PRELIMINARY CALCULATIONS AND CASTING STAGES OF A UHPFRC TRUSS FOOTBRIDGE

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Summary: An innovative design of a 45-metre span UHPFRC footbridge, its casting process, and also preliminary calculations are presented in this paper. The resisting system consists of two identical trusses of variable depth, in which the compressed chord is also used as a railing. There is an intermediate curved ribbed slab connecting both trusses which works as the bridge deck, as well as a third truss that connects the bottom chords. The diagonals of the main trusses are shorter at the supports than at midspan, making the transmission of shear loads along the footbridge possible. The whole footbridge is decided to be cast in four stages at a precasting factory, and transported to the final place in only one segment. The casting process generates construction joints making a special study necessary. Buckling problems on top chords and cracking process in tensile diagonals have also been studied. The final design results in a very aesthetic, functional and safe footbridge, which may become the first UHPFRC truss pedestrian bridge. Casting process and a brief study of structural problems are presented.

1 INTRODUCTION

UHPFRC is an innovative material with a compressive strength greater than 150 MPa, a high ductility conferred by steel fibres, and a high flowability due to powder materials and third generation high range water reducing in its mixture. However, the most important drawback of this material is its high cost. This is due to the high amount of cement and fibres that it contains, and the hard quality control needed on its production and handling. The high cost can be offset developing new structural systems which take full advantage of UHPFRC properties. That is only possible by understanding its mechanical behaviour, and by adapting its design to more efficient cross-sectional shapes and details.

Most researchers agree that precast prestressed applications represent the greatest potential for UHPFRC production [1], since a high quality control can be achieved and the high compressive strength of UHPFRC at few days allows to prestressed it heavily improving its tensile capacity. Precast prestressed bridge construction has become the most successful field in which UHPFRC has been used, and where the first applications took place. Since the construction of the first footbridge in Sherbrooke, Quebec, in 1997 [2], a lot of footbridges have been performed throughout the world. More and more, structural designs are bolder making the most of the material, thanks to its better understanding and the experience gained over the years.

Sherbrooke footbridge showed that prestressing strands can be used in UHPFRC and it can be cast in a precasting company. The whole footbridge was performed in six segments, each 10 metre long. Both bottom chord and diagonals are prestressed to counterbalance tension forces. In addition, diagonals consist of stainless steel with 150-mm diameter tubes prestressed and filled with UHPFRC
to avoid buckling and to achieve greater compression stress, confinement and ductility. Despite it was the first structural application in UHPFRC, the design was quite slender with a dead load of only 4.4 KN/m² [3].

The structure which likely best takes advantage of the UHPFRC properties is the 69-metre span arch that supports the main span of the Wild Bridge in Austria (2011) [4]. The whole arch consists of two connected polygonal arches, each one with a 6-cm thin-walled square cross-section. The arches are also prestressed to increase the flexural capacity and to make the construction system possible.

Since UHPFRC structures are becoming increasingly slender, designs are closer to steel than conventional reinforced or prestressed concrete ones. As a consequence, new problems such as vibrations or buckling appear when using UHPFRC, which are usually taken into account only in steel structures.

2 OBJECTIVES

The main purpose of this paper is to show that the use of UHPFRC can offer a huge range of possibilities in civil engineering applications that could not be imagined using traditional reinforced or prestressed concrete. With this aim, the preliminary calculations and major problems found, such as construction joints, buckling, and cracking, in the design of a 45-metre span UHPFRC truss footbridge are shown. All of them are described and briefly studied, as well as the measures taken to solve the design difficulties.

Although there are a lot of external conditions imposed that restrict several design alternatives [5], the footbridge design has been focused on taking advantage of all UHPFRC mechanical, durability and aesthetics properties as far as possible, in order to keep the footbridge design economical in comparison with alternative designs with traditional materials.

3 MATERIAL

Mechanical properties of the material were determined in previous tests developed at Universitat Politècnica de València (UPV) [6]. Compression tests were performed in six cubic specimens 100x100x100 mm at UPV and also in a precasting company. Average compression and deviation results are shown in Table 1. The low deviation and the parallel results in both cases denote good production stability, and confirm that UHPFRC can be manufactured in a conventional precasting company.

<table>
<thead>
<tr>
<th>Day</th>
<th>Lab conditions</th>
<th>Precasting factory</th>
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<tbody>
<tr>
<td></td>
<td>Average Value (MPa)</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>1</td>
<td>79</td>
<td>3.3</td>
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<tr>
<td>2</td>
<td>103</td>
<td>2.9</td>
</tr>
<tr>
<td>7</td>
<td>128</td>
<td>2</td>
</tr>
<tr>
<td>28</td>
<td>150</td>
<td>5</td>
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The tensile properties of the material were determined by means of flexural tests. A non-linear material model was used, assuming a trilinear stress-strain curve in tension according to [6]. The parameters of the constitutive law were adjusted to six flexural tests. The elastic branch has an elastic modulus of 44000 MPa up to a stress of 11.5 MPa with a 5% coefficient of variation. The ultimate stress in tension is reached at a strain of 3% corresponding to a stress of 13 MPa with an 11% coefficient of variation.
4 DESIGN

Design consists of a “U-shaped cross-section beam with a 45-metre span, and a variable depth from 1.34 m at abutments to 2.02 m at midspan (See Fig. 1 to 5). The footbridge lateral webs are two modified Warren trusses made with a 6V:1H transverse slope, which are connected at the bottom chord with an x-shaped truss, which keeps the same wave-shape as the main truss (Fig. 3).

The truss bottom chord is 0.15 m in depth and contains a total of 18 0.6” seven-wire prestressing strands. The top chord has a constant depth and a variable width. It is narrower near the support and its width widens towards midspan. A longitudinal lighting element is placed along underside of it.

The deck is located at an intermediate height and connects the two trusses. It is 30 mm thick and has two longitudinal ribs and transverse stiffening ribs spaced 1.6 m. The deck is made in linear segments.

The truss diagonal members are variable in length with a 150x120-mm cross section and are heavily reinforced. Diagonals in tension include four 20-mm diameter bars. Diagonals in compression include four 20-mm diameter bars to take transverse bending into account due to the wind action, and to prevent buckling of the top chord on that plane. The bottom X-shaped truss is formed by a 150x120-mm cross section with four 12-mm diameter bars.

The holes along the truss above the deck are closed by transparent glass without diminishing transparency, which also makes walking on the footbridge safe.

Figure 1: Longitudinal elevation of the footbridge

Figure 2: x-shaped truss at the bottom chord
Figure 3: Cross-section at S5. Chords and deck at a lightening section

1. Main truss
2. Bottom chord
3. Top chord
4. Longitudinal deck rib
5. Deck
6. Transverse deck rib
7. X-shaped truss (Fig.2)

Figure 4: Cross-section at S5. Secondary elements and shear reinforcement at construction joints.

8. Shear reinforcement
9. Construction joint
10. Lightening at top chord
11. Longitudinal lighting
12. Service Box
5 CASTING PROCESS

As the footbridge has a 45-metre span, it is possible to transport the whole structure from the precasting factory to the final location by means of special transport. The whole footbridge is very difficult to cast in one segment without any joint because of the complex truss webs, the deck, and the deck ribs. Due to its complex design, it was decided to cast the footbridge in four stages (Fig. 6).

The first elements (Fig. 7) to be cast are the two lateral trusses. These elements are cast on a horizontal position using a 45-m length, 120-mm height and variable width formwork, which follows the top chord curve. Inside the formwork, high-density polystyrene pieces of 120-mm thickness are placed to perform the truss holes. In this stage, the longitudinal deck ribs are also cast to be integrated with the truss. The truss also includes bars to connect the top and the bottom chords and the deck. In addition to shear keys, a superficial retarding is added after casting in the areas where the truss is in contact with the chords and deck. The purpose is to get a rough surface that improves the adherence between the lateral truss, the chords and the deck slab.

Casting begins at one side of the formwork. As the concrete is flowable, it moves along the formwork smoothly by itself (Fig. 7). In order to prevent the truss from any kind of undesirable joint
after casting, it is necessary to guarantee that new concrete always must be poured above older one avoiding a possible meeting between two concrete fronts. Otherwise, an undesirable weak and brittle joint would appear in the truss without fibres.

As surface finishes are aesthetically important for the global appearance of the footbridge, a special care is needed. On the one hand, all diagonals above the deck will be in direct contact with pedestrians once the footbridge is put in place. Since the air tends to rise to the upper side after casting, the upper surface is covered by a porous sheet to get a smooth surface removing any bubble. On the other hand, the truss face, which remains at the bottom of the formwork, is the face which can be seen off the footbridge. In this way, a polyethylene sheet is stuck at the bottom side of the formwork to get a brilliant surface.

The second elements to be cast are the top chords (Fig. 6). In this stage, the main truss keeps its horizontal position, and the top chord formwork is put in place with its corresponding lightening (Fig. 7) and reinforcement. As the top chord is the railing of the footbridge, concrete surface must be completely smooth, because any steel fibre at the surface could prick the hand of a pedestrian. When the two main trusses and their top chords are cast, both lateral trussed webs are placed with their definite slope. A traditional formwork to produce industrial prestressed concrete U-shaped beams is used as a support.

In the third stage, the bottom chord and bottom truss are cast on the floor, following the same process used in the lateral trussed webs. The prestressing strands are previously located and tensioned.
In parallel to this process, a series of precast linear deck segments are made in a fourth stage. The precast deck segments are raised to their final position. Finally, the two longitudinal connection ribs are cast, connecting the deck to the main truss. (Fig. 6, right)

Since the deck slab is a necessary element in terms of stiffness and stability, the prestressing release takes place after the fourth stage.

6 PRELIMINARY CALCULATIONS

The actions applied to the footbridge and their combinations were determined according to the Spanish Code for Actions on Bridges [7,8], which is based on Eurocodes. Table 2 shows the most important parameters considered. A 3D model was implemented in SAP2000 (Fig. 8) and a linear analysis was run to obtain reinforcement requirements.

<table>
<thead>
<tr>
<th>Table 2: Actions considered in the footbridge design</th>
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<tr>
<td>Dead load (KN/m2)</td>
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<td>-------------------</td>
</tr>
<tr>
<td>4,3</td>
</tr>
<tr>
<td>Basic Wind Velocity (m/s)</td>
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<td>18</td>
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There were some problems to deal with due to the complex design of the footbridge. First, as the deck is located at an intermediate height along the main truss, only the stiffness of the top chord and the diagonals can prevent the top chord from buckling in a transverse plane to the truss. In this way, both top chord and diagonals cross-section must be wide enough. Second, as tensile diagonals are bearing direct tensile forces, cracking propagation on them at service limit state has to be assessed. Another problem is the transmission of shear forces through construction joints.

Once the design forces were calculated including second-order effects, the structural concrete design was carried out according to the Recommendations of AFGC [9] for both ultimate (ULS) and serviceability limit states (SLS).

Figure 8: Footbridge FEM.
6.1 Top Chord

A buckling analysis performed in SAP2000 shows that there are two main buckling modes for the top chord. The first mode causes the top chord buckling on the truss plane, being the buckling length the distance between two consecutive joints in the top chord (Fig. 9). In the second buckling mode, the top chord buckling takes place in the transverse plane to the truss, being the buckling length twice the length corresponding to the first buckling mode. In this case, the top chord slenderness could generate second-order forces higher than those that the top chord can bear.

Figure 9: Top chord buckling modes
Second buckling mode is mainly controlled by diagonals stiffness. For this buckling mode, the design bending moment including second-order effects in the central compressed diagonals is 24 KNm. At this load level, a 60% flexural stiffness reduction due to cracking, compared with the initial stiffness has been estimated (Fig. 10). The bending moment-curvature curve for the central compressed diagonal is shown in Fig. 10 for both materials, UHPFRC, average and design behaviour, and ordinary concrete (OC). This diagram has been obtained using the UHPFRC average tensile mechanical properties previously determined (Fig. 12). To determine the design UHPC curve, characteristic stress values have been reduced by a safety factor of 1.5.

If an ordinary concrete with the same cross-section shape was used, the design would not be structurally admissible. Thus, higher tensile strength and flexural stiffness, even after cracking, are necessary to make this slender design possible.

Since diagonals in tension suffer cracking, the design of them is even more problematic than diagonals in compression. Thus, its stiffness reduction is higher and its flexural capacity lower compared with these ones in compression. Tensile diagonals shown in Fig. 9 have to bear a 262 KN design tension force, and a bending moment of 14 KNm to take second-order effects into account. The moment-curvature diagram of a tensile diagonal member under an axial load of 262 KN is shown in Fig. 11. In this figure it can be seen that only UHPFRC cross-sections reach a maximum bending moment greater than the design value. In this case, there is a 56% reduction in the flexural stiffness at ULS.
Figure 11: Tensile diagonals moment-curvature relationship

Figure 12: Average Stress-strain constitutive law in tension
6.2 Diagonals

The stress-strain law in tension for UHPFRC was previously calculated as it is shown in Figure 12. One of the most relevant properties of this material is that cracks are no visible up to a strain level of about 3%. The reinforcement yielding strain is similar to the strain at peak (Point B in Fig. 12) for UHPFRC. It means that only when the ULS load level is achieved visible cracks appear. This fact ensures the durability of the structure. This is why the use of UHPFRC is suitable to design tensile ties without prestressing and without visible cracking improving traditional designs with conventional concrete.

In addition, both concrete and reinforcement tensile capacity can be added at ULS. Thus, it is possible to take full advantage of the tensile properties of UHPFRC, as it is shown in the reinforced UHPFRC ties tests developed in [10].

6.3 Construction joints

The high quality control which is required for UHPFRC and the complex design of the proposed structure make impossible to cast the whole footbridge in only one stage. As it has been decided to cast the footbridge in four stages, it is necessary to evaluate the shear provisions at construction joints. As mentioned earlier, the transmission of shear forces at construction joints can be improved by means of a rough surface. However, the shear forces have to be previously calculated at these joints.

The shear forces in the connection between the main trusses and both top and bottom chords are due to an axial stress variation, caused either by axial or bending forces. There are two critical areas: abutments, due to prestressing effect, and knots, where a local axial force transfer takes place.

The fact that main trusses are solid at supports makes that part of the prestressing forces are transmitted along the main trusses towards top chord. This stress distribution generates an axial force variation in the bottom chord.

A linear analysis has been performed to obtain the shear forces distribution along the construction joint. In Figure 13, it can be seen the results of this analysis in the construction joint at the bottom chord along the first seven meters of the footbridge for the worst ULS combination. The distribution at abutments and at the first knot is shown. With these stresses, shear reinforcement needs at construction joint have been calculated.

Figure 13: Design shear forces stresses at bottom chord construction joint along the first seven metres of the footbridge.
7 CONCLUSIONS

A 45-metre span footbridge has been designed to be constructed in Alicante (E. Spain) and will be the first pedestrian bridge in Spain using UHPFRC. The whole design to be constructed in UHPFRC is intended to take full advantage of its mechanical properties such as high strength, ductility, high limit tensile strain, flowability, low dimensions particles, or durability. To this end, it is necessary to overcome several problems as buckling, cracking or casting process. The use of UHPFRC leads to much bolder and slenderer designs than in conventional reinforced concrete, and gives much more possibilities for designers. In this case, an original slender truss footbridge has been devised. The total dead weight is only 4.3 KN/m² and the structure is intended to be cast in a conventional precasting factory. The design becomes an economical and safe solution in comparison with other materials such as steel or traditional reinforced or prestressed concrete.

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