Case-Study on the Application of Precast Double-Curved Concrete Elements for the Green Planet Shell Structure

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Abstract. Double-curved structures in general, and monolithic concrete shell structures more specifically, can transfer forces very efficiently. As a result, the thickness-to-span ratio can be very low, which, material-wise, can lead to a very economical design. However, the construction of shell structures is very labour-intensive and comes with high formwork costs and shells in modern building practice are rarely constructed. Concrete shell structures can be cast in-situ making use of temporary formwork and falsework, but they can be (partially) prefabricated as well, like the Palazzetto dello Sport in Rome. Although precasting is an effective technology for the repetitive production of concrete elements, for double-curved structures, having a large variety of shapes, the advantages of precasting seem to diminish quickly as a result of high formwork costs. Another disadvantage of precasting shell elements obviously seems to be the complexity of the required connections. For shell structures, the loss of stiffness of the connections might even lead to a crucial reduction of the buckling stability. A combination of both building methods, the prefabrication of the supportive structure and a finish with a cast in-situ layer, solves this before-mentioned issues and the advantages of both methods are combined: reduction of the complexity of the connections with an in-situ cast concrete layer and integration of the supportive structure in the design for a more cost-efficient erection. This paper describes the study of an innovative, partially precast, alternative solution for the construction of shell structures, and specifically addresses the influence of connections between precast elements on the overall shell behaviour. The Green Planet gas station along the A32 highway in The Netherlands was selected as a design case for such a building method.

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1 Introduction

Shell structures break the linearity of daily practicality and often are unique; shells appeal to the imagination and constitute a landmark herein. Many concrete shell structures have been constructed and were either produced with prefabricated elements or in-situ cast. Three famous examples of prefabricated structures with the shape of a shell are the Palazzetto dello Sport [Rome/Italy (Bucur-Horvath and Saplacan 2013)], the Sydney Opera House [Sydney/Australia (Weston 2002)] and the Heydar Aliyev Cultural Centre [Baku/Azerbaijan (Zaha Hadid Architects 2016)]. Thin shells are characterized by two large dimensions and one smaller dimension (the thickness) and they have a curved middle plane. Therefore, they are able to resist out-of-plane forces by developing in-plane forces, called membrane forces. This makes shells strong and effective structures; their behaviour is described in the membrane theory. This theory holds for the largest part of the shell's surface, but in some regions the theory will not hold and compatibility moments will compensate the shortcomings of the membrane field. This disturbed zone should be analysed with the more complete bending theory. Together these theories are very useful for initial design and analysis of thin shell structures (Blaauwendraad and Hoefakker 2014).

State-of-the-art production of double-curved concrete elements for cladding or shell structures, which are produced in small production numbers, is expensive and a lot of waste is produced. With the use of an adjustable re-usable mould system the production of elements can be more economic and sustainable. The concept of the adjustable formwork has its origin in the ideas of Renzo Piano (Piano 1969). The original idea was to scale up a small element by measuring it with a machine which communicates the data to a flexible formwork system. The innovative flexible mould method for economically efficient and sustainable production of prefabricated elements has been further developed at Delft University of Technology (Schipper 2015) and it comprises the use of a flexible, CNC-controlled formwork, which is filled with self-compacting concrete (Schipper and Grünewald 2014). The production comprises casting of an element in horizontal position and, after a waiting period, the mould is deliberately deformed and positioned on pre-arranged mould supports (Fig. 1).

In the period between mixing and de-moulding, the concrete behaviour changes from a plastic to a solid state with changing contributions to the yield strength in time of thixotropic structural build-up and progress of hydration. The element geometry and applied mix design determine whether the criteria can be fulfilled and if so, the duration of the open window for adequate deformation. Especially, the early phase before setting is very important for the production with the flexible mould system. The element hardens in the deformed mould, which can be re-used for the production of elements having the same or a different geometry.

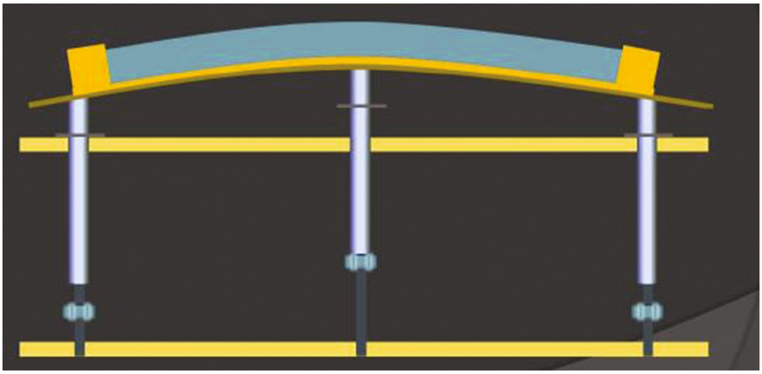


Fig. 1. Flexible mould system after the deformation of the mould.

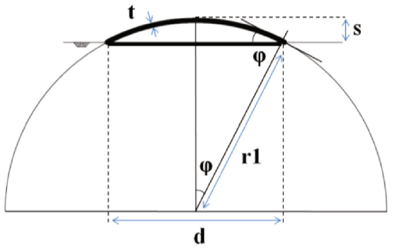
2 Design Case 'Green Planet'

The Green Planet (Fig. 2) is an existing, recently built structure and a supposedly future landmark. It is a (gas) service station built along the A32 highway in the North of the Netherlands; the double-curved structure was designed by ABT. As a unique feature the Green Planet is offering sustainable fuels, which is publicly exhibited by means of the shape of the structure. The shape represents a portion of the earth's surface. The surface of the globe on which we live and which is endangered of being compromised by the use of non-renewable fuels. The Green Planet structure was selected as a design case and benchmark for the innovative building method discussed in this paper (Witterholt 2016). The method consists of applying double-curved concrete elements produced with the flexible mould as an integrated part of the structure; two types of

Fig. 2. Green Planet gas station in the Netherlands.

Table 1. Dimensions of the Green Planet structure.

Geometry Green Planet	*Dimension*
Angle (φ)	27.66 degrees
Sagitta (s)	9080 mm
Span (d)	73730 mm
Vert. radius of curvature (r1)	79400 mm
Thickness (t)	200 mm
Shell surface area	ca. 2500 m^2
r1/t	400
d/s	8



solutions are possible: (1) prefabricated elements having the same thickness as the structure or (2) a combination of prefabricated elements with in-situ cast concrete.

The main structure of Green Planet consists of laminated wood beams and steel roof panels. The height is 9 m and the diameter is about 74 m (Table 1), which makes it a large span sphere-shaped shell structure, except that it is supported by columns. However, the Green Planet structure could have been produced in concrete as well, self-supporting and without columns. The structure provides a perfect application for this research and besides the feasibility of the building method it was possible to study the economically competitiveness compared to other building methods as well. The shape of the Green Planet shell structure is challenging and requires the production of many uniquely shaped double-curved elements. Normally, the prefabrication of all these different elements would be very expensive.

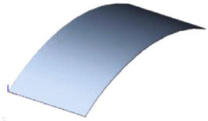
3 Analysis of the Structural Behaviour

A detailed analysis on the alternative design for the Green Planet structure was executed; in this paper the following four aspects are discussed: (1) Comparison with other more traditional shell structures, (2) foundation of the Green Planet (3) dimensioning of the structure and (4) effect of connection stiffness.

3.1 Comparison with Other More Traditional Shell Structures

The structural behaviour of the Green Planet shell was analysed by applying the finite element analysis (FEA) software, SCIA Engineer. To verify the unusual shape of the Green Planet structure the results are compared with results of comparable (having comparable dimensions and boundary conditions, a thickness of 200 mm and concrete quality C90/105) but more traditional shell structures, which were among others (1) a weakened (by an oculus in the top) dome structure and (2) a cylinder structure. The assessment was based on the structural behaviour aspects deformation, force distribution, moment distribution, support reactions and stability determined by linear (stability) analysis. Table 2 compares results of the analyses for the three different shell

Table 2. Comparison of FEM calculations for three different structures.

Structure	*1) Green Planet*	*2) Weakened dome*	*3) Cylinder*
FEM Model			
Self-weight [kN]	12230	24412	15904
Maximum tensile stress [N/mm^2]	4.55	0.12	60.24
Minimum compressive stress [N/mm^2]	-8.87	-3.90	-80.64
Vertical support reaction [kN/m]	681.1	109.6	473.7
Max. horiz. support reaction [kN/m]	1281.0	206.2	891.0
Maximum vertical displacement [mm]	20.50	5.39	1874.70
Critical buckling load [kN/m^2]	8.10	26.21	0.42

structures. The aims of this comparison were twofold: (1) to determine which (simple) shell structure is most comparable with the behaviour of Green Planet and (2) to verify the Green Planet model. The analysis with realistic loads in conformation with the relevant design codes indicated that multiple types of wind loads can be normative for the internal forces of the structure. The Green Planet structure is mainly subjected to compressive forces and only in certain areas, along the edge of the shell or near the supports, tension forces arise. The self-weight is the lowest for the Green Planet structure, whereas the self-weight is the highest for the weakened dome. The critical buckling load is the lowest for the cylinder (0.42) which is much lower compared to the weakened dome (26.21) which has the highest buckling resistance. The highest and lowest maximum membrane stresses were obtained for the cylinder structure; the maximal vertical displacement is also much larger. Therefore, with regard to maximum and minimum membrane stresses and maximum vertical displacement the Green Planet is more comparable with the weakened dome.

3.2 Foundation of the Green Planet

The analysis of the three structures confirmed that large thrust forces will act on the foundation. Furthermore and in reality, the hinge supports are not infinitely strong in each direction, as was assumed for the discussed types of structure. A more detailed study of the supports was carried out in order to simulate the behaviour of the shell structure in cooperation with the foundation; use was made again of the mentioned finite element program software. Originally, the relatively light wood-steel structure is supported by columns and therefore the concrete foundation was subjected to significantly smaller support reactions. The Green Planet model was analysed with the assumption that the supports were connected by long steel tension cables. The calculation showed that already due to small horizontal displacements caused by the elongation of the cables the resistance against buckling would never suffice. For this reason, it was recommended to make use of post-tension cables or another special foundation that prevents these deformations.

3.3 Dimensioning of the Structure

The finite element model of the Green Planet was studied with regard to mesh fineness (0,1 to 1 m); a 0.2 m mesh was selected because changes in resulting stresses and deformations were relatively small compared with smaller sized meshes. The stiffness of this shell structure strongly depends on the modulus of elasticity of concrete, but so do the building costs. The model was tested with different combinations of thickness of the structure (150 to 250 mm), material strength and modulus of elasticity (concrete strength class: C35/45-C90/105). In an iterative way, the structure was optimized by reducing the thickness down to 150 mm and by locally increasing the thickness to 300 mm in order to obtain the same buckling load factor of 6. In the final design, the Green Planet shell had a constant thickness of 250 mm, a material strength of C45/55 and the supports are hinged to limit the effects settlements have on the structure. In order to investigate the effect of the connections between the precast elements on the behaviour of the structure, the model was segmented. A realistic segmentation plan was implemented taking into account the boundary conditions with regard to production and maximum dimensions of elements.

3.4 Effect of Connection Stiffness

The connections between the panels were represented by springs in the FEA program. The spring stiffness of a connection was divided in axial, rotational and shear stiffness components which were determined and subsequently verified with basic mechanical models. For every type of stiffness theoretical and simplified but representative FEA models were assessed. The axial stiffness component was examined using a basic mechanical model consisting of two simply supported slabs axially connected and loaded. For the rotational component these slabs were subjected to a moment at each end and theoretically the only resistance of the connection is a rotational force. The shear component was determined using a basic mechanical model in which the shear force is constant near the connection and no other loads interfere. When combined again these formulas represent a three-dimensional connection stiffness, which was tested with other FEA models as well. The maximum difference between the results of the theoretical models and simulations with the proposed stiffness was 4.3%. From these verification studies, it was concluded that the combined formula for connection stiffness is appropriate to simulate the connection stiffness in SCIA Engineer. The analysis performed with a closed dome structure indicated that even a significant reduction of the connection stiffness has a relatively small influence on the buckling behaviour (Fig. 3).

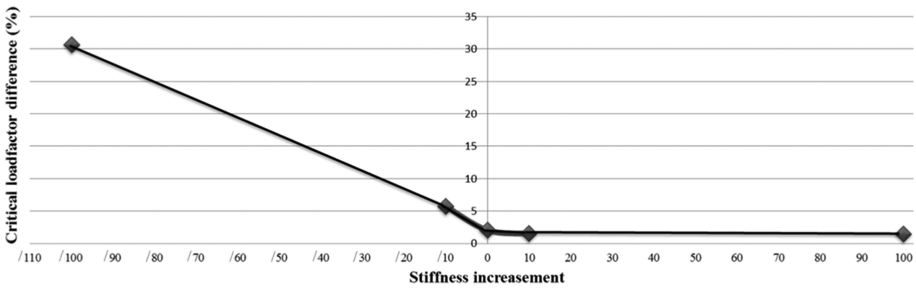


Fig. 3. Average critical load factor difference (in %) when the connection stiffness is divided (Fig. 3: left side)/multiplied (Fig. 3: right side) by a certain factor (max. 100).

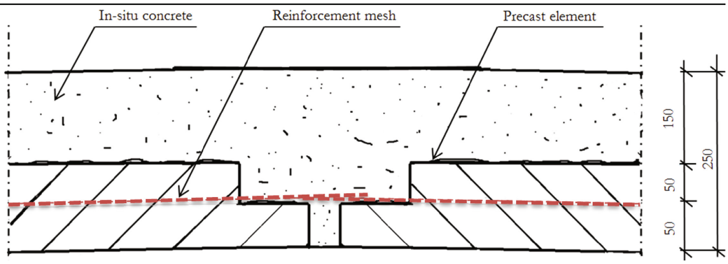
In this case, the connection stiffness simulated a continuous concrete shell structure (for example produced with prefabricated elements and in-situ cast concrete). It was shown that a large stiffness increase (combined formula stiffness multiplied by 10 and 100) only improved the difference with the initial model to a difference of 1.5%. A large stiffness reduction (combined formula stiffness divided by 10 and 100) resulted in a difference of 6% and 31% compared to the solid concrete structure model. The combined formulas for the connection stiffness were applied to the Green Planet model as well. The comparison of the results shows that there is a small maximum difference in the buckling load of 0.5% between Green Planet models if the stiffness of the connections is reduced by 50% (stiffness decrease with a factor of 2). Therefore, a simple connection will suffice for the final Green Planet design.

4 Execution and Economical Aspects

The basic idea of this research was to include prefabricated double-curved concrete elements in the shell structure. Two connection designs (Fig. 4) are presented hereafter, one representing an in-situ cast solution and the second being applicable for a structure produced with only prefabricated elements.

The wet connection (Fig. 4a) combines in-situ cast concrete and prefabricated elements having a base layer of 50 mm, on top of which a reinforcement mesh is placed, and a second concrete layer of 50 mm. The second layer needs to be smaller in width and in length, to provide space of approximately 100 mm around the prefabricated elements. The prefabricated anchorage solution (Fig. 4b) often is applied in tunnelling and assures the transfer of forces across the connection. When the bolt is tightened it induces a certain prestress level on the connection which assures that the connection remains in compression.

The economically competitiveness of the alternative Green Planet structure was not achieved (ca. 50% higher costs for the production of the structure) and it is questionable if this is possible at all since the original design is very economic (Witterholt 2016). With regard to the economic comparison it must be again noted that the original Green Planet structure is supported by columns while the presented alternative structure offers a column-free space, structurally and economically this makes a big difference.

<table>
<tr><th>Type of connection</th><th></th></tr>
<tr><td>Figure 4a)
Wet
connection</td><td>
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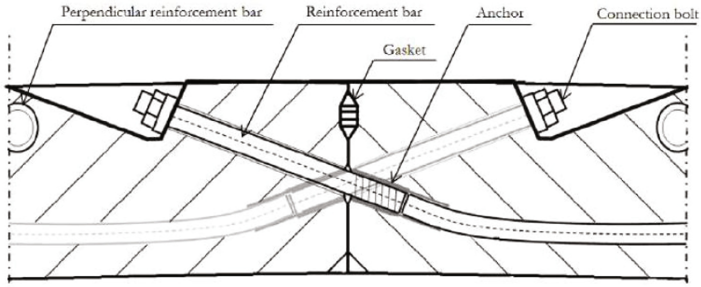
Prefabricated
connection</td><td>
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Fig. 4. Cross-sections of (a) wet connection and (b) the fully precast solution.

5 Conclusions

The aim of this study was to investigate the application of double-curved concrete elements produced with the adjustable formwork to produce an alternative Green Planet shell structure. The study offers a lot of ideas and challenges for future research and the following conclusions can be drawn:

– The Green Planet shell is mainly subjected to compressive forces. Tension stresses only arise along the edges of the shell and in the areas subjected to edge disturbance, which is the area near the foundation.
– In the FEA calculations, connections of elements were simulated by means of a spring with a specific stiffness, which was determined by theoretical analysis of its three components. The difference in the buckling load is only 0.5% between Green Planet models if the stiffness of the connections is reduced by 50%.

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