Pile supported self-compacting fibre reinforced concrete flat slabs

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Last years the use of steel fibre reinforced concrete (SFRC) increased significantly due to the acceptance of the material as a structural one in various countries throughout the world. In fact, it was an essential step forward, which motivated researchers to investigate possible application of SFRC in elements with high structural responsibility, as pile supported flat slabs for buildings (PSFSB). The implementation of this relatively new material for elements has considerable advantages in comparison with traditional solutions (reinforced concrete), such as optimization of resources, reduction of execution time, reduction of environmental impact and other social aspects. However, the use of SFRC for structural purposes is limited because there are still some aspects related to both service and ultimate limit states that are not suitably covered. For this purpose, a full-scale test on a four-field self-compacting fibre reinforced concrete PSFSB (5.00 by 6.00 m spans) has been performed within the context of an industrial-oriented research. The construction system has been analyzed and the prototype has been loaded in different stages with permanent and overloads in order to study both cracking and deformation responses and, eventually, led to failure. Results and outcomes of this industrial-oriented research are presented and discussed herein.

Steel fibre reinforced concrete (SFRC) is among of the most essential innovations in the field of concrete technology. The composition of SFRC includes steel fibres as an additional component in comparison with the conventional concrete. However, the presence of this component has a considerable influence on concrete properties, such as residual tensile strength, durability, crack resistance, thermal characteristics and fire resistance.

Until recently, the use of fibres in concrete mixes was oriented to non-structural purposes. However, during last decades the area of application of SFRC has been changed significantly due to publication of relevant design codes and recommendations which approved the above-mentioned material as a structural one [1–3]. As a result, elements with high structural responsibility have been executed using SFRC and pile supported flat slabs for buildings are among them [4–6]. Several examples of buildings and prototypes where PSFSB have been performed are presented in Tab. 1 (L_{max}: the maximum span, h: depth of the slab; C_f: steel fibre content in kg/m^3).

The provided information confirms that the executed SRFC slabs have the significant span-depth-ratio with minimal amount of traditional reinforcement. However, it is recom-

Tab. 1: Several examples of buildings and prototypes where PSFSB have been tested

Fibre Type Length [mm]	Diam. [mm]	C_f [kg/m^3]	L_{max}/h [m/m]	Traditional Reinforcement	Building / Prototype	Country
50	1,3	100	30	Yes[1]	Prototype	Luxembourg
37	0,5	90	6	Yes[1]	Prototype	Portugal
50	1,3	100	28	Yes[1]	Prototype	Estonia
–	–	100	24	Yes[1]	Building	Lithuania
50	1,3	100	27	Yes[1]	Building	Estonia
50	1,3	100	27	Yes[2]	Building	Spain

NB: Yes[1] – only presence of anti-progressive collapse bars [7];
Yes[2] – only presence APC bars + traditional reinforcement in the areas with particularly high stresses

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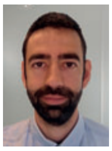

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mended the installation of anti-progressive collapse reinforcement in order to guarantee the stability of the total structure in the case of collapse of one slab field due to overloading or structural failure [8]. The APC bars should be placed in the bottom of the slab in alignment with the columns in both directions. Also, it should be highlighted that for this type of structures the steel fibre reinforced self-compacting concrete (SFRSCC) is required. The development of this type of concrete is quiet a challenging task due to the high content of steel fibres (up to 100 kg/m^3) [9].

In the case of the first Spanish experience with elevated steel fibre reinforced self-compacting concrete slabs (ESFRSCCS), an economic study was realized in order to justify the possible cost savings in execution of the abovementioned structural elements in comparison with the performance of the traditional reinforced concrete slabs [6]. The provided analysis demonstrated the financial advantage of new technology: the cost savings were around 12 % with APC bars included.

Although the benefits of SFRC application with structural purposes, there are still aspects which require in-depth study. Among them, the effect of long-term loads on ESFRSCCS in terms of deformations and cracking. On the other hand, the design of SFRSCC mixes requires further study with the objective to enhance the structural performance of the material. In order to cover the above described aspects in more detail, construction company SACYR and the research group from Polytechnic University of Catalonia have been carrying out a research project for the past two years aimed at covering these aspects

The main objective of the presented paper is to describe the obtained results, which contains the execution of ESFRSCCS and the posterior analysis of the structure under different load types.

Real scale prototype of ESFRSCCS

Development of SFRSCC mix

Extensive study of SFRSCC mixes preceded the execution of the real scale prototype of elevated slab. During the aforementioned study, 15 concrete mixes with different fibre types were analyzed, varying the fibre content from 60 kg/m^3 up to 120 kg/m^3. The obtained residual tensile strengths which correspond to crack mouth open displacement (CMOD) equal to 0.5 (f_{R1}) were in the range of 4.0 MPa to 14.0 MPa. The values of f_{R3} (CMOD equal to 2.5), were between 4.1 and 14.5 MPa. It should be noted that the represented values refers to the mean ones.

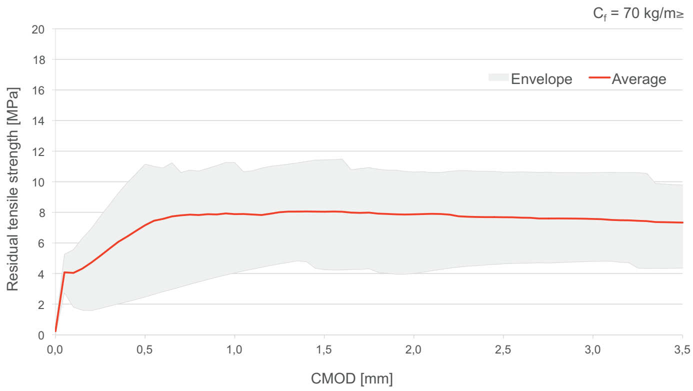

Fig. 2: Residual tensile strength – CMOD curve

Thereafter, the design of the proposed ESFRSCCS was carried out by means of yield line method and non-linear numerical analysis. The report provided by ACI [10] was used for the analytical solution, meanwhile the simulations were performed by means of the software “ABAQUS” using different constitutive models provided by RILEM [1] and fib Model Code 2010 [3].

Taking into account the design output and the results of the experimental campaign, it was decided to use 70 kg/m^3 of steel fibres to the concrete mix for the prototype in question which is considerably less in comparison to the previous experiences (Tab. 1)

During the execution of ESFRSCCS, cylindrical, prismatic and cubic samples were cast using concrete from each truck mixer. Produced samples were transported to the Laboratory of Structure Technology Luis Agulló at UPC to be tested.

As there could be some variation in mechanical properties of SFRSCC from different concrete mixers, 5 cylindrical Ø 150 x 300 mm, 4 prismatic 150x150x600 mm and 4 cubic 150 mm samples were cast from each of the trucks. The tests proven a suitable homogeneity of the material. The mean value of the compressive strength at 28 days was equal to 44 MPa, while the residual tensile strengths f_{R1} and f_{R3} were equal to 7.2 and 7.7 MPa, respectively. The results provided by three point bending test had the coefficient of variation around 20-25 %, which is common for this type of test [11,12]. The standard f_{Ri}-CMOD curve for the tested prismatic samples is represented in Fig. 2.

Construction of the flat slab and loading procedure

The construction of the prototype was carried out in the coldest period of the year Barcelona. These climatic conditions coupled with autogenous shrinkage of concrete led to minor cracking at the upper surface of ESFRSCCS. The abovementioned cracks were controlled by fibres and did not affect on the structural capacity of the slab since the width were bellow 0.1 mm.

Taking into account North American standards [8,10] and previous experiences (Tab. 1), the APC reinforcement was installed: 3 Φ12 in the alignment of the columns in both directions. As could be noted in Figure 3a, there was no traditional reinforcement because steel fibres in the concrete mix provided sufficient flexural and punching shear strength according to the analysis.

Fig. 1: a) Cast samples b) Laboratory of Structure Technology c) Three point bending test

Fig. 3: a) APC reinforcement b) Pumping of SFRSCC c) Constructed ESFRSCCS

A suitable workability was achieved with no "fibre balling" and the rheological properties of the material did not differ significantly in comparison to those observed in laboratory conditions (Fig. 3b).

After formwork removal, prisms were installed in order to monitor the deflections. Once the structure stabilized under self-weight, the loading process started. The main objective was to evaluate the response of the structure under long-term loads of considerable magnitude. For this purpose, the load

Fig. 4 a) Loading process b) 2nd phase of loading c) 4th phase of loading

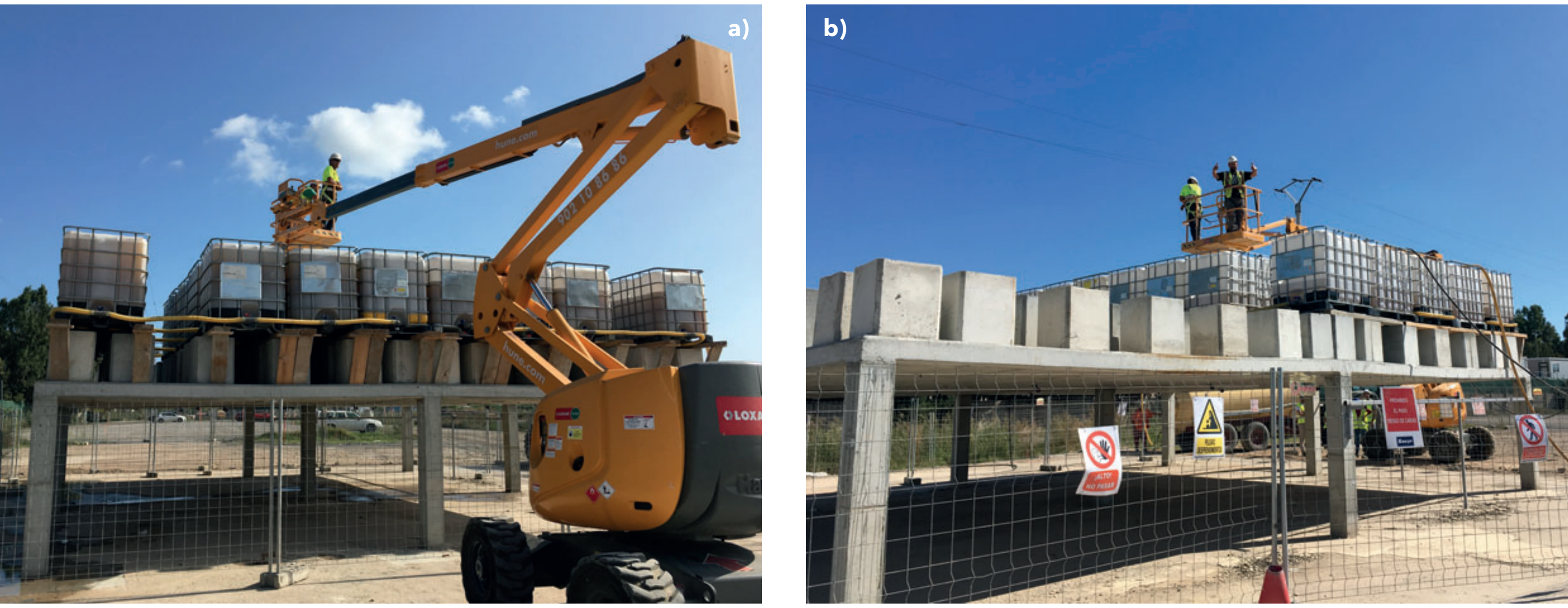

Fig. 5: Spans subjected to a total load of 16 kN/m^2

increment was provided by means of concrete cubes 0.5 x 0.5 x 0.6 m (≈ 350 kg each one). However, it was decided to load the structure gradually, therefore the whole process was divided into four steps. This approach permitted the estimation of both instantaneous and long-term deflections for different load magnitudes and distributions (Fig. 4).

The time spans between load phases depended on the response of the structure, i.e. the next phase could only be started when the deflections were stabilized. In addition, the crack patterns, which corresponded to certain load step, were evaluated.

After the 4th phase, the total load (self-weight included) was equal to 9.6 kN/m^2. The next step was to assess the mechanical response of the structure when subjected to a factored uniformly distributed load (including self-weight, dead loads and overloads) of 14 kN/m^2 according to the established loads and applied load partial safety factors. For this purpose, water tanks were placed onto the slab and filled gradually with water. Firstly, two adjacent spans were loaded up reaching the design load (14 kN/m^2). However, the ESFRSCCS exhibited still residual capacity to further increase this load. Thus, it was decided to entirely fill the installed tanks leading to a total load of 16 kN/m^2. Even with the increased load, there was no loss of structural integrity, therefore, the slab was left with this load until the next day. The following morning, the increment of long-term deflection was equal to 10 mm, this proving both the ductility and load redistribution capacity.

The last load phase consisted in placing the water tanks onto the two untested spans and in repeating the test procedure. Despite of already having half of the structure damaged, the remaining spans also resisted a total load 16 kN/m^2. The above-described process can be observed in Fig. 6.

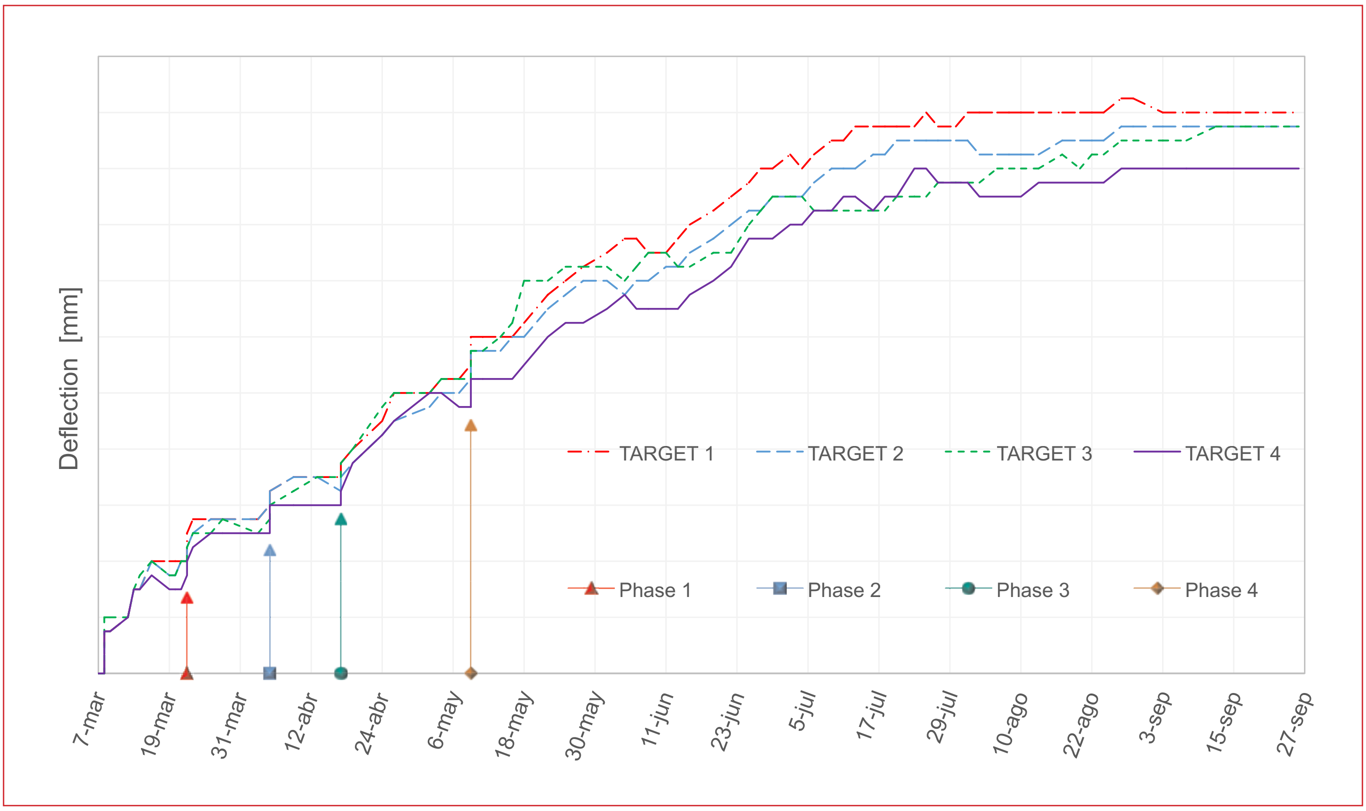

Fig. 6: Evolution of maximum deflection

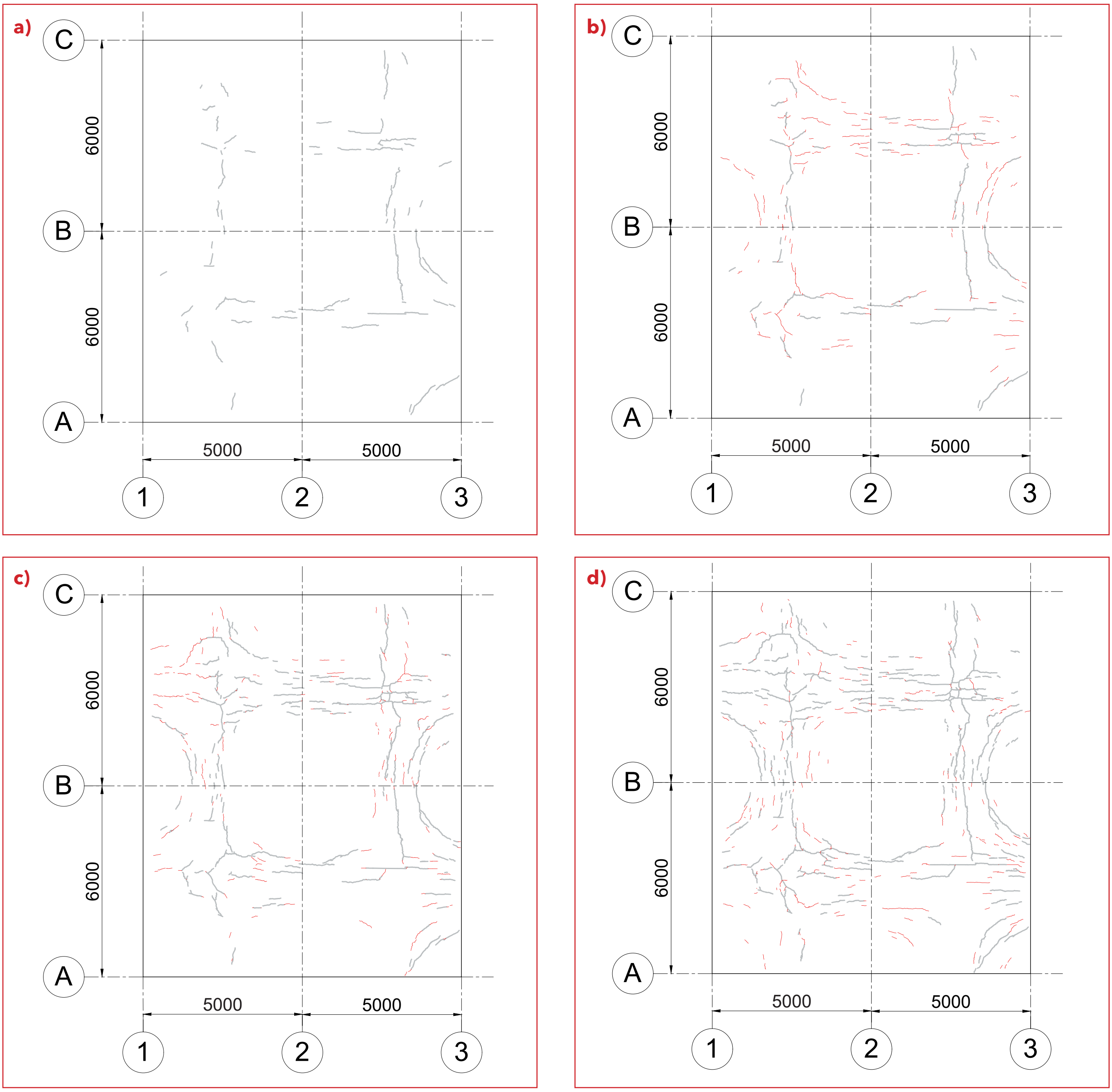

Fig. 7: Evolution of cracking pattern

Structural response of the prototype: deflections and cracking

The deformations of the structure were monitored by means of topography. Deflections were measured before and after every load step in order to evaluate the instantaneous deformations. Regarding the long-term deflections, the measurements were carried out three times per week. This procedure allowed establishing the load-deflection curve during the entire period of test:

The long-term deformation under 9.6 kN/m^2 (Fig. 4c) should be highlighted – it compounds ≈ 40 % of the total deformations. From the 3th loading phase, the cracking pattern of the bottom surface was evaluated several times. The results are represented in Fig. 7.

For better comprehension, the new cracks of the surface in comparison with the previous pattern are highlighted in red. The cracking pattern before testing to failure (Fig. 7d), is in line with those observed in previous experiences (with similar load types and geometric conditions) and corresponds to the one predicted by Johansen's theory [13,14] for the same boundary conditions.
Deflections from 9.6 to 16 kN/m^2 load levels were recorded. Fig. 8 gathers the registered deflection-load relationships for the first half of the slab tested.

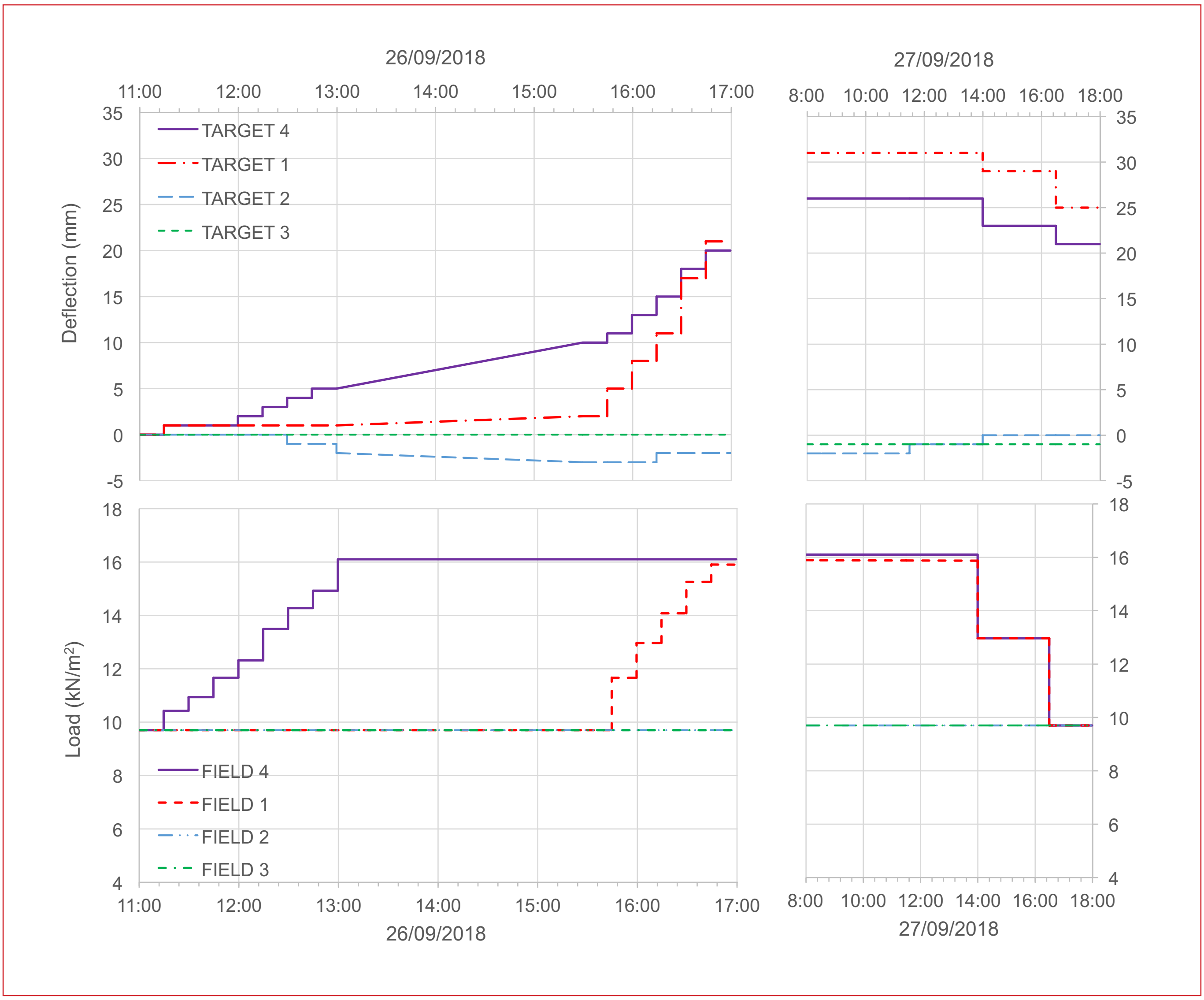

Fig. 8: Fragment of Time-Deflection and Time-Load Curves

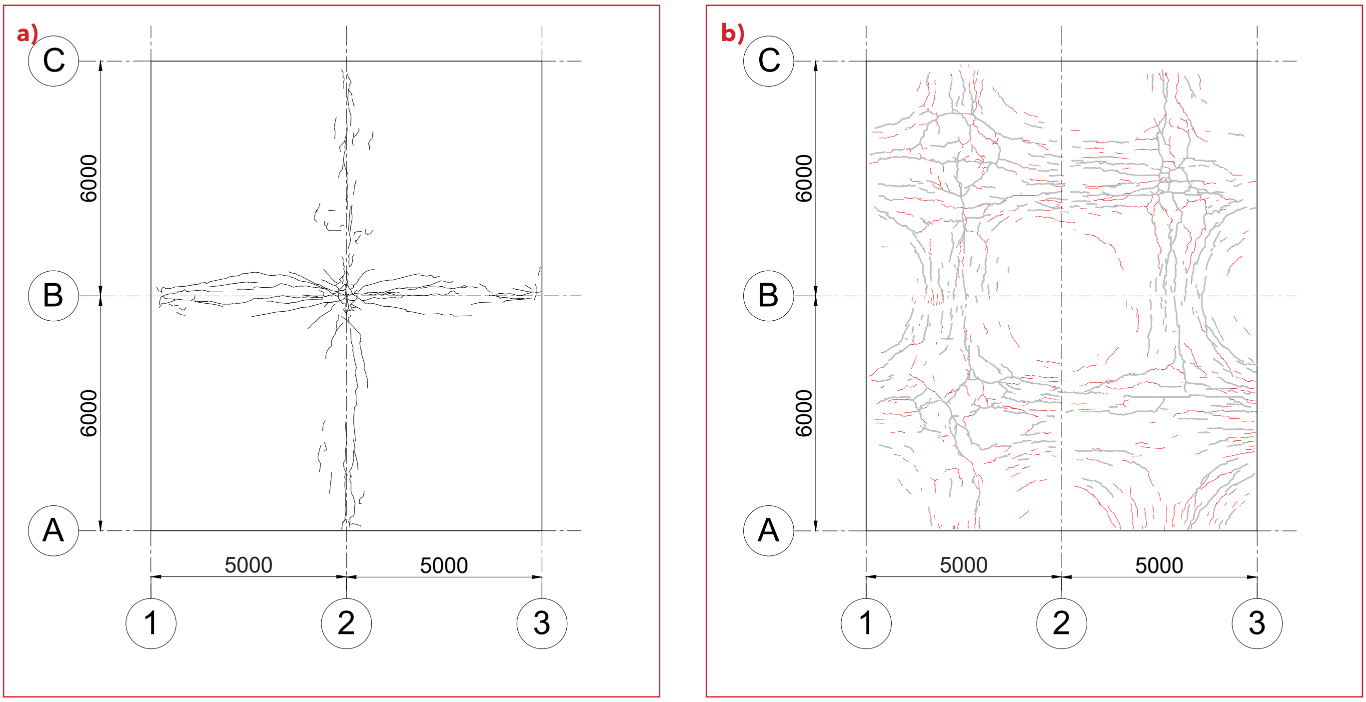

Fig. 9: Cracking patterns after testing at: a) Upper surface b) Lower surface

Once the test was finished, the prototype was unloaded and the cracking pattern of the upper surface could be assessed. The lower surface was also examined in order to have the final version of mentioned pattern (Fig. 9).

Demolition of the slab and posterior analysis

The prototype exhibited noticeable both ductility and structural capacities. Since there was no sufficient load to lead the structure to failure, the prototype was demolished as shown in Fig. 10. The next step of the study is to core cylindrical samples from the slab in order to analyze the distribution of steel fibres and to evaluate the fibre content in different zones of the element. These results will be of great importance to study the influence of fibre distribution on the performance of the structure. It is also essential to verify the obtained results with the design assumptions made.

Conclusions

Based on the obtained results, it can be stated that:

- It is possible to achieve the required bending and punching capacity in pile supported flat slabs with considerable span-depth-ratio using steel fibre reinforced concrete, without additional rebar reinforcement.
- The tested full-scale prototype has showed high ductility and structural capacity even beyond the design loads for which it was designed.

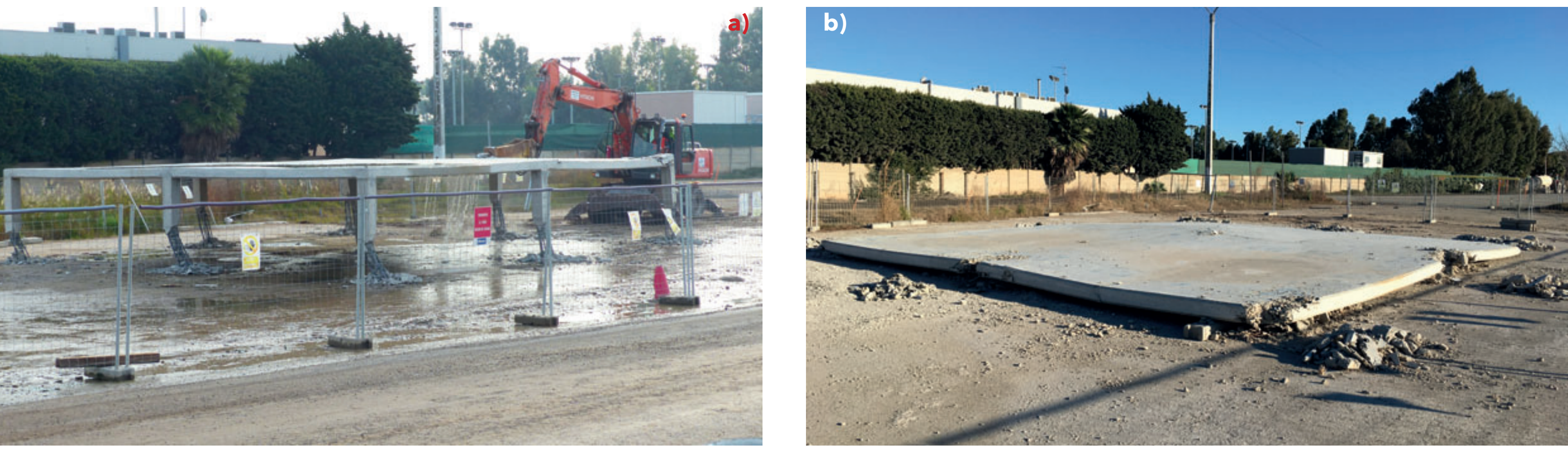

Fig. 10: Demolition of the prototype

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