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UHPFRC IN LARGE SPAN SHELL STRUCTURES

Richard N. ter Maten (1), Steffen Grünewald (2) and Joost C. Walraven (2)

(1) Mourik, Groot-Ammers, NL

(2) Delft University of Technology, Delft, NL

Abstract

Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) is an innovative concrete type with a high compressive strength and a far more durable character compared to conventional concrete. UHPFRC can be applied in structures with aesthetic appearance and high material efficiency. Shell structures are spatially curved surface structures of which the exceptional behaviour can be referred to as 'form-resistant structures' which resist loads by developing stresses in its own plane. This paper describes the optimization process for the application of prefabricated rib-stiffened UHPFRC-elements. A spherical shell is designed with a span of 150 m and a height of 37.5 m. The designed prefabricated elements have a weighted mean thickness of 44 mm and a 'thickness over radius'-ratio of 2130, which is about 20 times more slender than an egg shell. The study shows that a large span shell structure produced with UHPFRC-elements is a promising concept.

Résumé

Les bétons fibrés à ultra-hautes performances (BFUP) constituent une nouvelle gamme de bétons de résistance en compression élevée et de propriétés de durabilité bien supérieures à celles du béton ordinaire. Les BFUP peuvent être valorisés dans des ouvrages à enjeu esthétique et avec une recherche d'efficacité de l'emploi du matériau. Les structures de voûtes et coques sont constituées de surfaces courbes, dont le comportement spécifique peut être qualifié de "structures à résistance de forme", en effet elles résistent aux charges en développant des contraintes dans leur propre plan. Le présent article décrit le processus d'optimisation conduisant à l'application d'éléments préfabriqués en BFUP raidis. Une coupole sphérique est conçue, avec une portée de 150 m et une hauteur de 37,50 m. Les éléments préfabriqués projetés ont une épaisseur moyenne pondérée de 44 mm et un ratio « épaisseur sur rayon » de 2130, soit environ 20 fois plus mince qu'une coquille d'œuf. L'étude démontre qu'une structure en voûte ou coque de grande portée constituée d'éléments en BFUP est un concept tout à fait prometteur.

1. INTRODUCTION

1.1 Ultra-High Performance Fibre-Reinforced Concrete

Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) is a contemporary concrete with a high compressive strength in excess of 150 MPa, a ductile behaviour, a considerable tensile strength of up to 15 MPa, and, compared to conventional concrete, superior durability characteristics [1]. UHPFRC is an innovative building material with special characteristics for which new structural concepts need to be developed that better utilize the properties of UHPFRC. UHPFRC offers a high potential for sustainable and economical applications with slim design in various fields of engineering which are capable of resisting heavier loads and/or span larger distances. The excellent characteristics of UHPFRC are obtained by physical, chemical and adhesion optimization [2]. An important aspect of UHPFRC is the employment of fibre reinforcement which normally consists of (high strength) steel fibres. The failure of UHPFRC without fibres is of explosive nature; due to the effect of fibres the material behaviour becomes ductile. Additional advantages of fibre reinforcement are the contribution to crack width control and the enhanced resistance to concentrated forces [3].

UHPFRC is distinctive from other materials for its outstanding qualities in terms of durability. With a decreased average pore radius and a corresponding low porosity the resistance to transport of harmful materials is improved. With an enhanced durability the expected lifespan of structures can be much longer than 50 years. For the production of UHPFRC is highly demanding, a requirement for successful production are controlled casting circumstances and therefore, UHPFRC is most suitable for precast construction instead of in-situ casting. The combination of recognizable promising characteristics allows engineers to explore possibilities for existing as well as to develop new structural concepts.

1.2 Shell structures

Shell structures (Table 1) are spatially curved surface structures which support externally applied loads. The exceptional behaviour of shell structures can be referred to as 'form-resistant structures'. This implies a surface structure whose strength is derived from its shape, and which resists loads by developing stresses in its own plane. Shell structures have an immense structural and architectural potential and are especially interesting for the application of UHPFRC since an efficient use of the material minimizes the dead load which is a large part of the maximum load of this type of structure. Due to the initial curvature and low thickness to radius ratio a thin shell has a much smaller flexural rigidity than extensional rigidity. When subjected to an applied load it mainly produces in-plane actions, called membrane forces.

The design of a shell is mostly governed by requirements involving the buckling capacity; they are imperfection-sensitive structures concerning non-linearity in geometry and material behaviour. A shell can also fail due to material non-linearity, such as cracking and crushing, or by a combination of both non-linearity of geometry and material behaviour.

2. OPTIMIZATION OF A SHELL STRUCTURE

A study was carried out which combines both the potential of UHPFRC with the structural and architectural potential of shell structures. The design study and the choice of dimensions were based on a preliminary design for a project named ‘Fiere Terp’ by Maurice Nio (Nio architects) (Figure 1). This project was chosen because it is an existing shell design, open for an engineering solution and, as a first approximation, it can be modelled as a spherical dome. The recommendations for further design were developed subsequent to the initial design stage. The analysis included the calculation, the optimization and the consideration of: span to height-ratio; edge ring dimensions; element stiffening and configuration; lower-edge element thickness; connection requirements; dynamic response; thermal response.

2.1 Span to Height-ratio

Within the design for thin shell structures, with practicable proportions, the overall buckling capacity under vertical loading usually is the governing failure pattern over compressive strength as well as tensile strength. An intended span to height ratio of 4 was determined to be a feasible ratio for the material under consideration, the bearing capacity and the shell behaviour in circumferential direction (Figure 2).

Table 1: Survey of well-known shell structures [4]

Structure	**Year**	**Geometry**	**Dimensions**	**Radius [a]**	**Thickness (t)**	**Ratio (a/t)**
Chicken Egg [-]	$150*10^6$ B.C.	Surface of revolution	60 mm length	20 mm minimum	0,2 - 0,4 mm	100
Pantheon [Rome]	126 A.D.	Hemisphere	43,3 m diameter	21,65 m	1,2 m at the top	24
Jena Planetarium [Germany]	1923	Hemisphere	25 m diameter	12,5 m	0,06 m	200
Jena Factory [Germany]	1923	Spherical cap	40 m diameter	28,28 m	0,06 m	470
Algeciras Market Hall [Spain]	1934	Spherical cap	47,6 m	44,1 m	0,09 m	490
Beer Can [-]	1935	Cylinder	66 mm diameter	33 mm	0,08 mm	400
Hibbing water filter plant [Minnesota]	1939	Ellipsoid of revolution	45,7 m diameter	47,24 - 5,33 m	0,9 - 0,15 m	35 - 525
Bryn Mawr Factory [Pennsylvania]	1947	Elpar on a rectangular plane	19,6 x 25,3 m^2	25,0 - 32,9 m	0,09 m	300 - 400
Auditorium MIT [Cambridge]	1955	Segment of a sphere on 3 points	48,0 m between supports	34,0 m	0,065 m	520
Kanehoe Shopping Center [Hawaii]	1957	Intersection of 2 tori on 4 supports	39,0 x 39,0 m^2 between supports	39,0 - 78,0 m	0,076 - 0,178 m	500 - 1000
Palazetto dello Sport [Rome]	1957	Spherical cap with ribs	58,5 m diameter	30,9 m	0,12 m shell 0,33 m ribs	94
CNIT [Paris]	1957	Intersection of 3 cylinders on 2 supports	219 m between supports	89,9 - 420,0 m	1,91 - 2,74 m total; 0,06 - 0,12 m outer layers	47 - 153

Figure 1: Preliminary Design 'Fiere Terp'

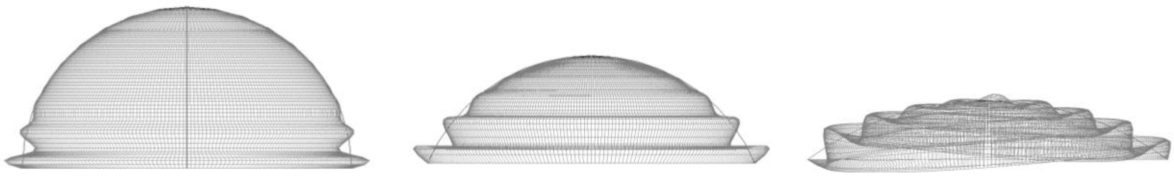

Figure 2: Buckling patterns under vertical loading (FEM-calculation, Scia Engineer)

2.2 Shell dimensions

The design aspects are combined for a final design of a spherical shell with a span of 150m and a height of 37,5m (Table 2), which was checked by Finite Element calculations on various load cases.

Table 2: Design parameters

Parameter	**Size / Weight**
Diameter [d]	150m
Height [h]	37.5m
Radius	93.75m
Arch length	~174m
Perimeter base	~470m
Shell Surface	~22000m^2
Structure Weight	2485 ton

The shell structure (Figure 3) consists of 945 elements with an average weight of 2630 kg. The UHPFRC-elements in the final design have a weighted mean thickness of 44 mm (plate thickness: 35 mm and ribs: 60 x 180 mm^2); the structure's slenderness is 2130 (ratio radius to element thickness). This means that the structure is far more slender than the shell structures displayed in Table 1. The study shows that the production of large span shell structures consisting of UHPFRC-elements is a promising concept.

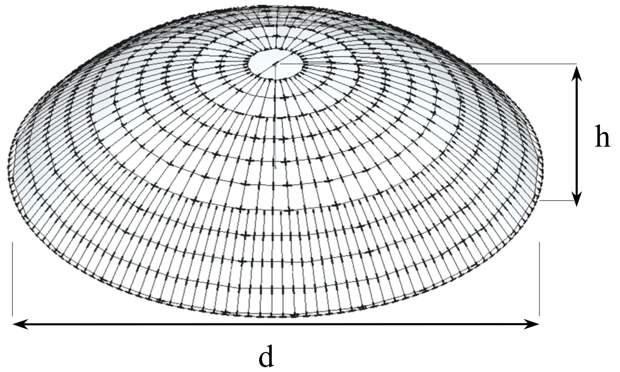

Figure 3: Overall dimensions final design

2.3 Edge Ring

Since shell structures are 'form-resistant structures' a prestressed concrete edge ring is applied which has a significant effect on the ultimate buckling load. After performing Finite Element calculations it was concluded that the buckling load in an ideal support condition can be approximated with an edge ring with a pretension force of 3650 kN, of which the calculation was based on Barlow's formula for pressure on cylindrical shapes.

2.4 Prefabricated UHPFRC-elements

The shell consists of rib-stiffened elements; the ribs are applied to improve the inertia and result in a more efficient design and a thinner average cross-section. For the design and the optimization of the shell elements a Finite Element analysis was applied. To optimize the ratio between the thin 'slab' of the element and its ribs multiple governing parameters were evaluated. Figure 4 shows results for the buckling load, the total weight of the structure as well as the correlation between the two aspects for an element thickness of 60 mm and multiple configurations. It is shown that the positive effect of rib-stiffening is indubitable and the marginal benefit of increasing the rib thickness declines for a rib to slab thickness ratio larger than 5.

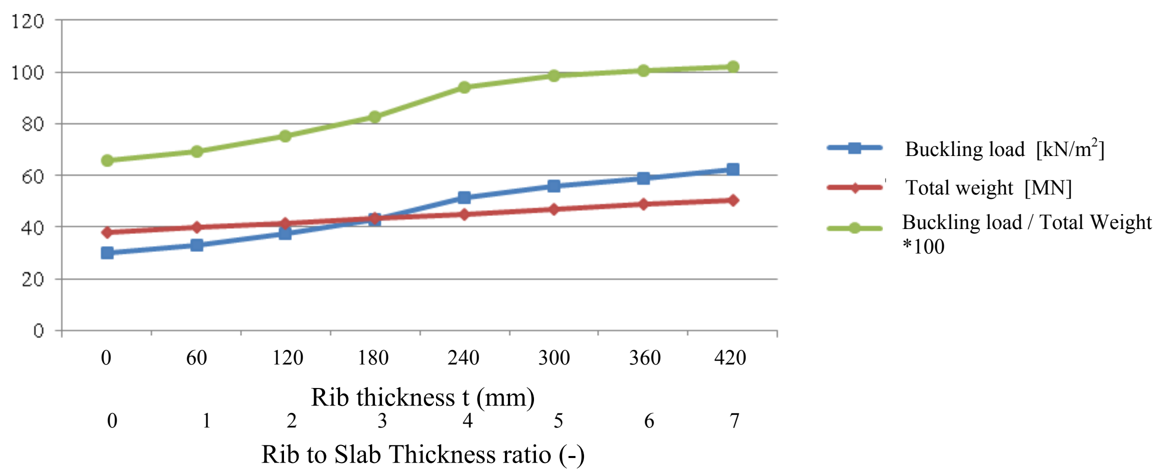

Figure 4: Calculation results for ribs & stiffener configurations (element thickness: 60 mm)

The ribs also allow connecting the elements. For practical reasons all precast elements are designed to be approximately rectangular which differ only slightly. All elements are curved (83 mm over 7.9 m length) to increase the bearing capacity of the shell. The size of the elements was, among other factors, based on transport, weight and production preferences. Like for the reference project of Pont du Diable [5], a production with a steel mould was chosen for its high accurate precision. An UHPFRC-element is shown in Figure 5.

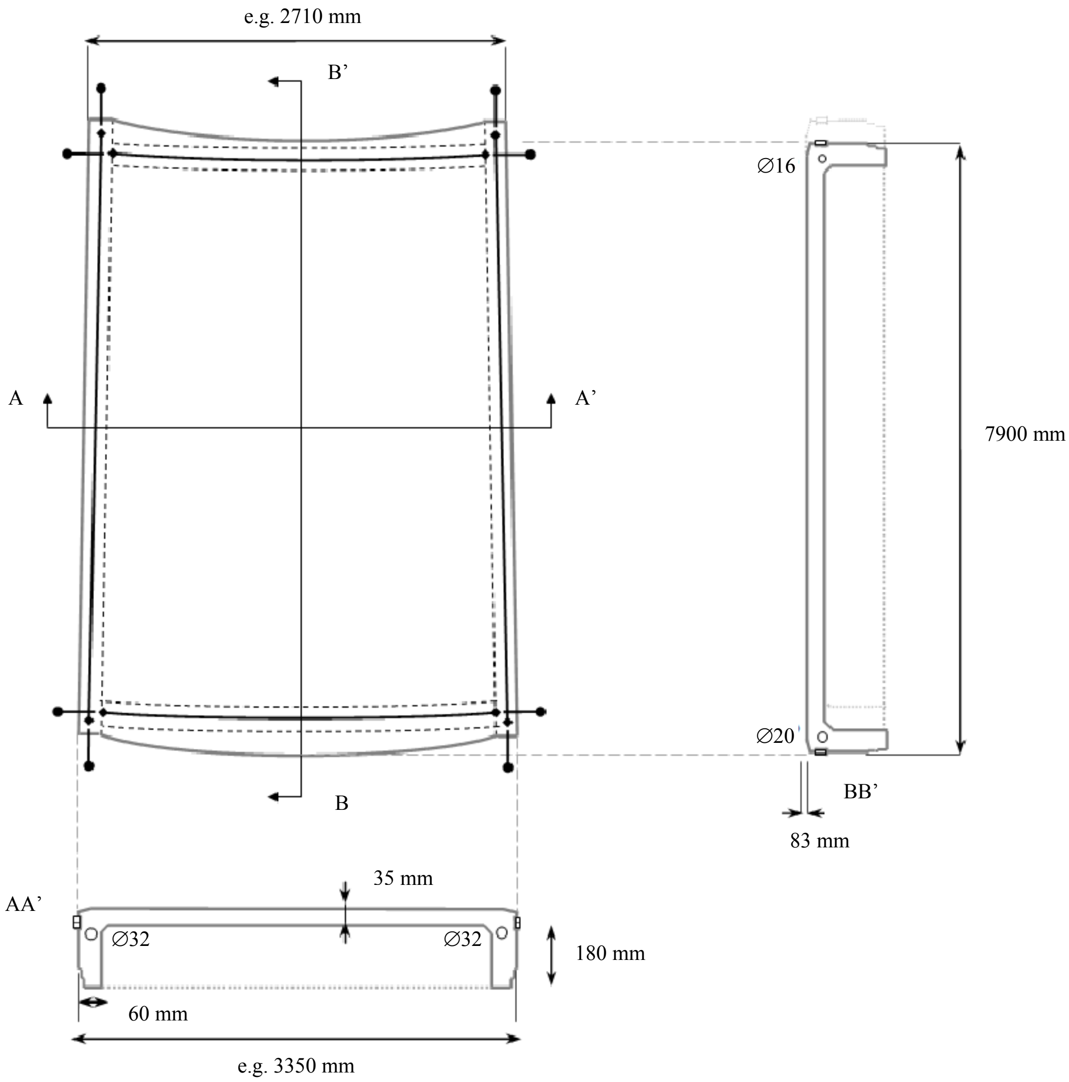

Figure 5: UHPFRC-shell element

2.5 Connections

At the edges of the elements a dowel and socket system is used to position and to connect the elements. Also, the elements are provided with neoprene gaskets which ensure a watertight connection. The joint construction is vital for an integral structure and criteria concerning structural and physical performance are demanding. Different connection methods were considered and are found to be suitable connection methods for precast UHPFRC-elements. The methods were compared with regard to load introduction, assembly method, suitability for UHPFRC, construction speed, durability and provisions to be taken. Two factors were decisive for the choice of the selected connection. Those are the fact that local force introduction can be realized with UHPFRC and the fact that immediate connecting is favourable to increase the construction rate. Local connectors demand local connection facilities, which asks for provisions to be cast in UHPFRC. The provisions in the elements are designed based on provision principles commonly applied for tunnel engineering.

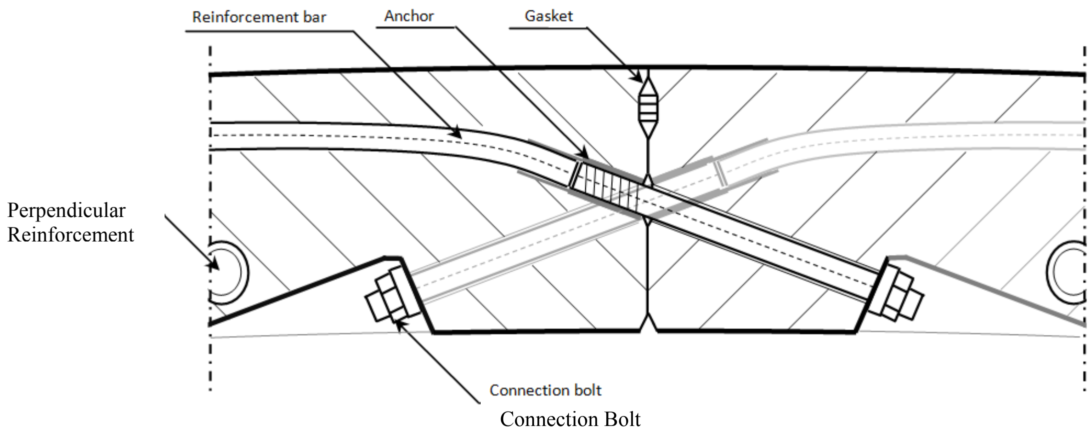

Figure 6: Connection principle

2.6 Construction progress

The realization of shell structures, especially with slender UHPFRC-elements, can be challenging. The potential of the application of UHPFRC and material savings for the construction phase were investigated. The application of temporary support was found to be inevitable but the lightweight construction with UHPFRC-elements shows a high potential for ease of construction and a short construction time.

In this study different construction possibilities were considered concerning handling, erection, form control and temporary supports during construction. It was concluded that the idea to connect elements at ground level and subsequently place segments consisting of as many elements as possible per lift is most promising. Because of the light-weight design a crane can lift and place numerous elements in a single handling. The shell was divided in 36 radial segments and can be lifted up by one mobile crane. The segment itself is highly sensitive to deformations and it was therefore proposed to be lifted by an assisting structure.

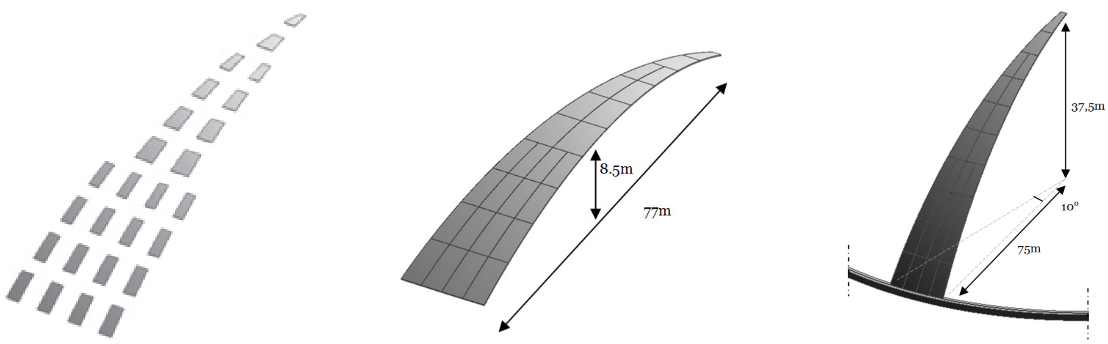

Figure 7: Step-wise presentation of construction assembly

3. CASE STUDY: TRANSFERRING RESULTS

The main aim of the research was to optimize the preliminary design for the 'Fiere Terp'. Within the case study the design for Fiere Terp was altered, with the assumption that fundamental modifications were permitted by the architect. The original design is based on the shape of a white water lily, as shown in the Frisian flag. The design was improved by structural analysis and shape optimization. Multiple designs for Fiere Terp were discussed and improvements were proposed by deliberation of multiple variants and the preferences for the design based on the conclusions of previous discussed design considerations. The original design was improved by increasing the curvature within the surface and around the edges. Also the surface was simplified to improve the structural behaviour as well as to promote element repetition and therefore production efficiency. Based on these reflections the most promising variant was chosen. The applied criteria were the positive structural behaviour as well as the resemblance to the initial architectural shape and favourable element production.

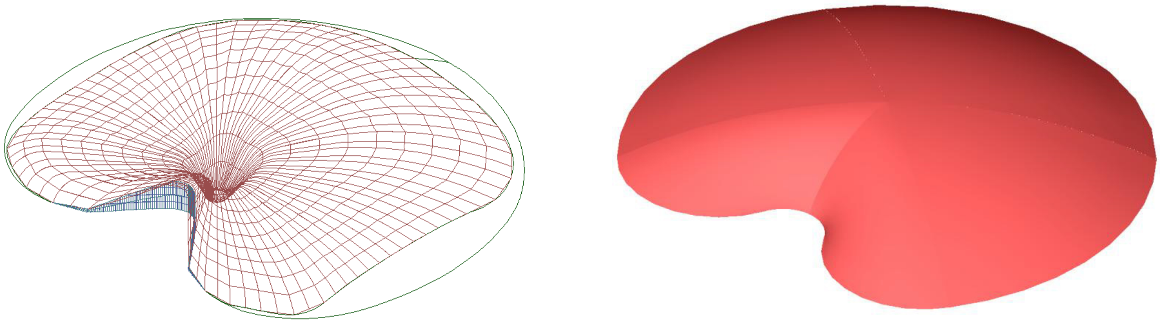

Figure 8: Case Study; Original and Proposed Design

4. CONCLUSIONS

This paper discusses a study that combines the potential of the material UHPFRC with the structural and architectural potential of shell structures. It is demonstrated that the combination of UHPFRC and large span shell structures has a high potential. The most advantageous aspects of the design are the overall savings on material use and corresponding lower total weight of the shell which decreases the load on the foundation and edge ring, the weight for transport and the number of handlings. The most important recommendations are to carry out further research and tests on the structural behaviour of prefabricated concrete shells, especially on the effect of the joint design. It is demonstrated that the shell can be built with the exploitation of the durability aspects of UHPFRC with a lifespan of at least 50 years.

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