# Synthetic Fibre Reinforced Concrete for precast panels: material characterization and experimental study

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ABSTRACT: The present paper describes an experimental study on structural behaviour of precast façade panels made of Self Compacting Concrete reinforced with synthetic fibres (SCFRC). The main research aims concern the material characterization and, at structural level, the possibility of replacing, in the external plates of precast panels, the traditional welded mesh with synthetic fibers. Fracture tests were performed on both normal weight and lightweight concrete where fibres may be particularly efficient in reducing the well-known brittleness of this material. The application of FRC to the production of precast panels is a promising technique since it allows several advantages; in fact the possibility of replacing conventional reinforcement with fibers allows for time and cost-savings and, since the minimum concrete cover is no longer required, may reduce the panel weight and the transportation costs. The experiments were performed on both traditional (RC) and SCFRC full-scale panels; they have been loaded up to failure to observe their response in terms of bending moment versus displacement and crack development.

## 1 INTRODUCTION

Concrete is a brittle material; in fact, when subjected to tensile stresses, it cracks already under small loads. Concrete may already crack before applying loads because of shrinkage or thermal effects. For this reason, steel reinforcement has been used to overcome the low concrete tensile strength and reinforced concrete (RC) became one of the most important construction techniques (Walraven, 1999). As a composite system, the reinforcing steel is assumed to carry all tensile loads.

Another approach to limit concrete brittleness concerns the use of discontinuous fibers to produce Fibre Reinforced Concrete (Romualdi & Mandel, 1964, Shah et al., 2004). In Fibre Reinforced Concrete, thousands of small fibres are dispersed and randomly distributed in the concrete matrix; therefore, they improve concrete properties in all directions (Balaguru & Shah, 1992).

Fibres enhance the post–cracking strength in tension, the fatigue strength, the resistance to impact loading and reduce temperature and shrinkage cracks (Ziad & Gregory, 1989; di Prisco et al., 2004). Only a few of the possible hundreds of fibre types have been found suitable for commercial applications (ACI 544, 1996).

Fibre Reinforced Concrete (FRC) finds applications in many areas of civil engineering where needs for repairing and durability arise.

Aim of the present study is to explore the mechanical properties of concrete reinforced with polypropylene fibres adopted to enhance its toughness. In addition, the paper reports preliminary results from full-scale tests on precast façade panels (Cominoli et al., 2006) made of ordinary reinforced concrete (as a reference) and SCFRC, where fibres substitute the welded mesh in the two external plates of the panel.

Material tests were performed on both normal and lightweight concrete where fibres may reduce the remarkable brittleness of this material.

The use of fibres in the precast industry is gaining particular interest (Failla et al., 2004). In particular, the use of FRC in the production of precast panels is a promising technique since it brings to several advantages. First of all fibres may replace the conventional transverse reinforcement, bringing to time and cost-savings, contributing to a major industrialization degree of the production process and avoiding the areas used for the storage of the welded mesh. Secondly FRC allows the design of wall panels to be dependent only on static requisites and not on cover limitations, and, finally, the use of lightweight concrete, beside the smaller concrete cover, may allow a reduction of the transportation costs.

For these reasons, FRC panels represent a competitive and cost-effective solution.

## 2 BEHAVIOUR OF SYNTHETIC FIBRES IN A CEMENT MATRIX

The precast panels studied in the present research work are made of Self Compacting Concrete reinforced with polypropylene fibres (*Self Compacting Fibre Reinforce Concrete, SCFRC*). The initial part of the research focused its attention on toughness properties of normal and lightweight concrete reinforced with structural polypropylene fibres.

The real advantage of adding fibres into concrete matrices becomes evident when fibres bridge these cracks and provide residual strength during their pullout process. The residual strength is significantly influenced by the volume fraction and by the aspect ratio of the fibers, as well as by the orientation in the concrete matrix. The other factors that control the performance of the composite material are the physical properties of the concrete, matrix as well as the bond between fibres and matrix.

Material tests were carried out on specimens made of Normal Self Compacting Fibre Reinforced Concrete (N-SCFRC) and Lightweight Self Compacting Fibre Reinforced Concrete (L-SCFRC), as summarized in Table 1.

Table 1. Composition of the Normal and Lightweight Self Compacting Fibre Reinforced Concrete.

| Composition of Normal SCFRC | | |
|---|---|---|
| Portland Cement 42.5R II A-LL | 320 | [kg/m$^3$] |
| Acrylic plasticizer | 3.3 | [l/m$^3$] |
| Water/cement ratio | 0.56 | [-] |
| Fresh Concrete Density | 2364 | [kg/m$^3$] |
| Slump Flow | 700 | [mm] |
| | | |
| **Composition of Lightweight SCFRC** | | |
| Portland Cement 42.5R II A-LL | 400 | [kg/m$^3$] |
| Acrylic plasticizer | 4.3 | [l/m$^3$] |
| Water/cement ratio | 0.56 | [-] |
| Fresh Concrete Density | 1835 | [kg/m$^3$] |
| Slump Flow | 650 | [mm] |

Two different types of polypropylene fibres were adopted. The first type (S40) had an equivalent diameter of 1.0 mm and a length of 40 mm (aspect ratio equal to 40), while the second type (S25) had the same diameter, but a length of 25 mm (aspect ratio equal to 25); their geometrical and mechanical characteristics are reported in Table 2.

Fibres were added to the concrete matrix in different combinations; in particular, fibres S40 were used with three different dosages, equal to 3, 4 and 5 kg/m$^3$ (corresponding to a volume fraction, $V_f$, of 0.33%, 0.44% and 0.55% respectively), while S25 fibres were used only with a dosage of 4 kg/m$^3$ ($V_f \approx$ 0.44%; Tab. 3).

Table 2. Geometrical and mechanical characteristics of the synthetic fibers adopted in the present research work.

| Fibre | S40 | S25 |
|---|---|---|
| Length ($L_f$) | 40 mm | 25 mm |
| Equivalent Diameter ($\phi_f$) | 1.0 mm | 1.0 mm |
| Aspect ratio ($L_f/\phi_f$) | 40 | 25 |
| Tensile strength [MPa] | 650 | 650 |
| Density [kg/m$^3$] | 920 | 920 |
| Elastic Modulus [GPa] | 5.0 | 5.0 |

Table 3. Fiber type and content in the different concrete mixes.

| Mix | | Fibre dosage [kg/m$^3$] | |
|---|---|---|---|
| | | S40 | S25 |
| Mix-1 | N-SCC | - | - |
| Mix-2 | N-SCFRC | 3.0 (0.33%) | - |
| Mix-3 | N-SCFRC | 4.0 (0.44%) | - |
| Mix-4 | N-SCFRC | 5.0 (0.55%) | - |
| Mix-5 | N-SCFRC | - | 4.0 (0.44%) |
| Mix-6 | L-SCC | - | - |
| Mix-7 | L-SCFRC | 3.0 (0.33%) | - |
| Mix-8 | L-SCFRC | 4.0 (0.44%) | - |

Table 4. Mechanical properties of the different concrete mixes.

| Mix | Elastic Modulus | Tensile Strength | Compressive Strength |
|---|---|---|---|
| | $E_c$ [GPa] | $f_{ct}$ [MPa] | $f_{c,cube}$ [MPa] |
| Mix-1 | 27.7 | 3.20 | 42.5 |
| Mix-2 | 26.5 | 3.71 | 39.7 |
| Mix-3 | 26.2 | 3.57 | 39.5 |
| Mix-4 | 29.5 | 3.46 | 43.2 |
| Mix-5 | 23.6 | 3.31 | 44.5 |
| Mix-6 | 29.8$^{*)}$ | 2.17$^{*)}$ | 33.1 |
| Mix-7 | 28.8$^{*)}$ | 1.94$^{*)}$ | 29.5 |
| Mix-8 | 28.8$^{*)}$ | 1.96$^{*)}$ | 29.7 |

*) Values calculated according to EC2 (2003).

Table 4 shows the mechanical properties of the different concrete mixes adopted, in terms of compressive strength from cubes ($f_{c,cube}$), elastic modulus ($E_c$) and tensile strength ($f_{ct}$).

Fracture properties were determined by using notched beams (150x150x600 mm), tested under four-point bending according to the Italian Standard (UNI 11039, Fig. 1a). Fracture tests were carried out with a closed-loop hydraulic testing machine (INSTRON-1274) by using the Crack Mouth Opening Displacement (CMOD) as control parameter. Additional Linear Variable Differential Transformers (LVDT) were used to measure the Crack Tip Opening Displacement (CTOD) and the vertical displacement at midspan and under the load points (Fig. 1b).

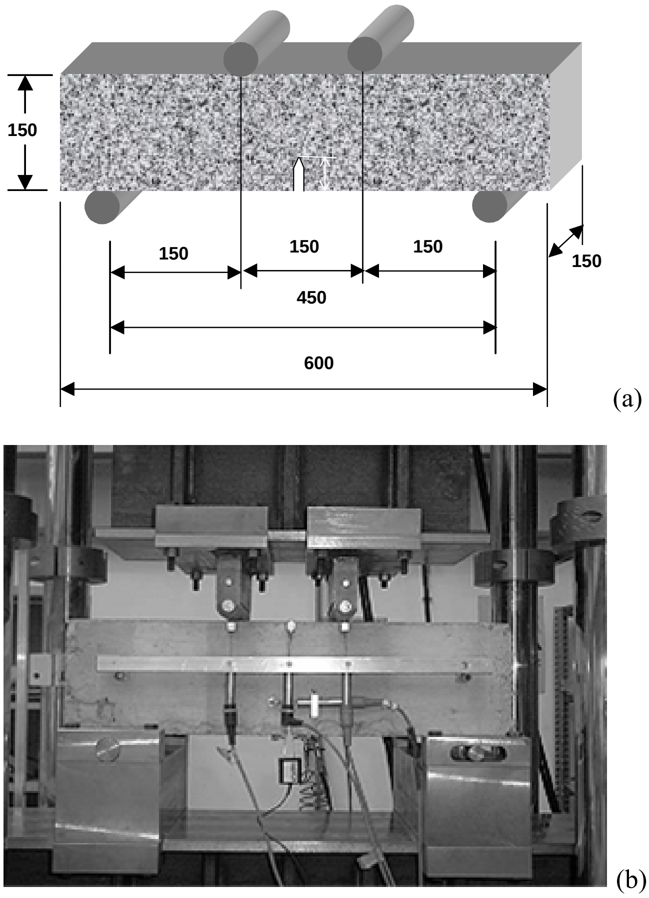



Figure 1. Geometry (a) and instrumentation (b) of the notched specimen for the bending tests, according to UNI 11039.

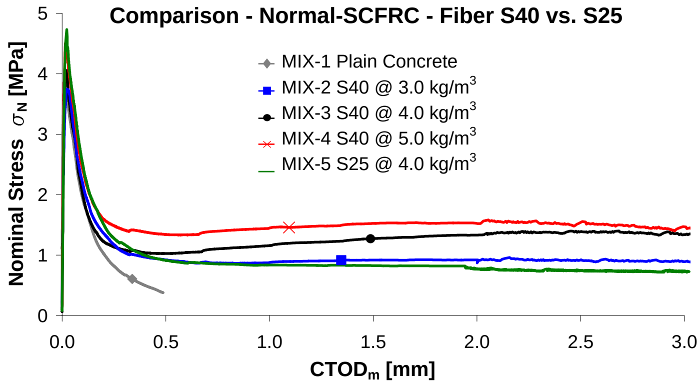



Figure 2. Nominal stress versus CTOD curves (average curves) obtained from bending tests on N-SCFRC specimens.

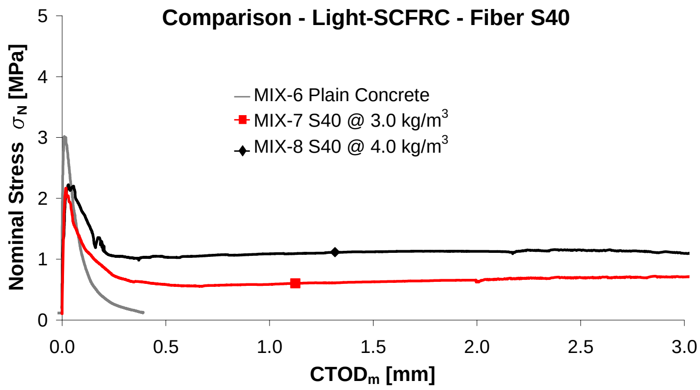



Figure 3. Nominal stress versus CTOD curves (average curves) obtained from bending tests on L-SCFRC specimens.

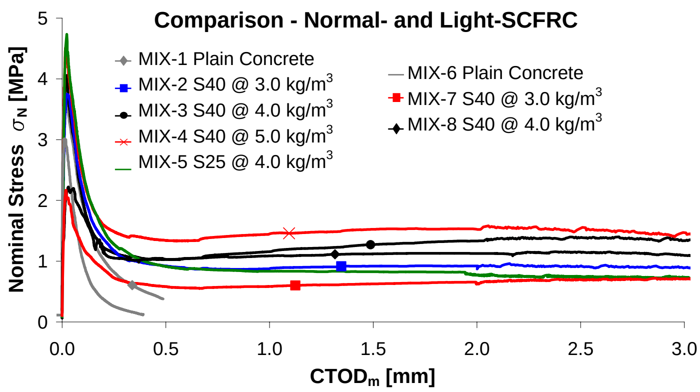



Figure 4. Comparison of the nominal stress versus CTOD curves (average curves) obtained from bending tests on both Normal SCFRC and Light-Weight SCFRC specimens.

The experimental results obtained from tests on SCFRC specimens are summarized, in terms of load versus CTOD curves, in Figure 2 (N-SCFRC) and in Figure 3 (L-SCFRC). It should be observed that specimens were characterized by different volume fraction of fibres (0.33%÷0.55% for N-SCFRC and 0.33%÷0.44% for L-SCFRC).

For an easier comparison, the figures show only one representative curve for each material which is chosen a the one closest to the average curve. It can be observed that fibre geometry and content remarkably influence concrete toughness (evidenced by the post-peak strength) while the peak stress is not significantly influenced by the presence of fibres (it mainly depends on the tensile strength of the concrete matrix).

Although polypropylene fibres are characterized by a low elastic modulus, it is quite apparent that the load carrying capacity of FRC under flexural loading is considerably increased (Figures 2 and 3). The residual strength is maintained until large values of the crack opening, greater of 3 mm (normally accepted in the concrete structures).

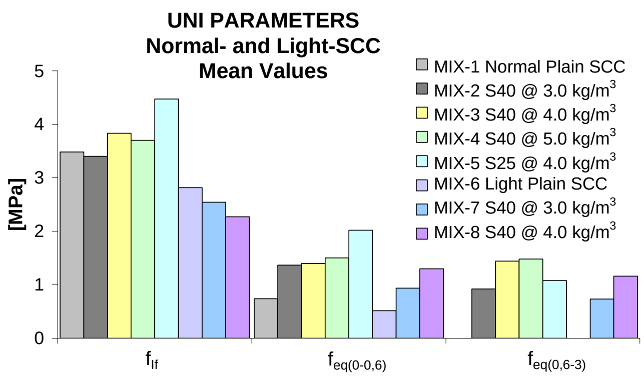
As far as the comparison between Lightweight and Normal SCFRC is concerned, in Figure 4 it can be noticed how the first one evidences a post-peak strength similar to those of the Normal-SCFRC, although the peak stress is lower (2.5 MPa for L-SCFRC and 4 MPa for N-SCFRC).

This is a significant potentiality of lightweight concrete that could be used in the prefabrication industry, with remarkable advantages from the structural and economical point of view.

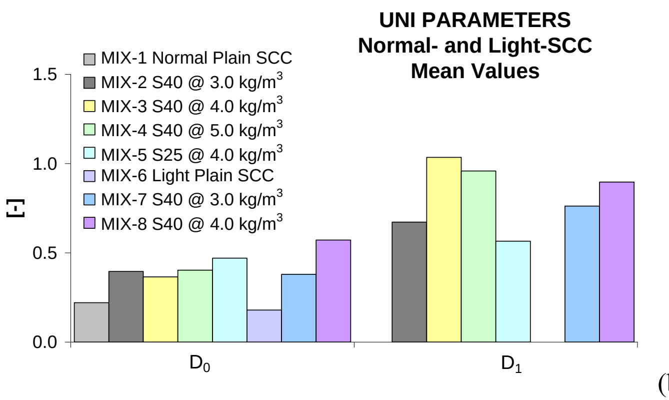
In order to better identify the post-cracking response of FRC, three independent parameters are proposed by the Italian Standard (UNI 11039, 2003): the first crack strength ($f_{lf}$) and two equivalent flexural strengths ($f_{eq,(0\text{-}0.6)}$ and $f_{eq,(0.6\text{-}3)}$). The first flexural strength ($f_{eq,(0\text{-}0.6)}$) corresponds to a Crack Tip Opening Displacement range of 0-0,6 mm (significant for the Serviceability Limit State) while the second one corresponds to a CTOD range of 0,6-3 mm (significant for the Ultimate Limit State). In order to better identify the reduced FRC brittleness, the Italian Standard also requires two Ductility Indexes that are defined as the ratios between the equivalent strength as follows:

$D_0 = f_{eq,(0\text{-}0.6)}/f_{If}$ ; $D_1 = f_{eq,(0.6\text{-}3)}/f_{eq,(0\text{-}0.6)}$.

The equivalent flexural strengths obtained from bending tests on FRC specimens are given in Figure 5a (mean values), while the two ductility indexes $D_0$ and $D_1$ are shown in Figure 5b.




(a)




(b)

Figure 5. First-crack strength and post-cracking equivalent strengths (a) and ductility indexes (b) according to UNI 11039.

Based on the experimental results obtained from the material characterization, a SCFRC panel was realized by using the SCFRC matrix reinforced with 3 kg/m$^3$ of S40 fibres.

## 3 FULL-SCALE TESTS ON FRC PRECAST PANELS

The research on full-scale façade panels aims to verify the possibility of replacing the welded mesh that is usually placed on the two faces of the panel, with synthetic fibres.

The research program took into consideration static, industrialization, insulation and weight reduction requirements.

In order to better estimate the contribution of fibres and to allow a useful comparison, the experimental program included a FRC panel and a traditional panel reinforced with welded mesh.

In order to reproduce realistic situations, a special experimental set-up was used to reproduce the combined bending effects of the panel weight and of the wind load.

### 3.1 *Panel geometry*

The panels are realized with two external plates, connected with stiffening ribs with interposed a layer of insulating material (characterized by low specific weight), with the function of lightening and thermal isolation. The density of this insulating material (10÷30 kg/m$^3$) and the extension of the ribbings determine the thermal insulation of the panel (Fig. 6).

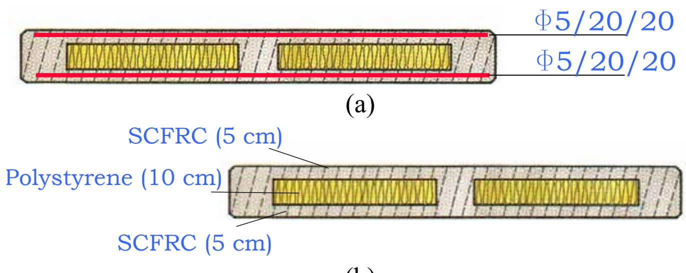



Figure 6. Geometrical characteristics of the transverse section of a traditional SCC panel (a) and a SCFRC panel (b).

The preliminary experimental program included two full-scale panels, having a length of 11,2 m, a height of 2,5 m and a thickness of 0,2 m, characterized by different reinforcement and materials, as described in the following:

- a first panel (RC) was reinforced with traditional welded mesh on the two plates and with reinforcing bars in the ribs (Fig. 7a);
- a second panel (FRC) was reinforced with 3.0 kg/m$^3$ of synthetic fibres, in substitution of the mesh fabric (Fig. 7b).

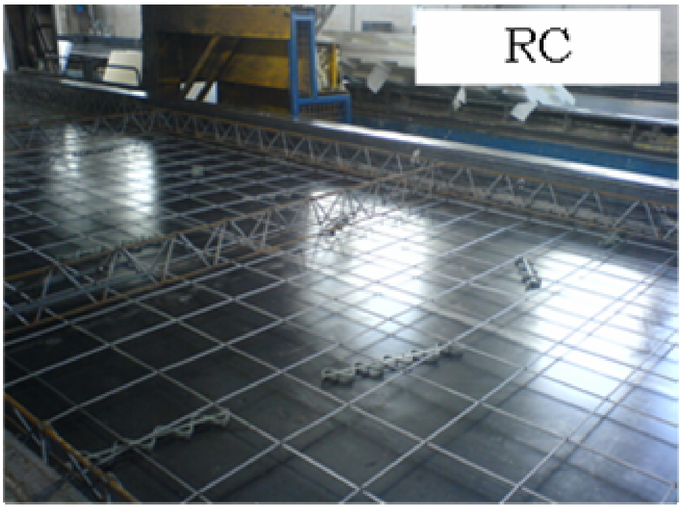
The cross section of the panels is composed of three different layers. In particular, from the internal toward the external side of the building, there is (Fig. 6):

- a layer of concrete (5 cm);
- a layer of polystyrene material (10 cm);
- another layer of concrete (5 cm).

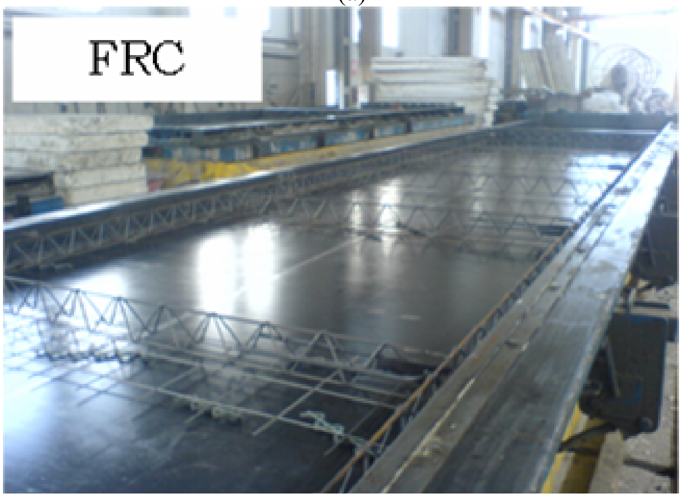
Table 5 shows the compressive strength of concrete measured on 150 mm side cubes ($f_{c,cube}$), the reinforcement type, the self-weight of the panels and the age of concrete at the time of the test. One should notice that panels had similar mechanical properties since they were made by using the same concrete mix (Tab.1).

### 3.2 *Test set-up*

One of the main issues concerning experimental tests on prefabricated panels is related to the test set-up. The experimental test set-up aims to reproduce the latter configuration (Fig. 8), because this is the most critical working condition. The bilateral restraint on the vertical edges, which is represented, in a real structure, by the columns, was realized by means of two vertical steel profiles which are also required to avoid overturning of the panel.




(a)




(b)

Figure 7. Traditional reinforcement of the RC panel (a) and FRC panels (b).

Table 5. Concrete and reinforcement characteristics.

| Panel | $f_{c,cube}$ [MPa] | Curing [days] | Fibre | | Weight [ton] |
|---|---|---|---|---|---|
| | | | Type | $V_f$ [kg/m$^3$] | |
| RC | 40.4 | 78 | Mesh | - | ≈9.5 |
| FRC | 39.1 | 80 | S40 | 3.0 | ≈9.5 |

Another problem is related with the application of the transverse load to simulate wind effects. This was accomplished by means of an electrical screw-jack, which acts on a loading distribution system, made of three different levels of steel beams, properly connected to each other by means of bilateral pinned restraints, necessary to allow panel unloading.

In order to simulate the wind effects, the front face of the panel was loaded by means of four loading strips, positioned in such a way to obtain the same maximum shear force and bending moment, as for an uniformly distributed pressure (Fig. 9).

During the test, the horizontal displacements were recorded in several points, as shown in Figure 10. Compressive and tensile deformations (or the opening of a flexural cracks) were also measured on the panel faces. The displacements were measured by means of either Linear Variable Differential Transducers (LVDT), or potentiometric transducers with 250 mm stroke.

Figure 8. Panel placement on the reaction frame.

More details about the test set-up can be found in Cominoli et al., 2006.

### 3.3 *Experimental results and discussion*

The ultimate load of the panels was reached after submitting the specimens to different cycles of increasing intensity (fraction and multiple of the service bending moment, $M_s$). At the end of each step, the panels were unloaded in order to check the residual deformation. Finally the load was increased up to collapse.

The bending moment under service load ($M_s = 25.3$ kNm) was determined by assuming the panels as part of a precast building located in wind Zone I and Category IV, according to the Italian Standard (D.M. 14-09-2005).

The curves of the maximum bending moment versus the horizontal displacement of the midspan section, the final crack patterns and the effects of fiber reinforcement are presented and discussed in the following.

Figure 11 shows the experimental curves of the bending moment as a function of the horizontal deflection (C3 in Fig. 10) for the two tested panels. It can be observed that the traditional panel (RC; Fig. 11a) exhibits an ultimate load and a stiffness, in the cracked stage, different from the FRC panel (Fig. 11b), even if the latter is characterized by better ductility. In both cases, a considerable stiffness reduction is observed when the first crack appears (I stage); as a result of the formation of this crack, the behaviour is still almost linear, even if there is a remarkable loss of stiffness (II stage).

The transition from the first to the second stage in SCFRC panels occurred for a smaller bending moment than in the traditional panel (approximately 12 kNm versus 20 kNm). However, the stiffness in the initial (uncracked) stage is similar.

The tests continued until reaching the ultimate moment, approximately of 50 kNm (III stage).

One should notice that the horizontal displacement in service conditions for FRC panel is about 1/600 of the span length and that the maximum moment is about 1.4 times the service moment.

It is necessary to emphasize that panels were already cracked before starting the test, due to shrinkage phenomena; when increasing the load, these cracks tends to concentrate in the midspan zone of the element, where the maximum bending moment is present.

The use of fiber reinforcement is also effective in reducing the crack width so that it enhances the durability of the panels.

Figure 12 illustrates the final crack pattern of the panels; in all cases, failure involved longitudinal bending with transversal cracks along the whole height.

It can be noticed that the RC panel is characterized by the formation of a main crack (Fig. 12a), whose width is already important at the moment of its appearance. In the FRC panel, instead, the crack pattern is diffused and the maximum cracks width is reduced (Fig. 12b).

Table 6 shows a comparison between the maximum experimental bending moment ($M_{max}$) and the service moment ($M_s$).

Table 6. Comparison between the maximum experimental bending moment and its service value (Ms).

| Panel | $f_{c,cube}$ [MPa] | $M_{max}$ [kNm] | $M_s$ [kNm] | $M_{max}/M_s$ [-] |
|---|---|---|---|---|
| RC | 40.4 | 48.74 | 25.3 | 1.93 |
| FRC | 39.1 | 34.65 | 25.3 | 1.37 |

Once again, it should be noticed that, in the two preliminary panels, the maximum bending moment was larger than its design value for ultimate limit state.

## 4 CONCLUDING REMARKS

The present paper deals with the mechanical characterization of a self compacting concrete reinforced with structural synthetic fibres and with its use for the production of precast panels.

The initial part of the research work concerned the evaluation of the mechanical properties of normal and lightweight concrete reinforced with polypropylene fibers, used with a volume fraction ranging from 0.33% to 0.55%.

The second part of the research work concerned full-scale tests on precast panels where polypropylene fibers replaced the welded mesh in the external plates of the panel. By doing so, fibers allow for time and cost-savings and may reduce the structural weight, decreasing the transportation costs. In fact, the absence of conventional reinforcement may allow for a reduction of the slab thickness, since the minimum concrete cover is no longer required.

In order to better appreciate the benefits provided by fibres, a test on a panel reinforced with the traditional welded mesh was also performed.

From the experimental results, the following conclusions can be drawn:

- the Fibre Reinforced Concrete panel exhibited a behaviour similar to the traditional panel reinforced with mesh fabric, even if the ultimate load was lower;
- the maximum load applied to the FRC panel was about 1.4 times the service load;

In summary, FRC represents a promising material for the precast industry since it enhances the production process by reducing the time for placing and for the storage areas for conventional reinforcement.

Figure 9. Global view of the experimental set-up for the full-scale panels.

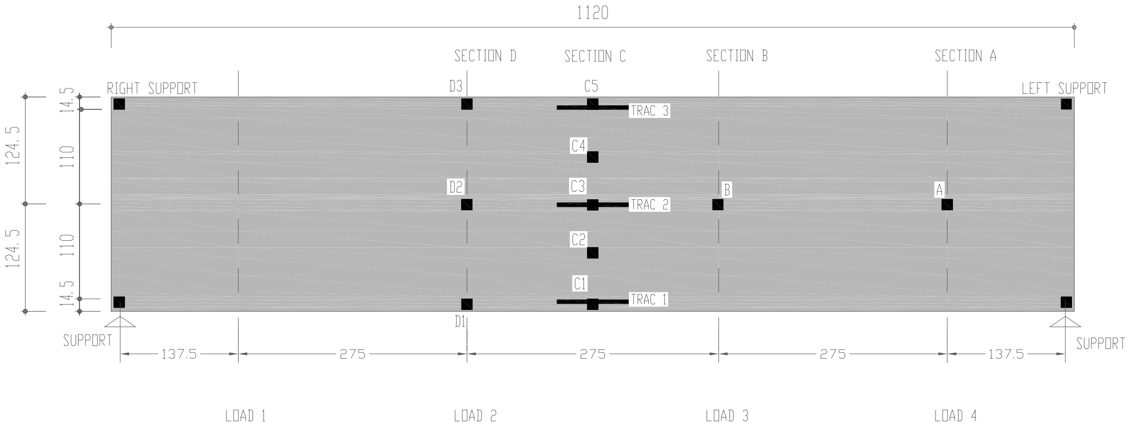
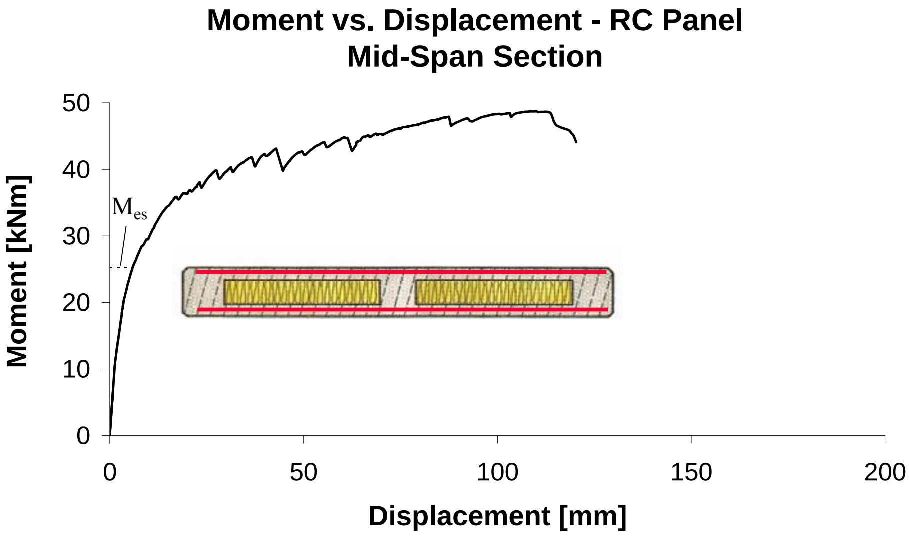



Figure 10. Instrumentation used during the tests.



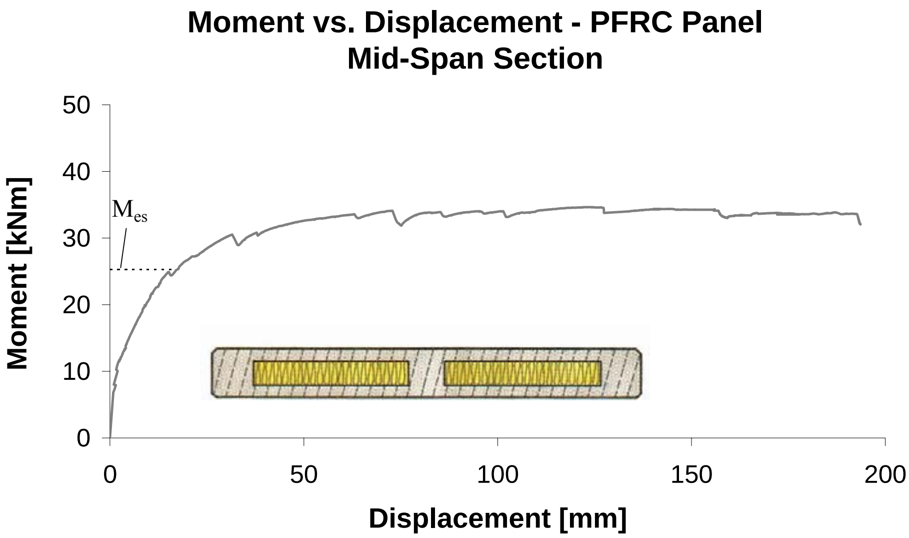
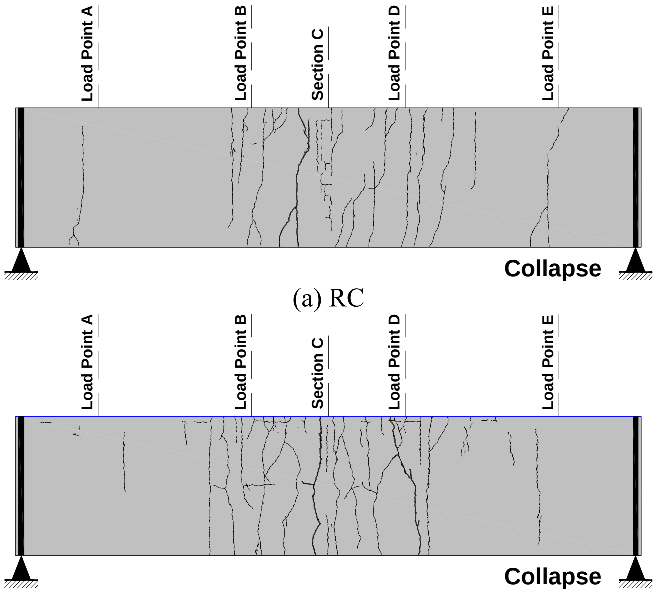




Figure 11. Comparison of the mid-span bending moment - deflection curves for the tested panels.




(b) FRC

Figure 12. Comparison of the cracks distribution in the tested panels after the test.

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