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Production and Structural Performance of Thin Doubly Curved Elements Prestressed With CFRP Tendons

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Abstract

In the 1960's and 1970's doubly curved roofing elements (hyperbolic paraboloids) with spans up to 25 m were built and standardised in Germany. Since these elements mathematically consist of a family of straight lines, they were produced as pre-tensioned concrete members. The precast elements showed high load-bearing capacities, especially compared to their small thickness and low weight. The thin concrete covers may have been the reason to presume a vulnerability to corrosion of the steel reinforcement. Over the years, a decline in production resulted and today hardly any of these structural elements are applied. In order to account for this concern, non-corrosive prestressing tendons made of carbon fibre reinforced polymer (CFRP) are advantageous. Additionally, ultra-high performance fibre reinforced concrete (UHPFRC) with high strengths may make reductions in thickness possible.
The paper reports on the production methods and experimental investigations on doubly curved elements made of UHPFRC and pre-tensioned CFRP tendons. An adjusted formwork and prestressing frame were necessary for the production. Results of tests under flexural loading are discussed.

Keywords: CFRP tendons, ultra-high performance concrete, doubly curved elements, slender roofing shells

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Introduction

In the past, double-curved elements were often built for wide-span roofs. Due to their geometry, they are architecturally sophisticated and have a higher load-bearing capacity than flat elements. However, prestressing of the elements is necessary, for which previously only steel tendons could be used. These have the disadvantage that an adequate concrete covering is necessary or the elements show no sufficient durability. Despite the double-curved geometry, the so-called hyperbolic paraboloids (HP) can be prestressed with straight-line tendons (cp. Figure 1). With the materials available today, ultra-high performance fibre reinforced concrete (UHPFRC) and carbon fibre reinforced polymers (CFRP), it is possible to produce durable, load-bearing and thin HP shells.

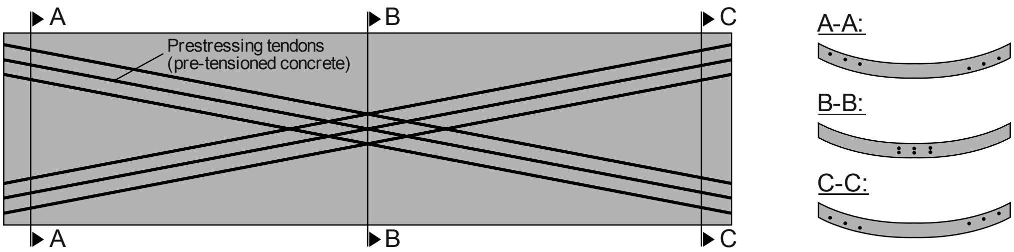

Figure 1: Prestressing tendons in doubly curved elements [1]

In a total of two German Research Foundation (DFG) funded research projects in the priority programme SPP 1542, the production of prestressed hyperbolic paraboloids, the load-bearing capacity and the theoretical background were determined [1].

Materials

Due to a high corrosion resistance and a high tensile strength of about 2,500 MPa CFRP tendons are suitable for slender concrete structures. The doubly curved shells were produced with CFRP bars and CFRP seven-wire strands from Tokyo Rope Mfg., Co., Ltd.. To enhance the bond behaviour these CFRP tendons are wrapped with coated carbon fibres. The properties given by the manufacturer are shown in Table 1.

Table 1: CFRP Material Properties [2]

Designation [-]	Diameter [mm]	Eff. cross-sectional area [mm²]	Guaranteed capacity [kN]	Young's Modulus [GPa]
U 5.0∅	5.0	15.2	38	167
1x7 7.5∅	7.5	31.1	76	155

All test specimens were fabricated with a fine-grained UHPC with straight steel fibres. The fibres with a length of 9 mm and a diameter of 0.15-0.17 mm (tolerances) were added to ensure a satisfactory ductile behaviour and sufficient pouring quality [3]. The steel fibre ratio

in the mixture was chosen to 0.9 Vol.-%. For the production of thin elements the maximum grain size was set to 0.5 mm.
In order to determine the compressive strength of the fine-grained UHPFRC used, cubes with dimensions of 150x150x150 mm³ were produced simultaneously during casting of doubly curved shells. After 28 days of hardening, the uniaxial compressive strength was about 175 MPa and about 80 MPa after one day, i.e. release of prestressing. The Young's Modulus, determined on cylinders with a diameter of 150 mm and a high of 300 mm, was about 45,000 MPa (32,000 MPa after one day). Furthermore, the flexural tensile strength was measured on prisms (40x40x160 mm³), 19 MPa were observed after 28 days and 9 MPa after one day. All tests were conducted in accordance to German standards.

Production

The doubly curved shape and the use of self-compacting steel fibre concrete made a production of the elements in a closed formwork necessary. For the construction of this formwork, the principle of straight but skew lines was used (cp. Figure 2). The shells were cast in a horizontal position to ensure, that the steel fibres in the UHPFRC mixture were mainly aligned in longitudinal direction during concreting. Hence, the fibres were able to bridge flexural cracks. The elements were cast upside down to avoid discontinuities from casting at midspan (highest position) of the elements. Therefore, at both ends of the formwork openings were provided to cast in the UHPFRC. Thus, the resulting discontinuities were placed close to the supports, which did not negatively affect structural performance. The UHPFRC mixture was cast from only one side until the formwork was filled up. Hence, ventilation was guaranteed and smooth surfaces with only small air inclusions were producible.

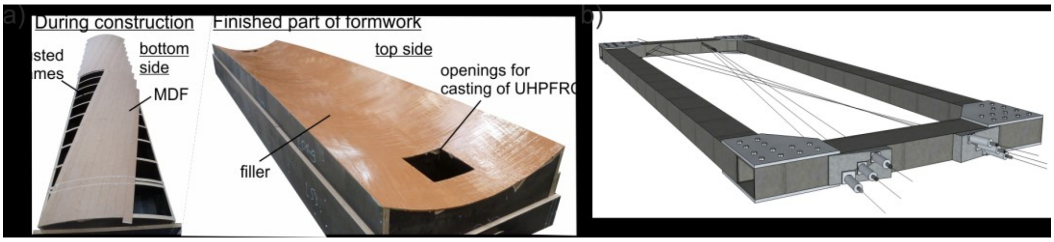

Figure 2: a) Formwork for doubly curved elements and b) model of the clamping frame [1]

A rigid steel frame was constructed for the prestressing of the doubly curved shells, which was adapted to the diagonal position of the tendons (Figure 2 b)). The tendons were anchored at one side. Hollow piston cylinders were applied for jacking at each CFRP tendon on the other side. Due to the sensitivity to lateral pressure perpendicular to the longitudinal direction of CFRP, it was necessary to develop a new anchorage system. The anchors consist of three aluminium wedges in a 80 mm long steel barrel [1]. After one day of concrete hardening and stripping of the top side of the formwork, the prestressing forces were released. Afterwards, the elements were turned into final position.

Four-point bending tests

For the four-point bending tests, a total of five test specimens with bars and 7-wired strands were produced. The number of tendons and the applied prestressing force were varied (Figure 4). The investigations were done in the laboratory on 4.1 m long and 0.8 m wide elements. The thickness was set to 0.06 m due to tests on the transfer length to provide a crack-free cross-section. The cantilever in the longitudinal direction was about 0.05 m and in the transverse direction about 0.10 m. For continuous support and load application, 10 cm wide moulded parts were produced. The setup of the four-point bending tests is shown in Figure 3. All specimens were loaded displacement controlled with 1.0 mm/min.

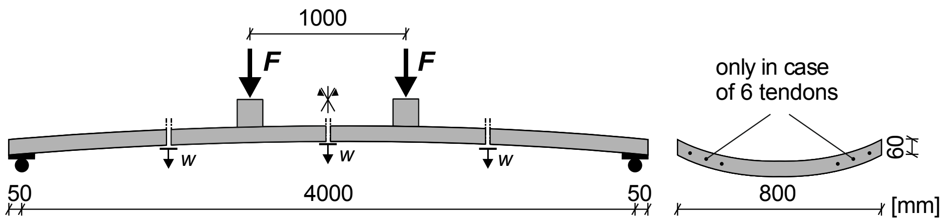

Figure 3: Test setup of four-point bending tests [1]

Figure 4 shows the load-deformation curves of the five test specimens. Depending on the degree of reinforcement and prestressing, maximum loads of 25 to 60 kN were obtained. Except of the specimen with six untensioned bars, in which failure of the reinforcement was detected, failure of the pressure zone was observed for all shells. Crack widths remained less than 2.5 mm until 80 % of maximum load. All test specimens showed a linear elastic behaviour and, after the first crack appeared, changed into the plastic region with nearly the same gradient of the load-deflection response. Figure 4 a) and b) shows that pre-stressed strands lead to an increase in load-bearing capacity of 80% compared to untensioned bars. In addition to the prestressing, the larger cross-section of the strands leads to this increase. If the prestressing force of the test specimen with four strands is doubled, only a load increase of 25% could be determined. The same ratio occurs if two more strands are inserted, but the preload force remains the same.

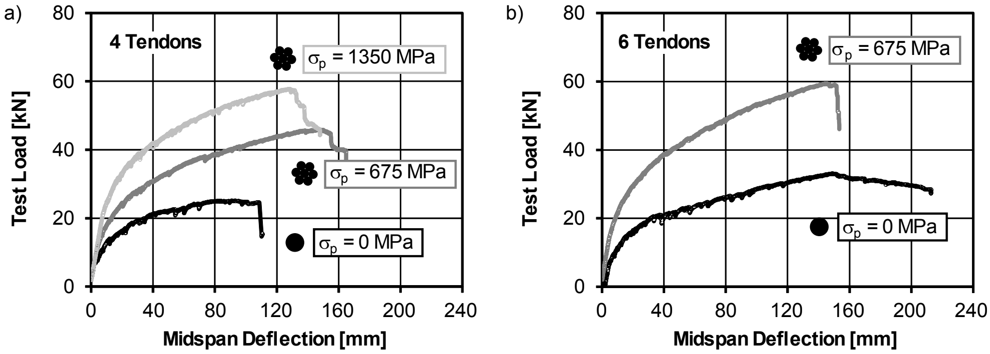

Figure 4: Load deflection graphs with a) 4 tendons and b) 6 tendons [1]

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