TURNKEY PROJECTS OF ULTRA-HIGH-PERFORMANCE FIBRE-REINFORCED (UHPFRC) FOOTBRIDGES

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Abstract

The very high resistance and durable properties of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) are making possible to overcome traditional reluctance to introduce new technologies in construction sector, as well as barriers due to economy and lack of standardisation. As an example, this document shows the advantages of turnkey projects of standardized UHPFRC footbridges up to 40 m span and 3 m width with an average cost of 620 €/m^2 without considering substructures. The present work shows the economic and constructive viability of the first two footbridges performed following this process in the V-21 highway in Puzol and in the town of Guadassuar, both located in Valencia (Spain). The geometry of this UHPFRC standard design is described, as well as more relevant issues about fabrication, transport, casting, and cost, proving that UHPFRC structures can be competitive even when long term benefits are not considered in the economical evaluation.

Résumé

La très grande résistance et les propriétés durables du Béton Fibré à Ultra hautes Performances (BFUP) permettent de surmonter la réticence traditionnelle à introduire de nouvelles technologies dans le domaine de la construction ainsi que les obstacles liés à l'économie et au manque de normalisation. À titre d'exemple, ce document montre le les avantages de projets clé en main de passerelles standardisées en BFUP jusqu'à 40 m de portée et 3 m de largeur, avec un coût moyen de 620 €/m² (hors fondations et appuis). Le présent travail montre la viabilité économique et constructive de deux premières passerelles réalisées suivant ce procédé sur l'autoroute V-21 à Puzol et dans la ville de Guadassuar, toutes deux situées dans la province de Valence, en Espagne. La géométrie de la conception standardisée en BFUP est décrite, ainsi que d'autres points importants concernant la fabrication, le transport, la mise en œuvre et le coût, démontrant que les structures en BFUP peuvent être compétitives même si les avantages à long terme ne sont pas pris en compte.

1. INTRODUCTION

According to [1], Ultra High Performance Fibre Reinforced Concrete (UHPFRC) can be defined as a cementitious-based material which combines three of the most significant technological advances in concrete: (i) a compressive strength exceeding 130 MPa with ductile behavior, (ii) ductile tensile behavior thanks to the use of a high amount of fibers, (iii) a special selection of fine and ultra fine particles, which should be selected to maximize the packing density but also the selfcompactability in fresh state.

UHPFRC integrates the advances of these three ideas, providing also significant improvements in terms of toughness, durability, crack width control, impact resistance, fatigue, concrete-steel bonding… All these improvements lead to new possibilities in the design of the structures: (i) elements can be lighter, slenderer, and performed with an important reduction of volume used, ordinary reinforcement and workforce associated; (ii) structures have an improved durability and then, maintenance costs are significantly reduced. The lifetime of the structures is longer and the carbon footprint over the complete life-cycle is smaller.

The full advantage of UHPFRC is taken for applications and constructive systems different than for ordinary concrete or steel. These are the fields where UHPFRC has major competitive advantages respect to other solutions. In order to guide engineers to the use and design with UHPFRC, several international recommendations have been developed in the last years. The most relevant is the French, which has already become a standard [1]. Spanish recommendations are expected at the end of 2017.

Recommendations are being a key foundation for the development of structural UHPFRC applications [2-5], showing that it is a material with high potential in civil engineering when the structure is designed to exploit the material capacities.

One of the most dynamic fields for the use of UHPFRC in the last decade are the footbridges [6-8]. In this market segment the team of engineers of the Spanish firm Research & Development Concretes (RDC) has developed a design and a standard procedure for the production of UHPFRC precast prestressed footbridges. The solution reaches spans of up to 40 m, usable width of up to 3 m and an average cost of 620/m^2 not considering substructures. The manufacturing, control and commercialization of these elements are carried out by the company IDIFOR, which manages the first Spanish plant focused exclusively in manufacture UHPFRC precast products. The material is developed with local components and it has been used to produce and commercialize housing panels, 500 m^2 floating platforms for mussel farming, in-situ stairs or handrails.

This document describes the design of a standardized UHPFRC Howe truss footbridge and the key points of the material used, quality control developed, production and assembling costs. Data are based on the two first UHPFRC Howe footbridges manufactured by IDIFOR, one over the V-21 highway at Puzol (Spain) and other at the town of Guadassuar (Spain). Both have shown the economic and constructive viability of this UHPFRC product.

2. FORMEX®

The UHPFRC used by IDIFOR (registered as Formex®) fulfils the durability requirements stipulated by the French guidelines [1], which are also expected to be a reference in the upcoming Spanish recommendations elaborated by ACHE.

These requirements are:

- Water porosity at 90 days lower than 9 %
- Accelerated chloride ion diffusion coefficient at 90 days lower than $0.5\cdot10^{-12}$ m^2/s
- Oxygen permeability at 90 days lower than $9\cdot10^{-19}$ m^2.

Besides, according with the expected classification for the Spanish recommendations of this UHPFRC can be defined as follows:

UHPFRC-135/CA/13/E3, SH-7/0.9/2/1

This classification implies that the material is defined as a material with a compressive strength in cylindrical sample of 135 MPa or 150 MPa in a cubic element of 100 m of size. The term CA refers to the exposure class, and will depend on the project, not on the material properties. The following number refers to the maximum length of fibers used (13 mm in the case of these footbridges). Finally, as in the Spanish Structural Concrete Instruction EHE-08, the term E3 refers to a slump flow value according to EN 12350-8 between 750 and 850 mm.

Regarding tensile properties, it is said that UHPFRC is SH when it presents a pseudo-plastic branch in tension with multi-micro cracking in the standard characterization test. Such is the case of the UHPFRC used for the footbridges, which has a characteristic tensile strength of 7 MPa, with a hardening coefficient of 0.9, a peak strain of 2‰ and a crack opening at the intersection of the first softening line to the *w* axis of 1 mm. These values are presented in the characteristic tensile stress-strain and stress-crack opening law shown in figure 1. Based on these laws and on the design criteria proposed in French Norm [1], the designs proposed here were verified for different spans to guarantee the structural safety, its service suitability, and its lifetime.

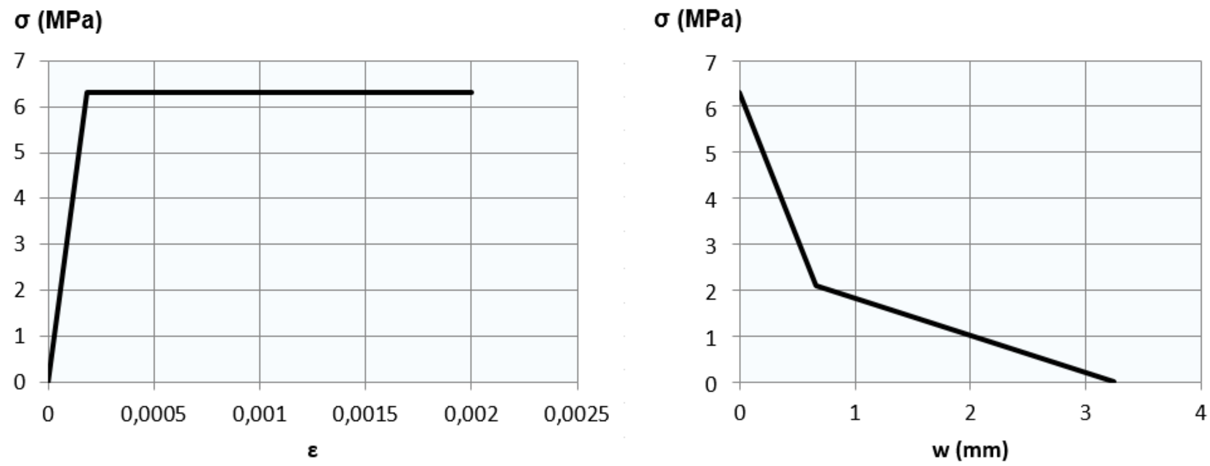

Figure 1. Characteristic tensile laws of the UHPFRC used: stress-strain law to peak (left) and strain softening law stress-crack width (right)

Figure 2 shows the unnotched 4-point bending tests carried out with the UHPFRC in 100 x 100 x 500 mm (L/h = 4.5) beams used for the footbridges. An inverse analysis specifically developed by López [9] was carried out to obtain the tensile stress-strain law of the material and verify its capacity to comply the tensile requirements.

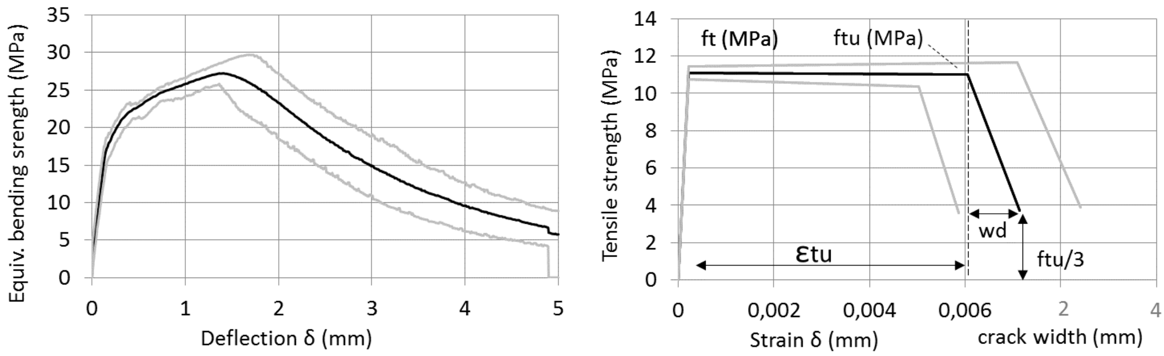

Figure 2. Bending tests performed to 8 prisms of the UHPFRC used in plant and average tensile stress-strain and stress-crack width laws obtained with inverse analysis

The use of this material for the development of the footbridges had, among others, the following advantages:

- Complete removal of the secondary shear reinforcement and reduction of the steel placement operations.
- Reduction of the bonding lengths and sections.
- Adoption of a geometric cover of 25 mm for passive reinforcements and 30 mm for the prestressing steel, ensuring a minimum lifetime of 100 years for any exposure class.
- The design flexural strength for 35 mm thickness slabs is of 14 MPa, value that allows to use a deck without ordinary reinforcement with this thickness.
- High capacity of cracking control, which allows the design of no-prestressed reinforced ties with a stress of 320 MPa in the reinforcing bars, average distance between cracks below 20 mm and crack opening under 50 microns in service. This value is admissible even for the most aggressive exposure classes defined at the Spanish Structural Concrete Instruction.

3. DESIGN OF THE STANDARDIZED HOWE TRUSS FOOTBRIDGE

The standardized Howe truss footbridge is a U-shaped section composed by two lateral Howe-type trusses, which are connected at their bottom side with a Vierendel beam. The latter is designed to resist the wind actions, and contains the tensile steel reinforcement and the prestressing steel required along the longitudinal length. On this bottom beam are placed 35 mm thickness UHPFRC shells. They are cast without reinforcement and with an anti-slipping texture, as they are placed to generate the flooring surface.

The footbridge has a constant thickness, so the truss itself is the handrail of the structure. The top chord is 1.20 m height. The voids along the truss are covered by safety glass.

Figure 3 shows a standardized Howe footbridge with different spans installed in Guadassuar (Spain), where the Howe lateral truss and the bottom Vierendel truss can be seen. Figure 4 shows a bottom view with the safety glass and the 35 mm deck already installed. Figure 5 shows the Puzol footbridge finished, and a detail of the specific UHPFRC anti-slipping surface of the deck.

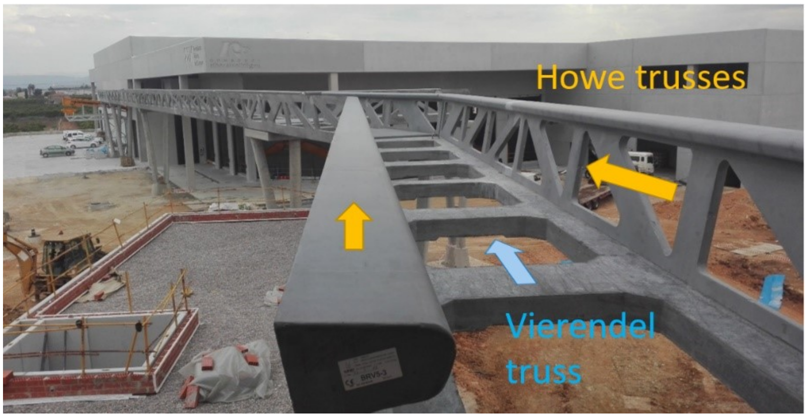

Figure 3. General view of the footbridge at Guadassuar during the assembling

Figure 4. Bottom view of the UHPFRC Howe footbridge in Guadassuar

Figure 5. Internal view of the footbridge over the V-21 in Puzol and flooring detail

The competitiveness of this solution is reached for standardising the section, procedures and formworks for a range of spans at the precast company. Some of the relevant aspects to be highlighted are:

- The lighting designed for the Howe truss allows the adaptation to different spans modifying the thickness of both the struts and the ties and maintaining the same geometry. This allows to obtain economies of scale in the production process.
- The lighting of the Vierendel bottom truss can be adapted to different lateral trusses.
- The top compressed chord (upper part of the handrail) is designed to ensure the stability to buckling for spans up to 40 m.
- The truss depth is the result of both the structural demands and the geometrical constrains required for a handrail to meet the pertinent safety requirements of the norm. Thus, the material is exploited in a double sense, as the top chord is the handrail and at the same time it plays a structural role.

This design provides a versatile footbridge that can be adapted to a wide range of spans, keeping competitive prices and with an additional durability compared to traditional solutions, as steel or ordinary concrete. The UHPFRC Howe footbridges count on a weight comparable to the structures made of steel, with an average weight of 1.5 ton/m of length for the span ranges considered. This implies that, besides of a more aesthetic and slender structure, it provides remarkable savings in transport, assembling and foundations.

The UHPFRC Howe footbridge in the considered span range can be transported in a single element from the manufacture plant to the definitive site. Being there, a crane chosen according to the span of the footbridge will place it in the final position. The traffic disruption in the affected driving lanes is reduced to few hours. Figure 6 shows the process of placing 33 m of span of the Puzol footbridge over the V-21 highway. The process was carried out during the night to keep a fluid traffic flow in both sides through temporary detours.

Figure 6. Placement of the 33 m span length Howe structure over the V-21 highway in Puzol

4. QUALITY CONTROL

Never should it be forgotten that the durability assurance in a structure does not depend only on an adequate design, but also on a suitable implementation. In the case of fiber reinforced concretes, it is required an intense control of the manufacturing processes to guarantee an homogeneous distribution of the fibers in each section of the element. Two are the main reasons which can result in an inadequate fiber distribution:

- Concrete segregation when the fluid yield stress is more reduced than the stress that the fiber applies on it, so the fibers tend to sink
- The casting process carried out is inadequate

The first of the effects can be prevented carrying out a slump-flow test before casting each of the batches. By doing so, it can be guaranteed that all the UHPFRC used to cast the element has the adequate rheological properties and segregation is discarded. In order to minimize the number of batches rejected, it is required to develop a previous and intense control of the water added. Besides, the project of the UHPFRC structure should integrate the development of trial batches in the casting project to ensure that:

- The real fiber orientation will be comparable to what was considered in the project calculations.
- There are no cold joints, i.e. sections without fibre.
- The required steps to reach an adequate surface finish will be carried out.
- The additional actions to be adopted in case of cold or hot weather are defined.

Assuming that fiber distribution is the desired after an adequate casting, it is required to verify that the hardened concrete fulfils the tensile and compressive requirements considered in the project. To do so, after 28 days of the casting it is required to control the concrete of each of the precast elements with the appropriate compressive and flexural tests.

Figure 7 resumes the quality control process that should be carried out in UHPFRC structures. The picture highlights in bold the two key points that are specific of UHPFRC, and for any other FRC.

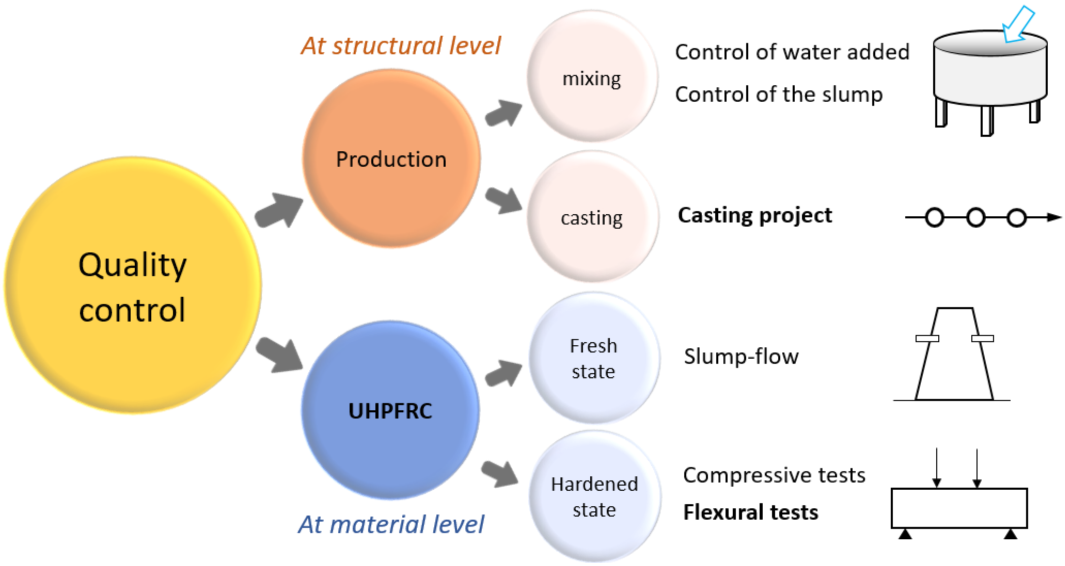

Figure 7. Quality control to be carried out in UHPFRC structures

In contrast to ordinary concretes, in fiber reinforced concretes it is strictly necessary to develop a casting project to ensure that the fiber orientation factors employed in the element calculation are realistic. Moreover, the development of the flexural strength tests is necessary to ensure that the tensile properties that the material has reached match with what was considered in the calculations. Whereas conventional FRC is usually tested in a three-point bending test with notch (EN-14651), UHPFRC is generally tested in an unnotched four point flexural test (defined in AFNOR, NF P18-710 [1] for strain hardening materials).

5. COST

The final cost of the UHPFRC Howe footbridges proposed has a close and linear relation to the weight of the structure. The reasons are that (i) production processes are standardized, i.e. resources employed in the production of the footbridge are the same regardless of the span length, and (ii) the dimensions of the elements are the same, having only very small differences in the formworks and on the reinforcement. Obviously, shorter spans imply a more reduced transportation and installation cost, but they require higher number of foundations and piles. Substructures costs have not been included in this analysis, as they can vary significantly per project.

Figure 8 (left) shows the weight of different spans of a standard UHPFRC Howe footbridge. As can be seen, it linearly increases with the span length. The same happens with the number of safety glasses used in each span (figure 8, right). The price of the standard transparent safety glass used in Puzol project was of 72 €/glass including the fittings and the assembling. The use of a special glass with color gradient as the used in Guadassuar (figure 4) can increase the price up to 40 %.

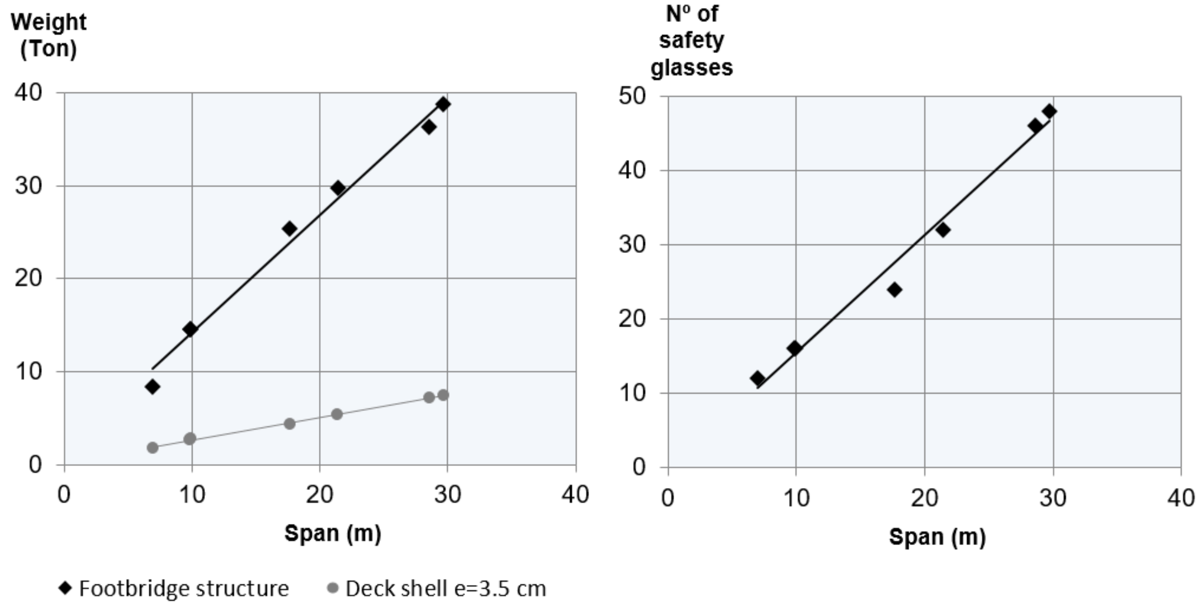

Figure 8. Relation between the span length and the weight of a standardized UHPFRC Howe footbridge (left) and number of safety glasses used (right)

The cost per kilo of structure (only the precast element, not including glasses) has not a linear relation with the span length, but describes a curve as the shown at figure 9 (left), varying between 0.87 and 0.94 €/kg. The average cost for the UHPFRC used for the development of these footbridges is of 680 €/m^3.

The experience on the footbridges developed provided an accurate estimation of the installation costs for different span lengths (table 1).

Table 1. Installation costs estimated per linear meter of footbridge

Span range (m)	€/m
10-20	120
20-30	180
30-40	250

Transportation costs vary depending on the distance between the precast company and the final destination and the transport logistics. Generally speaking, it can be estimated that transportation costs represent a 5-10 % of the total structure costs. It has been considered at 7.5 % in this document.

Considering all the previous concepts, the whole cost of the structure including the standard safety glasses, transportation and installation is shown at figure 8 (right), ranging between 600 and 650 €/m^2 for standardized UHPFRC Howe footbridges between 10 and 40 m of span. As an example, a 25 m span footbridge with 3 m of usable width has an approximate price of 47.000 €, placed in the final location and not including the cost of substructures and the elaboration of the project.

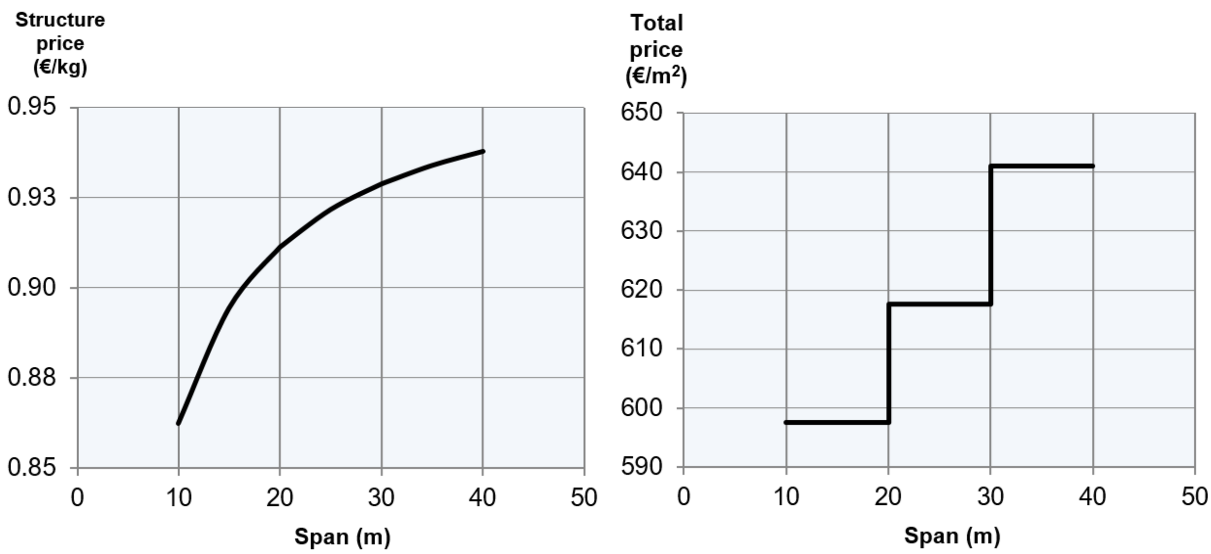

Figure 9. Price per kilo of structure (left) and price per m^2 of complete footbridge (right)

It is very frequent that accesses to footbridges are designed with a combination of ramps with lengths up to 9 m and landings. For that cases was designed a UHPFRC beam with a self-weight of 500 kg/m and an approximate cost of 380 €/m^2 including an aluminium handrail with safety glass, transportation and assembling.

6. CONCLUSIONS

Precast standardized UHPFRC footbridges are being produced in the Spanish market with a price between 600 and 650 €/m^2 not including substructures. Their maintenance costs compared to steel structures are reduced to almost zero even for the most aggressive environments. Besides, the structure does not require a final paint, as the material can be produced in varied colours.

These elements have a weight reduction of 60% to 70% compared with those designed with ordinary concrete, being comparable with the weight of a similar steel solution. However, compared to steel the workability of the material makes easier to create unique designs. Compared to ordinary concrete, UHPFRC provides more slenderness, less visual intrusion, and a significant aesthetic enhancement.

ACKNOWLEDGEMENTS

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