Hybrid UHPFRC thin walled "π" beams for flat roofing applications

Esteban CAMACHO, Pedro SERNA

Polythecnic University of Valencia

Edificio Caminos II, ICITECH, Camino de Vera s/n, 46071, Valencia

escator@cam.upv.es

Abstract

The main hybrid UHPFRC properties are the high tensile strength it can achieve with a ductile behaviour and the close cracks it can develop during the strain-hardening, whereby its durability is improved. Those characteristics make this material especially suitable for carry tensile and flexural efforts in more slightly and new shapes elements, dispensing of conventional reinforcement. In this research, several hybrids UHPFRC mix compositions were designed and characterized for different levels of requirement in cost or strength, achieving values from 35 MPa to more than 45 MPa of equivalent linear elastic flexural tensile strength. The material composition includes high elastic limit steel fibres of two different sizes. Silica fume, aggregates type and qualities were also variables for this study in order to obtain different cost concretes. The workability of the mixture was designed for being high in order not to be compacted. A flat roof with similar purposes than conventional unidirectional flats was designed using thin walled π cross section beams made with UHPFRC. Advantages on minimizing materials consumption, reducing self weight, construction procedures, transport facilities and other improvements make of this solution an interesting alternative to conventional solutions. To analyze the structural behaviour three thin walled π cross section beams were made at actual dimensions in laboratory with different hybrid UHPFRC. Beams were tested in flexural four point bending tests. The load and associated deflection, the maximum load and cracking pattern were analysed and evaluated.

Keywords: Ultra High Performance Fiber Reinforced Concrete, Roofing, "π" beam, testing

1. Introduction

Ultra High Fiber Reinforced Concrete resists very high strength thanks to the good quality of its raw materials and specific casting/curing processes. That enables designs that minimize the used volumes and transported weight, increasing besides the live period of the structure. Thus, the structural solutions with this material result to be compromised with the sustainable development and decrease the construction times with the high industrialization of the precast solutions.

UHPFRC combines the technologies developed last decades in self-compacting concrete, high performance concrete and fiber reinforced concrete. Commonly this material contains

a high quantity of cement and silica fume, very low W/C ratio, high content of fibers with high tensile strength, selected arid with reduced maximum diameter and need the last generation additives for increase the workability of the mixture.

The behavior in tension of the UHPFRC differs of the traditional concretes: After the first cracking the strength capacity continues its increase, with the opening of several cracks (strain hardening). The highest strength valor is reached when one of those cracks begins to develop, starting a process called strain-softening where the load capacity decreases with ductility.

The properties associated to UHPFRC are a high compression and tensile strength, very good corrosion resistance, abrasion and impact resistance and a high ductility that allows to design without conventional reinforcement. The absence of communicated voids avoids the diffusion of gas and water, improving the durability, although creates some disadvantages in fire conditions.

The applications of UHPFRC are still very specific, although are expanding the last years. Many footbridges have been built, with a considerable reduction of the self weight. Different shells have been built too with absence of conventional reinforcement, since it let design the shapes with a lot of freedom. The expansion of this material in Spain is conditioned to the development of code to standardize the use and structural design.

1. Research significance

In this research the use of UHPFRC in a π cross section beam for a very common structural application as a part of unidirectional flat roofs has been developed and experimentally evaluated. Its shape was adapted using these material properties. The viability of this application has been studied, comparing with conventional current solutions in an economical and technical aspect.

For this aim the main goals of this research were:

- Design and characterize several UHPFRC mixtures made with local raw materials and analyze the dosage influence.
- Adapt the mixing process for the different work conditions and evaluate the influence of mixing process on the concrete properties.
- Design a thin walled π cross section beams to be applied in flat roofs using UHPFRC.
- Cast and test beams in actual section and evaluate the structural behaviour in laboratory.

2. Dosage influence analysis on UHPFRC mixtures.

3.1. Experimental program

The UHPFRC was conceived to be produced as a self compacting concrete (SCC), and avoiding any steam curing, trying to reduce the costs and attaining an easy casting method. With this it is assumed a reduction in the final properties for simplify and economize the process.

After some preliminary works, and based on the literature recommendations an experimental program was developed in order to design and characterize several UHPFRC mixtures and analyze the mix proportioning details influence.

A reference concrete with 800kgr/m^3 cement content, 10 % addition of silica fume (SF) (80kgr/m^3) and siliceous 0/2 mm low absorption aggregates. The solids size distribution was adjusted in agreement with the Andreasen & Andersen theory [10].

Two high yield strength fiber types from Bekaert were used: 13mm length and 0.16mm diameter (OL 13/0.16) and 40mm length hooked and 0.5 mm diameter (RC 80/40 BP).

Two cement types were analyzed: low water demand (I 42.5 SR), high water demand cement (I 52.5 R). A mix of each cement type at 50% was also tested.

The W/C ratio was kept constant for each kind of cement, but it was different between them in order to provide the same concrete fluidity (0.22 for cement I 42.5 SR, 0.24 for the I 52.5 R and 0.23 for the mix). Fluidity was measured with a like mini-slump test method.

Fibers dosages from 1% to 3% and the short/long fiber ratio were also variables for this study. Its effect on workability was compensated with the superplasticizer dosage. The used superplasticizer was Glenium C355 from BASF. Table 1 shows these program variables.

Table 1. – Mixtures tested to define the dosage influence on UHPFRC properties

Cement type (W/(C+SF) ratio)	Fiber dosage F / concrete volume - % (Ad. – superplasticizer weight/(C+SF) - %)	% fibers OL 13/0.20 – on total fibers content
I 52.5 R (0.24)	F - 1 %; Ad. - (3.5 %)	0 %
	F - 1.5 %; Ad. - (3.75 %)	33.3 % (*)
	F - 2 %; Ad. - (4 %)	50 %
	F - 2.5 %; Ad. - (4.25 %)	66.7 % (*)
	F - 3 %; Ad. - (4.5 %)	100 %
I 42.5 SR (0.22)	F - 2 %; Ad. - (4 %)	33.3 %
		50 %
		66.7 %
Mix (0.23)	F - 2 %; Ad. - (4 %)	33.3 %
		50 %
		66.7 %
Additional mixtures		
I 52.5 R– 880kgr/m^3 (0.26) No Silica Fume	F - 2 %; Ad. - (4 %)	50 % 66.7 %
I 52.5 R (0.24) 0/4 calcareous sand	F - 2 %; Ad. - (4 %)	50 % 66.7 %

(*) – Only for 2% fiber dosage concretes

Additional mixtures were tested to analyze the effect of the replacement silica fume by cement, or the use of local limestone sands (by mixing crushed and rolled sands) instead of the silica aggregate always in agreement with the Andreasen & Andersen theory [10]. (Table 1)

3.2. Casting and testing methodology

For each mixture 1 liter concrete was elaborated in a mortar mixer (fig 1) [12]. The mixing process based in the experiences of other researchers was:

- Addition of the cement, silica fume and aggregates - medium speed - 90 sec.

- Addition of water and half of the superplastizer, - 90 sec.

- The mixer is stopped 120 sec.

- Turn on the mixer at medium speed - add the rest of the superplasticizer - mix 360 sec.

- mixing at high speed -120 sec,

- At medium speed - add fibers, first the shorter ones and later the longer ones (if needed).

- Continue mixing until 17 minutes from the beginning of the casting.

From each mix, besides control the concrete workability, a 320 x 70 x 40 mm specimen was cast by pouring and without any additional compaction system.

Specimens were conserved at 20ºC and 95% RH until the test time at 28 days. For the test specimens were disposed (fig 2) on two supports with a 240 mm span and loaded at two symmetrical points spaced 80mm. throughout the test the load – central deflection curve was registered.

Flexural stress was evaluated assuming an elastic linear behavior in the rupture section.

Figure 1. Mortar mixer   Figure 2. Specimens test setup

As the π beams production needs an important concrete volume, beams were cast in an industrial mixer (see 4 paragraf). Due to the different mixing energy the use of a 5% of a more efficient ACE 31 superplatizicer from BASF and some dosage changes in the mixture were required to find similar workability. The final concrete mix proportioning was:

Optimum Strength Concrete: Cement type I 52.5 R - 800kgr/m^3, silica fume 80kgr/m^3, W/(C+SF) ratio = 0.24, siliceous 0/2 mm low absorption aggregates

Economical Concrete: Cement type I 52.5 R - 960kgr/m^3, no silica fume, W/C ratio = 0.22, local limestone 0/4 sands.

In both cases a 2% fibers were dosed, 50% type OL 13/0.16 and the rest of RC 80/40 BP).

To characterize those dosages and compare the effect of the mixing process a 320 x 70 x 40 mm specimen was cast with concrete produced with the industrial mixer in the same conditions as the one used to cast the π beam. With this same dosage another 320 x 70 x 40 mm specimen was cast with concrete produce in the mortar mixer.

These specimens were conserved in moist room conditions and tested at the beams time test.

3.3. Experimental results and analyse
The 320 x 70 x 40 mm specimen tested showed (figure 3) that flexural strength are found when a I 52.5 R cement is used, even considering that these concretes are produced with a higher water content to compensate its higher water demand. Analyzing mixes with the same cement type and total fiber content it is noticed that the most efficient fiber effect is obtained when a 50% of each fiber type is dosed.
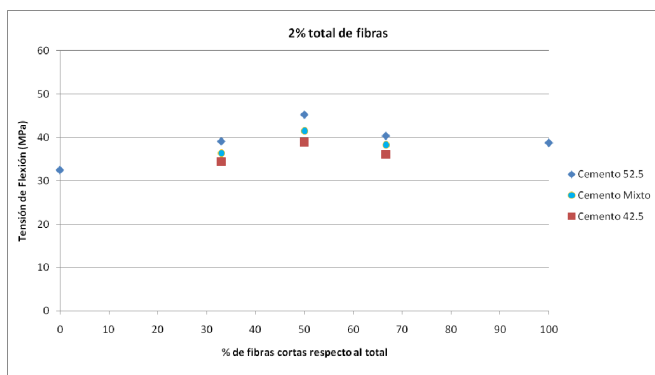

Figure 3: Flexural strength with different cement type and fiber combination

This effect is bigger as much as bigger is the content of fibers of the mixture, (figures 4, 5 and 6). This fact shows the synergic effect when two different fibers type work together, as it was signalized by Marković [1]. Short fibers avoid the first micro-cracks opening, allowing the material reach high levels of strength with a pseudo-elastic behavior. The longer hooked steel fibers control the macro-cracks development. Its addition increases the strain - hardening area in the load-displacement diagram.

The 50 % hybrid UHPFRC with fibers content between 1% and 3% showed that the strength increases with the fibers dosage (figure 7). Nevertheless the tendency is reduced for too high fiber content. On the other hand, the workability is considerably reduced with the increase of fiber content needing a raising superplaticizer dosage, and the cost increases. It can be deduced then that in most cases is not interesting add contents of fibers greater than 2%.
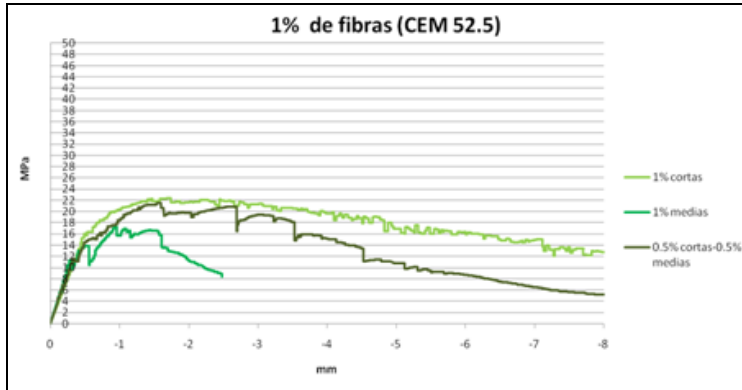
Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
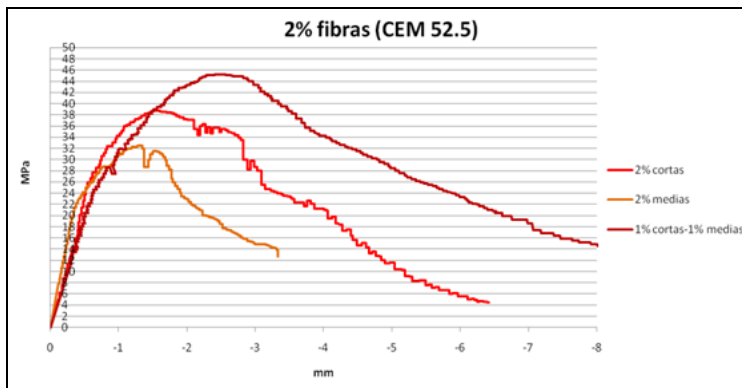Alberto DOMINGO and Carlos LAZARO (eds.)

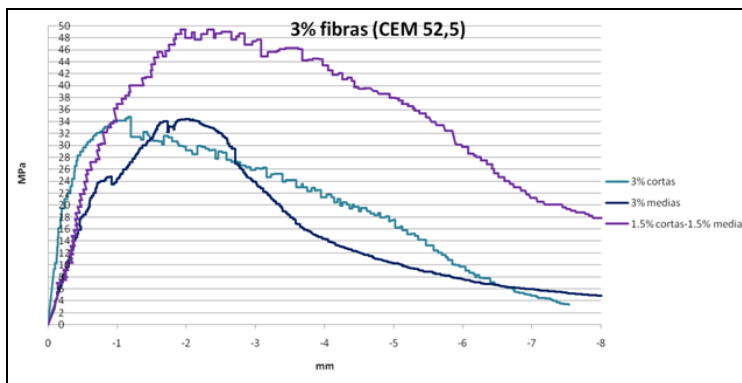Figure 4: Flexural stress - deflection behavior for mixtures with 1% of fibers

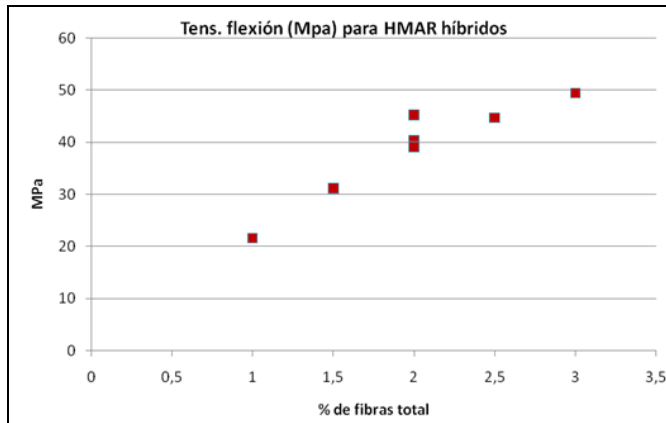Figure 5: Flexural stress - deflection behavior for mixtures with 2% of fibers.

Figure 6: Flexural stress - deflection behavior for mixtures with 3% of fibers.

Figure 7: Flexural strength for hybrid (50% of each fiber type) mixtures

The modified UHPFRC mixtures made for evaluate other variables showed decreases of flexural strength comparing with the base dosage. To use cement replacing silica fume lead to a strength reduction of 11%, and the use of local limestone aggregate reduces a 33% the concrete strength.

The results of flexural test for the concretes used for beams casting are shown in fig. 8
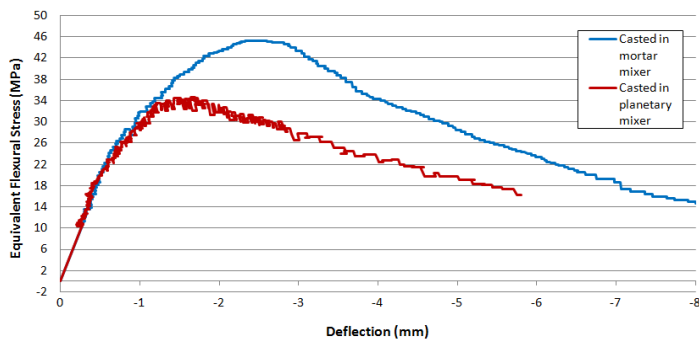
a) Optimal strength concrete
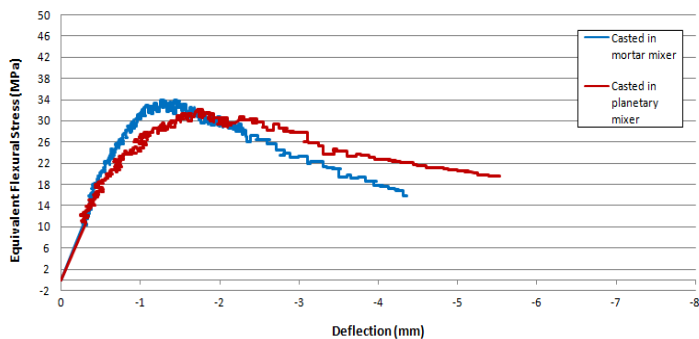
b) economical concrete

Figure 8 Flexural stress / deflection curves for concretes used for casted beams

The concrete called "optimal strength concrete" shows a clear streength reduction (more than 25%) when casted in the industrial mixer. On the opposite the economical concrete reachs the same strength in boths casting methods. These results shoud may indicate that silica fume decondensation is not possible in the industrial mixer due to its limited mixing energy. It should be taken in account that power by casted concrete volume for the mortar mixer is 9 times higher than for the industrial one.

3.4. Proposed Stress – Strain diagram in tension for UHPFRC.

Based on the experimental results from 320x70x40mm specimen tests a multilineal diagram to characterize the stress – strain behavior of a UHPFRC was developed [11] by inverse analysis. For that the linear strain section hypothesis and smeared crack was assumed. The multicrack shape in the specimens after test, and until high deflection levels makes obvious these hypotheses. Figure 9 shows the results of such an analysis for the two concretes used for beams casted, when concrete is produced in mortar mixer. From the results show in figure 8 it can be asumed that if concretes is produced in industrial mixer the behaviour of both concretes will be like this one of the "economical concrete".
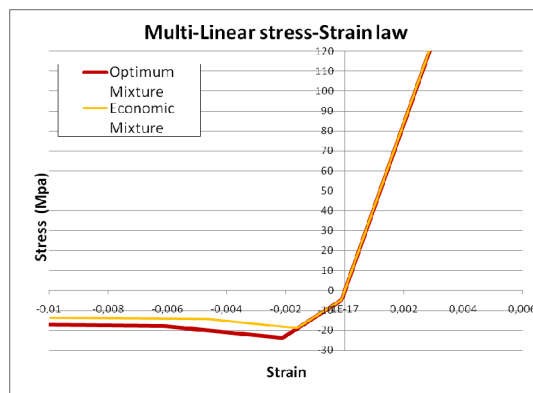

Figure 9 Proposed tension stress / strain diagram for concretes used for beams casted.

This diagram, with maximum tension strength with no macro crack pattern allows the material to support considerable tensile efforts both under service loads and when it is being prestressed in the precast concrete plant.

3. Roof and beams design elaboration and testing

The roof design is shown in figure 10. It consists on thin walled "п" cross section beams and 20 mm thick plates to attain a continuous horizontal surface. This configuration cans woks for similar purposes than 240 mm depth conventional unidirectional flats.

The roof beams units (fig.11) are thought for be casted, with UHPFRC, with two 7 wires prestressed strands 13 mm diameter; Y-1860-S7 one in each wing, without conventional

reinforcement. To guarantee a wall thickness between 20 and 40mm a precast production is required.

The shape of the beams designed allows an accumulate system that take the full advantage of the transport (fig 12). Minimizing materials consumption, reducing self weight, construction procedures and other advantages are also important improvements that should be taken into account.

Figure 10: Transversal section of the flat roof, including the 20 mm thick plates disposed for create continuity between structural elements
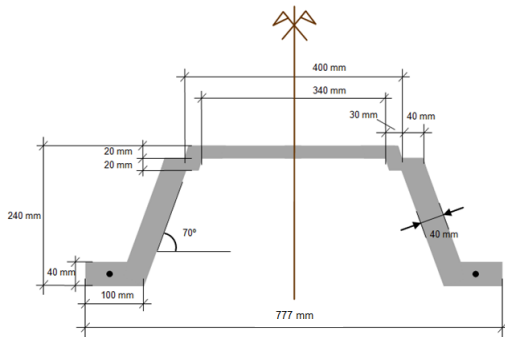
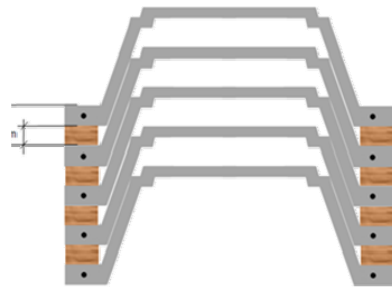Figure 11: unidirectional element design.

Figure 12: Pile-up system for transport and store.

The concrete for the roof beams was elaborated in a 100 liters capacity like industrial mixer (fig 13). Two beams made with different concrete (called Optimum Strength Concrete and Economical Concrete according to 3.2 paragraph) were casted. No strands were used for this test. The mixing process was:

- Mix the dry materials 60 sec
- Add water and the half of the superplasticizer during 90 seconds.
- Stop for 2 minutes.
- Turn on the mixer, add the rest of superplasticizer and mix during 7 minutes.
- Add fibers
- Continue mixing until 17 minutes from the beginning of the casting

The concrete elaborated was thrown over a wood framework with the geometry of the beams. Beams were conserved in laboratory conditions and tested at 28 days.

To test, beams were placed on two supports with 2 meters span and loaded in two centered points spaced 300mm. Vertical displacements in center span and others points were

controlled with LVDT (fig 14). A system of steel bars to avoid the wings opening during the test was disposed.

Fig 13. Industrial mixer

Fig 14. Beams test setup

Figure 15 shows the load - central deflection curves obtained from the test. It was noticed that there is no clear differences between the tested beams.
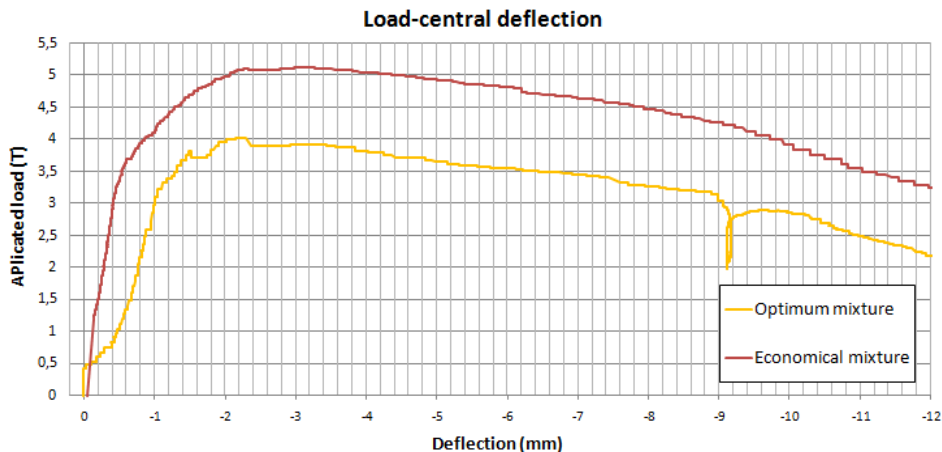

Figure 15. Load - central deflection in tested beams

During the test no important crack opening were observed until high deflection level. At rupture, final crack is develop with a smeared crack pattern around (fig 16).

Evaluating the element with the tensile stress-strain law deduced in paragraph 3.4, the maximum load reached should be 42 kN, approximately the obtained maximum load in the tested beams (fig 15). This shows that the method applied to obtain the stress-strain law was sufficiently correct, even if should be detailed more in future researches.

Figure 16. Crack pattern around the principal crack at rupture time.

Results lets accept this design criteria to evaluate elements made with this section. The prestressing introduction will improve the mechanical capacity of this designed flat roof.

With this designed flat roof made with UHPFRC elements increases the industrialization, decrease the thickness of the roof, reduces the execution periods, and increases the structure life time thanks to its high durability. The use this UHPFRC beams implicates important environmental advantages, reducing the transport and the use of raw materials.

4. Conclusions

It has been developed UHPFRC with own mixture and mixing process. The combination of two different types of fibers, short and medium hooked, resulted to improve the flexural concrete behavior. The research proves that, with fiber contents from 1.5% till 2%, the flexural linear equivalent strength can be more than 45 MPa with an acceptable workability. The type of cement that provides best results was a CEM I 52.5 R despite it has a high water demand.

It was observed that a high mixing energy is needed to obtain the full advantages of raw materials and tixotropic admixture properties.

With an inverse analysis a stress – strain law for UHPFRC was deduced.

It has been designed a flat roof solution using a "π" cross section beam. It has been possible cast with UHPFRC lineal elements in laboratory in absence of conventional reinforcement and as SCC. Those elements were tested and its behaviour was in agreement with this one evaluated with the proposed stress – strain law.

Results lets accept this design criteria to evaluate elements with this section. The viability of a flat roof like this one made with UHPFRC opens new possibilities in the precast industry offering new products with advantages execution periods, durability, transport cost and use of raw materials.

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