in place.

Bond deterioration between steel reinforcement and concrete is one of the main reasons for structural degradation of corroded r.c. beams [24-25]. Both flexural capacity and ductile behavior are impaired by corrosion induced bond weakening.

One of the main problem of steel reinforcement, in fact, is its high corrosivity due to external atmospheric agents, which produce a fast degradation of constructions. It is a very important problem to face for concrete buildings in order to keep them reliable and operative for a long period of time.

This research is only preliminary but it gives new perspectives to the use of FRP for concrete reinforcement with the aim of giving a longer life to concrete structures.

The study presents the results of a series of preliminary tests on concrete specimens reinforced with PET and CFRP arranged inside the element as bars and continuous strips, respectively. Results are shown and discussed to highlight the different behavior and the pro and cons of the two techniques.

2. EXPERIMENTAL PROCEDURE

Six specimens in concrete were realized: three specimens were reinforced with PET bars and three specimens were reinforced with carbon fiber pultruded (CFRP) strips. All specimens had the same geometrical dimensions but are manufactured utilizing two different concrete typologies with aggregates of different sizes, as better described in sect. 2.1.

2.1 Characteristics of the materials

2.1.1 Concrete

Two different concrete castings were prepared during two different periods of the year, with different environmental conditions.

Concrete type 1:

C20/25 concrete [26-27] with a maximum diameter of the aggregates ≤ 20 mm and a consistency class equal to S4 from the slump test, at an external temperature of 25°C.

Concrete type 2:

C20/25concrete, with a maximum diameter of the aggregates ≤ 10 mm and a consistency class equal to S4 from the slump test; in this case the external temperature was lower, around 20°C and there was a rather strong wind.

It must be highlighted that the second concrete casting was much more fluid and, therefore, more workable respect to the first one.

2.1.2 PET reinforcement

PET is not much used in Structural Engineering, unless as a material for thermo-acoustic isolation. In Civil and Geotechnical Engineering it is principally utilized as geo-composite cover for drainage.

In the present paper we want to investigate on the possible use of this fiber reinforcement with the same function of steel reinforcement inside a structural element. This kind of research started some years ago at the Technical University of Bari on the use of polymers and waste polymers (i.e. bottles of water) to improve the brittle behavior of concrete.

The possible use of PET for reinforcement of structural elements in concrete is quite new. Its ductility and resistance to chemical attacks from aggressive environment (such as marine environment, industrial environment) make it a possible substitutive of steel in absorbing the tensile stress in structural elements. In addition its high ductility makes it good to be utilized in those cases where impact loads can occur (airport pavements, new jersey, and so on).

PET utilized for the specimens is provided as long bars by the production company, Plastotecnica Emiliana s.r.l., Bologna, Italy. Its mechanical characteristics are shown in Table 1; they have been obtained at a temperature of 20-21°C.

Table 1. Mechanical properties of PET provided by Plastotecnica Emiliana s.r.l., Bologna, Italy.

Density (g/cm^3)	1.38
Tensile strength (N/mm^2)	90
Elongation at break (%)	>20
Elastic modulus (N/mm^2)	3000
Resilience (KJ/m^2)	KB
Hardness test with ball identer (N/mm^2)	180
Coefficient of friction against steel	0.22
Absorption of moisture in the standard climate (%)	0.2

2.1.3 CFRP reinforcement

CFRP has been utilized in the tests in the shape of strips having the mechanical characteristics provided by SIKA S.p.A, Switzerland (see Table 2). The strips adopted in the tests are of CarboDur type, specifically Sika CarbonDur M.

Table 2. Technical data sheet of CarboDur (by SIKA S.p.A, Switzerland).

Sika CarboDur sheets		
Description	Polymer reinforced by carbon fibers in an epoxy matrix	
Volume content of fiber	> 68%	
Density	1.60 g/cm^3	
	Sika CarboDur S	**Sika CarboDur M**
Elastic modulus E	165000 MPa	210000 MPa
Tensile strength	3100 MPa	3200 MPa
Strein at break	> 1.70%	> 1.35%

CFRP strips are utilized as a high resistance reinforcing system for different structural materials such as reinforced concrete, masonry, stone works, steel, aluminum and timber. They have a reduced weight, are easily manageable, and can be directly cut on site to the desired length with a hacksaw. They are usually utilized as reinforcing element for retrofitting of existing structures: bending and shear reinforcement of beams, consolidation of arches and vaults, recovery of columns with the method of hooping. Figure 1 shows some different shapes of CFRP sheets and strips.

Fig. 1. CFRP Sheets and strips.

Table 3 collects the principal mechanical characteristics of the materials utilized for the test specimens, steel, PET and CFRP. They have been obtained from the technical data sheets provided by the production companies of each product. The values shown for steel are those codified in the Italian standard [26].

Table 3. Mechanical characteristics of steel, PET and CFRP.

	STEEL	**PET**	**CFRP**
Density (Kg/m^3)	7.86	1.38	1.60
Tensile strength (N/mm^2)	540	90	3,200
Ultimate strain in tension (%)	>7.5	>20	>1.35
Tensile Young's Modulus (N/mm^2)	200,000	3,000	210,000

In total 6 specimens have been prepared, three for each kind of reinforcement. All specimens had the same length L=1.04m and a 150mm x 200mm cross-section. Two specimens have been manufactured with Concrete type 1, called D20 because of the maximum dimension of the aggregates equal to 20 mm; four specimens have been prepared with Concrete type 2, called D10 because of the maximum dimension of the aggregates is equal to 10 mm.

A minimum number of long steel bars were utilized in order to keep the stirrups in their position. Once the steel bars were assembled, we applied a concrete cover of 20 mm by mean of spacers and then, before the casting, we wet the formworks.

2.2 Specimens with PET bars

Specimens with PET bars were realized with the following characteristics (see Figure 2):

- Top reinforcement: 2Φ8 steel bars, 1.0 m long, curved at 90° at the ends;
- Bottom reinforcement: 3Φ12 PET bars, 1.0 m long;
- Concrete cover equal to 20 mm per each side;
- Steel stirrup reinforcement (Φ8/7")

Fig. 2. Bars in PET.

Preliminary calculations had been developed on the PET bars, assuming for them the mechanical characteristics shown in Table 3 [28].

The ultimate bending moment was obtained:

$M_R = 0.9\ h\ R_t\ A_s = 49426$ Nmm

where h represents the effective depth (depth of the specimen except the cover), R_t the tensile strength and A_s the area of PET reinforcement.

The maximum load during the test had been obtained:

$P \approx 21.54$ kN

assuming a perfect concrete-PET adherence.

In addition, the specimen was reinforced with a minimum reinforcement of 2Φ8 1m long steel (B450C [26]) bars with improved adherence. Stirrups are made with Φ8/7" bars arranged in the central part of the specimen (see Figure 3).

Figure 4 shows a photo of the steel cage of the specimen with the reinforcing bars in PET positioned in the lower part of the cage itself.

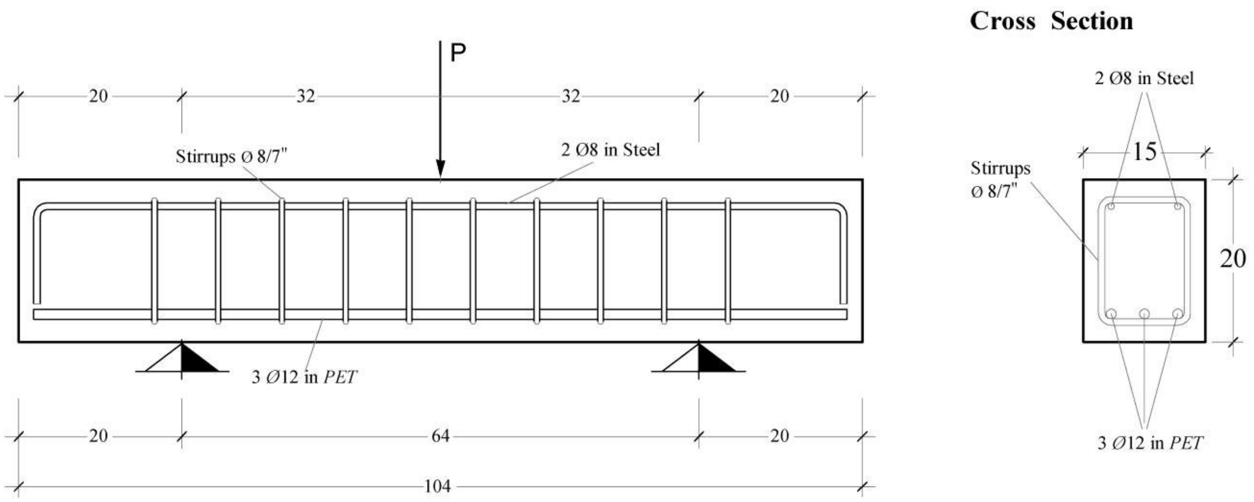

Fig. 3. Longitudinal and cross-section of the specimen reinforced with PET bars.

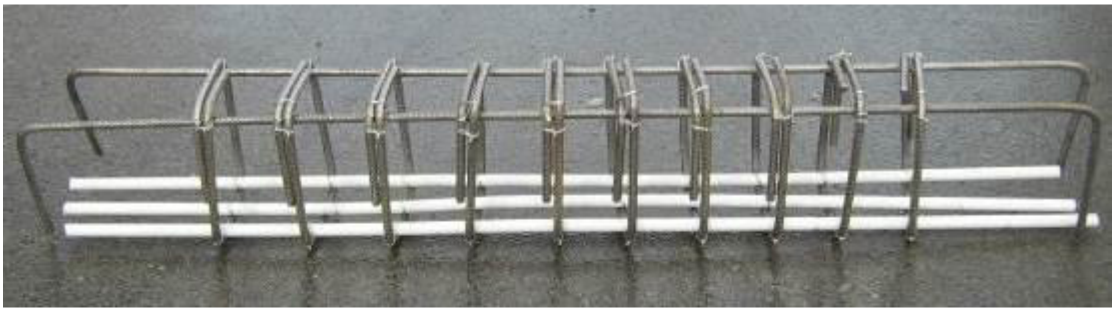

Fig. 4. Positioning of PET bars inside the reinforcing steel cage of the specimen.

Specimens reinforced with PET bars were completed by simply reversing the vibrated concrete in the formworks, as shown in Figure 5. They were disarmed after about 30 days and then tested.

Fig. 5. Phases of realization of the specimens with PET bars.

2.3 Specimens with CFRP strips

The specimens reinforced with CFRP strips had the same dimensions and the same number of stirrups of the specimens with PET bars. As in the previous specimens the stirrups have the same steps and are positioned in the central part of the specimen inside the supports (Figure 6).

In the present tests 4Φ8 longitudinal steel bars were arranged for the steel cage of the specimen, two bars in the upper side of the specimen and two in the lower side. Inside the reinforcement cage, two CFRP strips were positioned, each one spaced about 20 mm of concrete from the other (Figure 7).

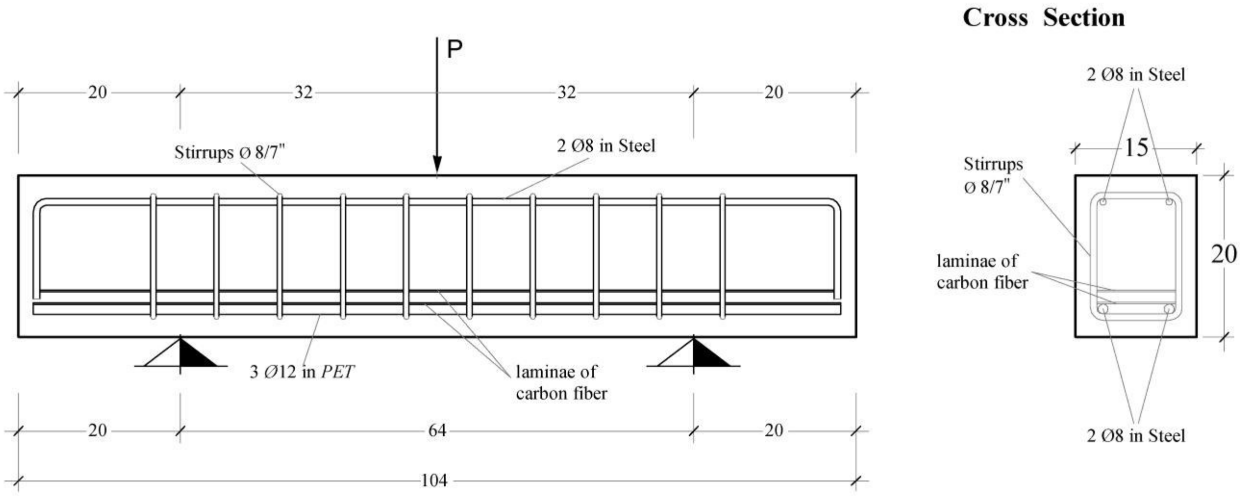

Fig. 6. Realization of the cage for the specimens reinforced with CFRP strips.

Fig. 7. Realization of the cage for the specimens reinforced with CFRP strips.

The beam specimens were manufactured as in the following. Once the stirrups had been fixed to the cage, we applied a first vibrated concrete layer about 20 mm thick, then a first layer of CFRP strips was introduced;

successively another vibrated concrete layer about 20 mm thick was added. Finally, we applied the second layer of CFRP strips and completed the casting (Figure 8).

Fig. 8. Constructive phases of the specimens reinforced with CFRP strips.

3. BENDING TESTS

3.1 Test set-up

The bending tests were performed after about 30 days in order to determine the maximum failure load. A testing set-up was arranged to stress the specimens to bending forces (Figure 9b): it was made of two parallel supports with a span L= 0.84 m and a point load applied at the mid-span by a piston attached to the upper moving beam of the loading equipment.

The tests were performed at a constant speed of 0.05 m/s; a loading cell measured the force generated by the piston. A data acquisition system collected the mid-span deflections monitored by two displacement transducers (Figure 9a).

a) b)

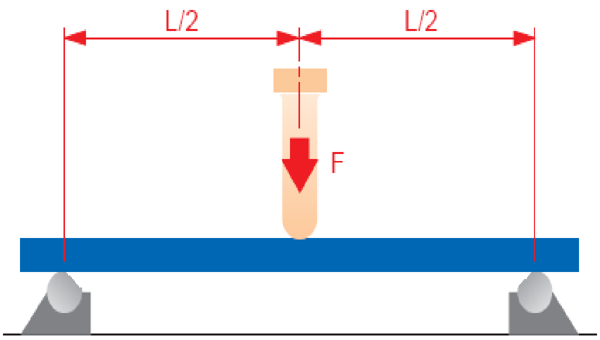

Fig. 9. a) Photo and b) scheme and of the testing set-up.

3.2 Results of the tests

After the tests the crack pattern gave the possibility to have a clear idea of the behavior of the specimens. The specimens reinforced with PET bars exhibited a brittle behavior, typical of concrete (Figure 10a), while the bars reinforced with carbon fiber strips showed cracks inclined at about 45° typical of a ductile behavior (Figure 10b).

a) b)

Fig. 10. Detail of the different behaviors; a) specimen reinforced with PET bars; b) specimen reinforced with CFRP strips.

The results shown in the load-deflection relationship in Figure 11 refer to the first couple of specimens realized with the first kind of concrete casting; Figure 12 shows the results of all the six specimens.

For each test the results are arranged considering the applied forces and the corresponding value of the maximum deflection at the central section of the beam.

You should consider that the specimens were not manufactured in the same day. Therefore they have been subjected to different environmental conditions. However, from the results it is possible to affirm that this factor has only slightly influenced the results.

Figure 13 shows the behavior of only the specimens reinforced with PET bars. From a first analysis of the plots in Figure 13, the specimens reinforced with PET bars show the classic behavior for brittle failure. In the first branch of the plot, the load increases up to a peak value at quite low loads. At this value the first cracks appear in the concrete section; concrete cracks with a very low collaboration from PET due to its reduced section if compared to concrete. In the following phase, after failure, an increment of load is supported only by the PET bars: the first crack widens up to 30–40 mm, due to the high ductility of the PET bars that elongated and partly recovered the tensile load (increment of the load with the maximum deflection).

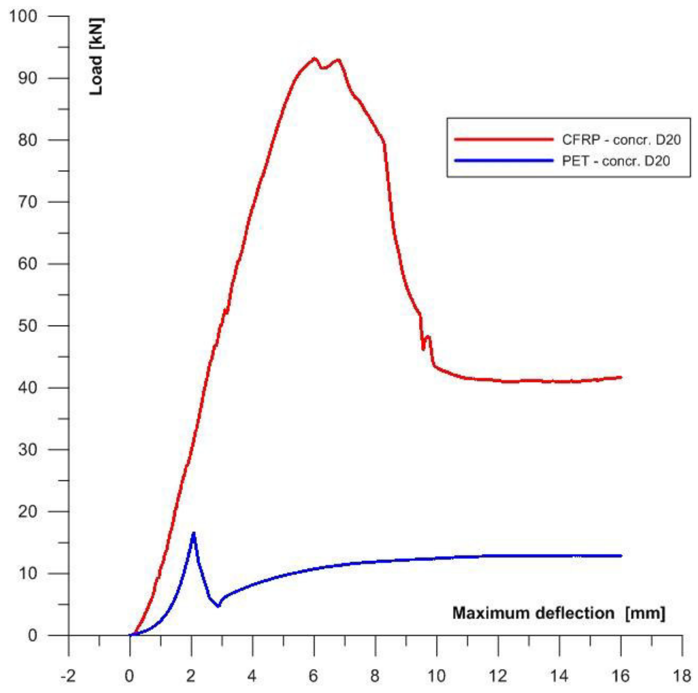

Fig. 11. Results of the bending test for specimens realized with concrete C20/25 S4 D20.

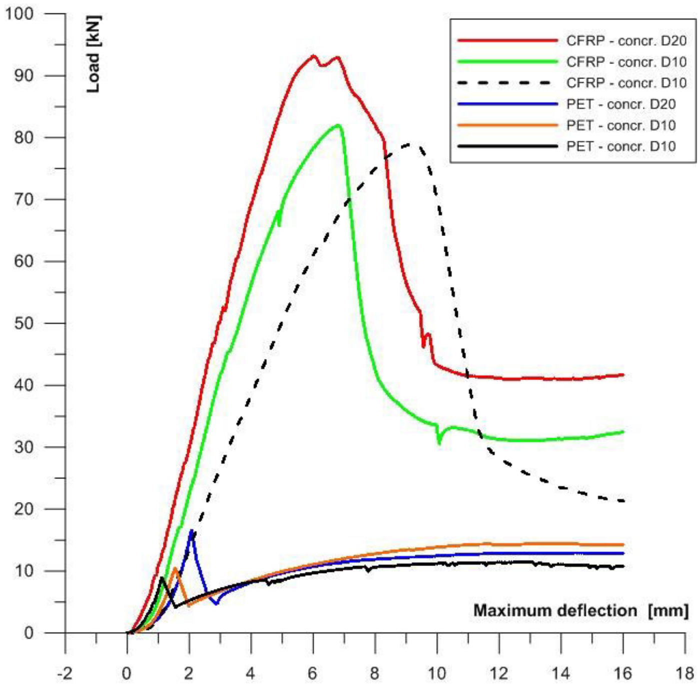

Fig.12. Results of the bending tests for the six specimens.

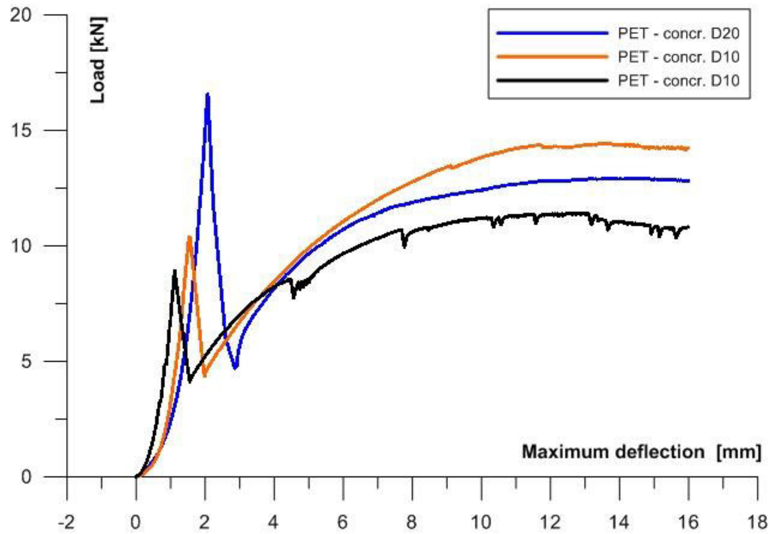

Fig.13. Results of the bending tests for the three specimens reinforced with PET bars.

Specimens behaved as they were monolithic isotropic blocks in reinforced concrete simply supported at their ends and subjected to a concentrate load. Increasing the load, the middle section of the specimens cracked in correspondence of the tense side of the section. Therefore, in this case the section cracked before the compressed concrete reached its maximum strength. It seems that the fiber reinforcement did not collaborate up to the failure of the section. When concrete cracked, then the PET bars started to work. However, in this case the compressed concrete was not exploited because it did not reach its maximum strength.

On the contrary, the specimens reinforced with CFRP showed a more ductile behavior; they clearly evidenced an upper compressed part of the section and a lower part subjected to traction, with failures inclined at 45° towards the supports (Figure 14). This result is also evident from the plots in Figure 12; the figure shows that in presence of CFRP reinforcement the values of the load at failure are much higher than those obtained for the same specimens reinforced with PET bars. Therefore CFRP strips well collaborated to bending and shear stresses reaching the first crack for a load equal to about 80 kN and a maximum deflection equal to 8 mm. These values have been obtained neglecting the $2\Phi8$ long steel bars utilized to allow the positioning of the CFRP reinforcement in the reinforcing cage. The two bars, in fact, contributed in absorbing the total stress, even if for a very low percentage.

Fig. 14. Cracking patterns on the concrete specimen C20/25 S4 D20 reinforced with CFRP strips.

Referring to Figure 12 for the specimens reinforced with PET bars we can observe that those realized with C20/25 S4 D20 concrete reached a higher failure load (≈ 16.55 kN) if compared to the other two realized with C20/25 S4 D10 concrete that reached a peak value equal to 10.40 kN and 8.98 kN, respectively. The maximum deflection is, respectively, 2.076 mm, 1.562 mm and 1.12 mm. Therefore, for specimens with similar reinforcement the kind of concrete casting influenced the results; in particular, the size of the aggregates in the concrete played an important role. In fact, for specimens made with C20/25 D20 concrete, the loss of strength was reached later respect to C20/25 D10 concrete. However, they are far from the operating loads of a beam (around 50 – 60 kN).

Comparing the results of the specimens reinforced with CFRP strips, we can notice a high difference between those realized with C20/25 S4 D20 concrete and those realized with C20/25 S4 D10 concrete (Figure 12). The first ones cracked for a load equal to 93.16 kN and the second ones for a load around 82 kN, showing a difference higher than 11 kN.

3.3 Evaluation of the maximum stress

To evaluate the maximum deformation of the materials during the tests we followed an approximate calculus. For comparison aims the maximum failure load reached during the tests has been considered, that is 93.16 kN for specimen in C20/25 S4 D20 concrete.

In case of PET bars the Young's modulus has been assumed E = 3000 N/mm^2, while for CFRP strips E = 210000 N/mm^2; it is obtained ($\varepsilon = \sigma_{Max}/E = (F_{Max}/A_s)/E$):

$\varepsilon_{PET\%}$ = 1.6%

$\varepsilon_{CFRP\%}$ = 1.13%

Moreover, the maximum stress on the fibers has been evaluated in an approximate way. Referring again to specimen in C20/25 S4 D20 concrete, which cracked at the highest load with both reinforcement, and assuming:

$$\sigma_{Max} = \frac{M_{Max}}{W}$$

where M_{Max} is the maximum bending moment on the beam and W the resistance modulus of the cross section, it is possible to obtain the following.

For specimens reinforced with CFRP strips:

F_{Max} = 93.16 kN

σ_{Max} = 1.96 kN/cm^2

For specimens reinforced with PET bars:

F_{Max} = 16.55 kN

σ_{Max} = 0.347 kN/cm^2

From these results it is clear that for specimens with CFRP strips the stress is higher than for the same specimens reinforced with PET bars.

Another consideration is about the adherence; it develops along the contact surface of the bars (or the strips) transmitting the sliding stresses between the two materials. It is due to the molecular chemical adhesion and the geometric interpenetration due to the roughness of the contact surfaces.

It is clear that for specimens reinforced with CFRP strips, adherence is higher than for specimens reinforced with PET bars. In the last case, in fact, when the failure and a higher level of cracking are reached, we observed a significant detachment of concrete from the bars, which is due, of course, to the smoothness of the bars.

In addition, the good characteristics of adherence evidenced by CFRP strips are, of course, due to a wider contact surface with concrete respect to the bars, and also because they are coated with a sandy film to improve the transmission of the contact forces.

4. CONCLUSIONS AND FUTURE RESEARCH

Based on the results of this experimental investigation on concrete specimens reinforced once with PET bars and once with CFRP strips, the following conclusions are drawn.

1. For both cases of PET and CFRP reinforcement it is noticed that they limit the presence of cracks and, especially, avoid the corrosion processes in reinforced concrete structural elements. In particular, the concrete-fiber adhesion and the global behavior of these fiber reinforced concretes are observed in order to evaluate the possibility of future investigation. However, a better behavior is obtained for specimens reinforced with CFRP strips.
2. CFRP strips inside the concrete specimens subjected to bending worked well, both for the supported loads and for adherence; it confirms its wide use as material for structural reinforcement in buildings and structures.
3. It was not obtained the same performance in case of concrete specimens reinforced with PET bars; in this case the failure loads are lower and the behavior is more brittle. This was probably due to a reduced area of the reinforcement and the shape of the bars that have a lower adherence to concrete respect to the strips. However, PET bars sewed the crack and, in this way, avoided the complete

failure of the specimen; in addition PET bars include the use of a waste material with promising results.

In conclusion, PET bars could be utilized for concrete pavements in substitution of welded steel mesh or for soil restraints if there are high moisture problems and steel corrosion. In this case a material indifferent to these phenomena must be utilized; however, they can be used in all those cases where the operational loads are low. In addition, it must be considered the costs of the material that, from an approximate evaluation, are not cheap, probably due to its little use in buildings. Differently, if they are obtained as re-use of waste PET objects like bottles of water, the costs reduce a lot.

On the contrary, CFRP could be considered as a valid substitute of steel reinforcement for elements subjected to bending.

In future researches and studies we could develop the possibility to utilize CFRP strips and also PET in the shape of strips as reinforcement inside concrete beams and the effects due to different shapes. An extensive test campaign should be organized to get a wider knowledge of the behavior of such fiber reinforcement for structural elements.

Moreover, we could obtain another interesting comparison regarding the adherence analyzing the behavior of the same concrete beams reinforced once with CFRP strips and once with PET bars, having the same total quantity of reinforcement and the same contact surface to concrete for both cases.

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