A FAESABLE WAY TO MAKE FREEFORM SHELL STRUCTURES.

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1. Abstract

Researching the reconstruction of the Philips Pavilion, we described a way to make the anticlastic forms of the pavilion by spraying shotcrete against a pre-stressed membrane mould [5]. Sinclastic forms can be made with inflatables [1]. Binni shell, Monolithic-dome and Solid-house are organisations using inflatable moulds to make domes. It is possible to combine inflatable's with pre-stressed membranes to make "free-formed" surfaces that are sinclastic and anticlastic. To elaborate the possibilities, columns, cables, and beams can be added. Columnspushing the membrane will introduce high points, cables pulling the membrane will introduce low points. The introduction of stiff, bent beams will influence the form of the surface as well as the cable structure covering the membrane. The membrane can be manipulated in 4 different way's.

-anticlastic by a prestressed membrane
-sinclastic by an inflatable membrane
-high points by columns / low points by cables
-arches, beams or cables pushing or pulling the membrane can be used to make (curved) lines.

The behaviour of "Free form" surfaces made out of manipulated membranes is difficult to modulate. The behaviour of cable-nets allows more freedom in the making of patterns. Therefore we replaced the presstresed membrane by a cable net. The cable net will make the form of the surface and is manipulated by inflatable's cables and columns. The net structure is covered with a finer grid and rigidised with shotcrete. To prove this we made a small blob structure. The paper will describe the experiments with the cable nets and the making of the small blob structure. It is possible to make al kind of free formed shapes with standardized inflatable's in combination with standard cablenets. The researchers have applied for a patent on this method that leads to a feasible way for making "FreeForm-shellstructures".


Fig. 1, 2 Blob structure rigidised with shotcrete.

2. Introduction

In the 60-s and 70-s elegant irregular curved shell structures with a harmony between force and shape where produced. In time the high costs of scaffolding and formwork for these concrete shells became a significant problem. Frei Otto and his team tried to solve this problem by introducing grid shells in 1962: shells of timber laths or steel members (b-Hennicke 1976). Another solution, working with inflatable's had already been introduced in 1942 by Neff, and was further developed by several others during the last century. Noway's inflatables are used to construct regular shaped domes, like binni-shell, Monolithic-dome and Solid-house. Researchers are looking for a way to construct irregular curved shells with pre-stressed membranes. [5]

3. Diagram.

The distinctions of structural typologies by Heino Engel [9] are used in this research as a theoretical base to compare different structures (fig 2). If form active structures are compared to surface active structures, there is a strong similarity in structural behavior and form. The difference in construction; in situ versus prefab is the most obvious. The ability of form active structures to be prefabricated moulds for surface active structures, is used in the fabrication of domes. The ability of form active structures to make other forms is known and therefore interesting for the construction of freeform shell structures. [8] It is possible to make; synclastic domes with inflatables, Anticlastic shell structures with pre stressed tensile structures, and grid shells with a cable net. With the combination of anticlastic and synclastic forms used for form active structures,many architectural free form shell structures can be made. Based on 4 materials able to make a transition from fluid to solid, we have made a new diagram. (fig 4) The 4 materials are: concrete; water/ice; polymer composites; and glass. The techniques we have distinguished are: 1 the way the material is put on the mould; 2 the kind of form active mould that is used; and 3 the reinforcement of the rigidizing material. This diagram gives the possibility to categorize different projects, and the opportunity to look for new combinations.

3. Philips Pavilion

In 1958 the Philips Pavilion was built according to a design of Xenakis, employee of Le Corbusier, for the world exhibition in Brussels. The Philips Pavilion was built to promote the synergy between modern technique and art. The pavilion was a symbiosis between architecture, music and visual art. The techniques investigated were: structural design of a shell structure in a very large space frame; the possibilities of electrical amplifiers and synthesizers; and the projection of light and pictures.

The possible reconstruction of this project led to various techniques being developed after 1958. The techniques we have been looking for have used a membrane as a mould on which concrete is sprayed or cast. Generally known, are the methods, where inflated moulds are used on which concrete is sprayed. [Beijing 2006] [1] [7] In our case, the anticlastic forms desired cannot be made with inflatable moulds. Therefore, we used anticlastic pre-stressed membranes. In one of the experiments in this project, a mould of distance-fabric for casting concrete is used. Although the results of the distance-fabric tests are promising, the conclusion of the survey is that spraying concrete on a membrane should be preferred due to the fact that the production of a double curved distance-fabric, will ask for high investments in production-machines.

Fig.3 Philips Paviljoen at the World axhabition of 1958 in Brussels, The red part is the one that has been reproduced.

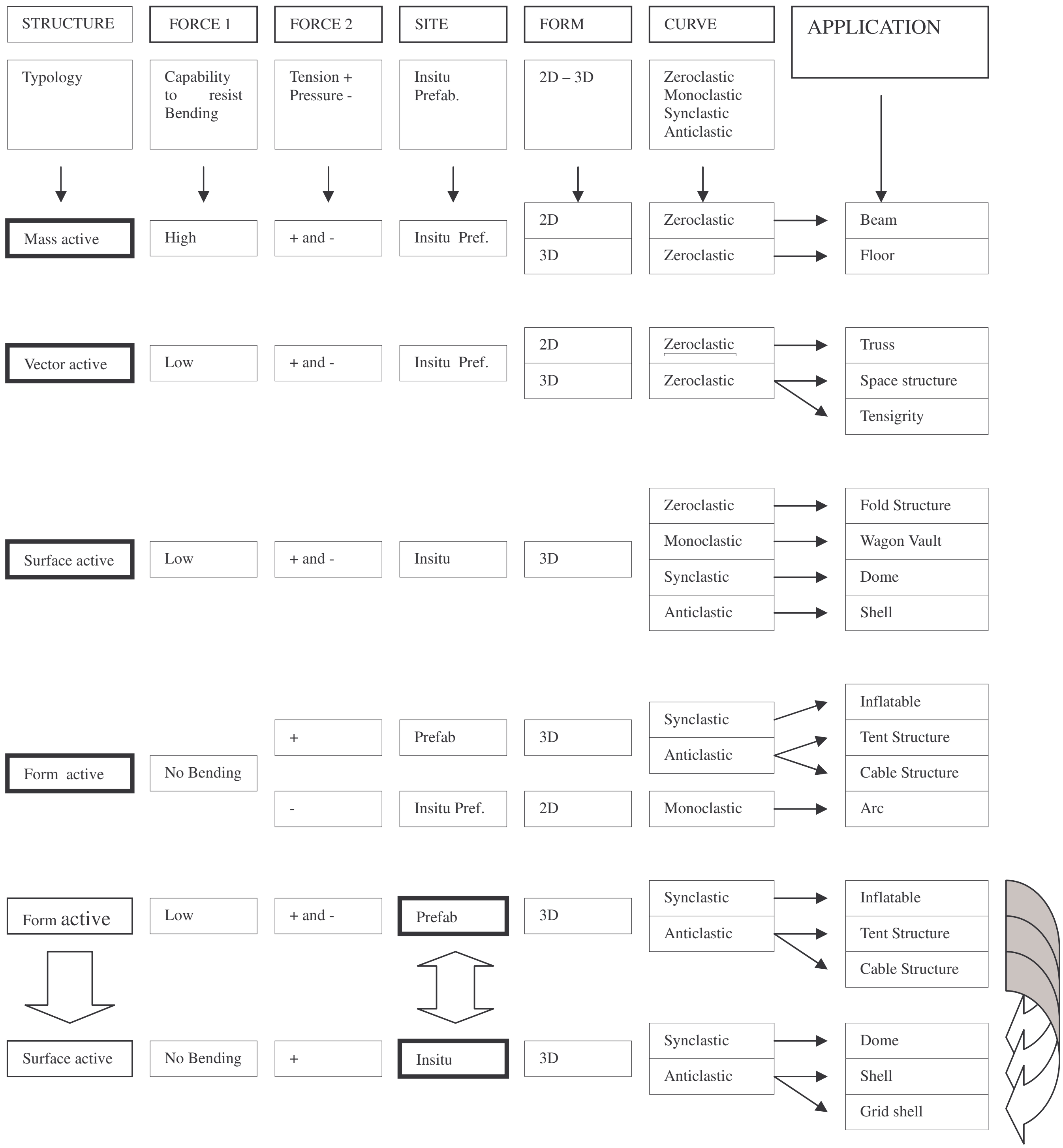

Fig. 4 Diagram based on Structure systems by Heino Engel making surface active structures out of form active structures.

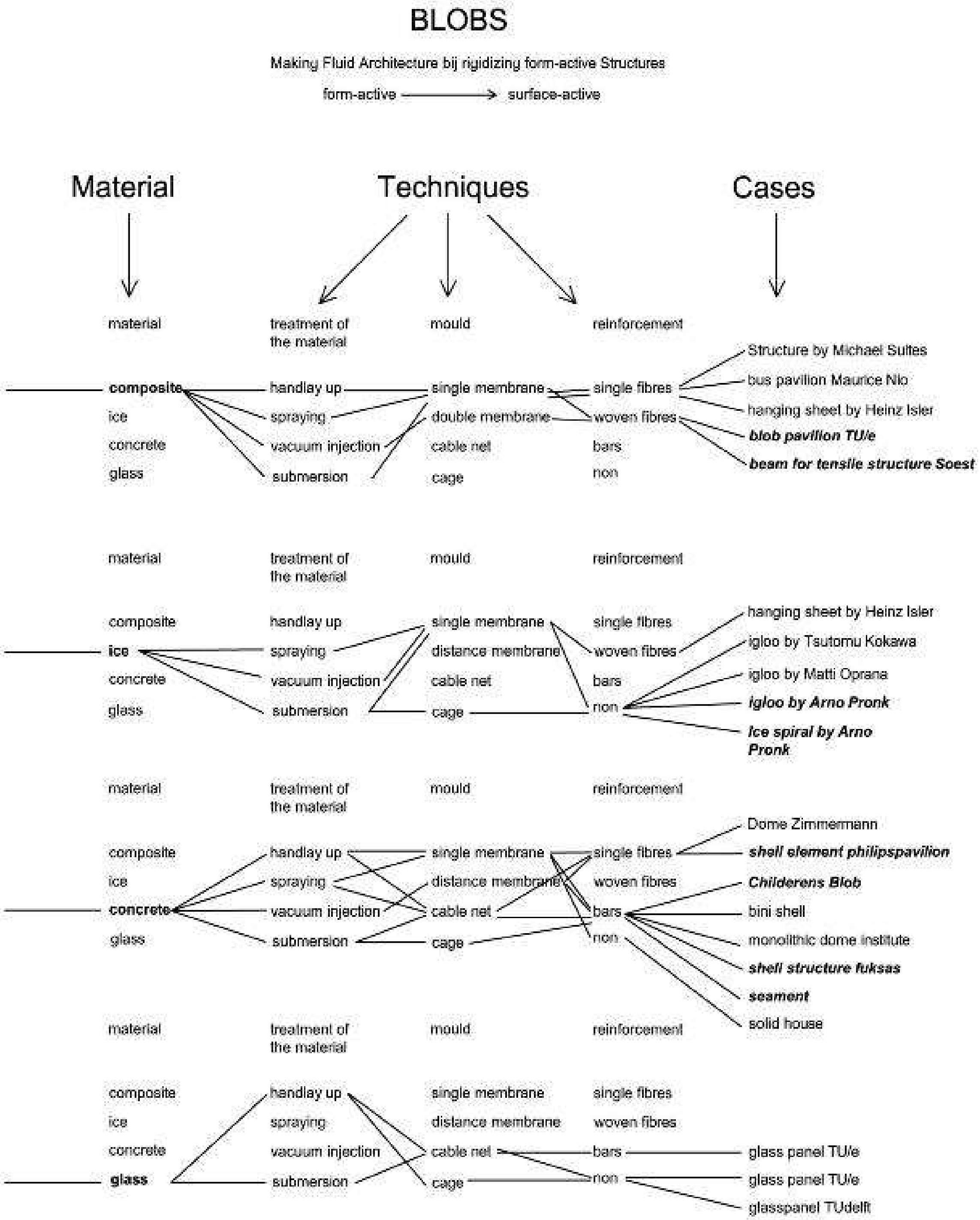

Fig. 5 Diagram of materials and techniques to make fluid architecture by ridgidizing form-active structures

 

Fig.6, 7 The reconstruction of the red part of the Philips Pavilion by spraying shotcrete against a pre-stressed wire frame.

4. Patent

Wire frames are able to subscribe many forms when they are transformed by forces and volumes. The ability to transform is used in many applications, for example to hold oranges' together in a net. The wire frame will subscribe more or less the minimal surface including the volumes inside the net, influenced by the form of the mesh and deadweight of the net. (fig7)
If desired the form to the net can be influenced by pulling or pushing local point(s).

Fig. 8 Orange net.

The combination of a pre-stressed wire frame, covering the inflatable rigidized by shotcrete making irregular shellstructures, is new. The inflatable's can be standardized and re-used, with wire-nets available in many applications. The method is extremely effective, and it is possible to make many different shapes with the same inflatable's. Therefore, we have applied for a patent to protect and explore this method for making free formed shellstructures.

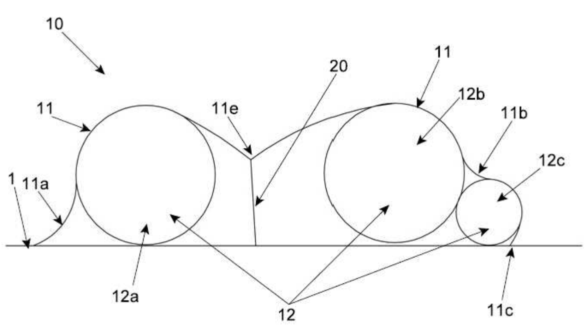

Fig. 9 drawing of section with inflatable volumes curved with a wire frame

4. Blob Prototype

4.1 Introduction

The following project elaborates the earlier discussed experiment with the Philips Pavilion and will prove the method subscribed in the patent. To prove if the wire mesh is also employable for more complex forms, a blob prototype was designed. The prototype should be movable and should allow children to climb as well as crawl in it.

Fig. 10 Blob structure: playing object for small children.

A number of balloons are combined with the help of a so-called blob-mesh. (See figure below) This operation simulates a physical model in which an elastic material (for example a panty) was stretched over a number of balloons.

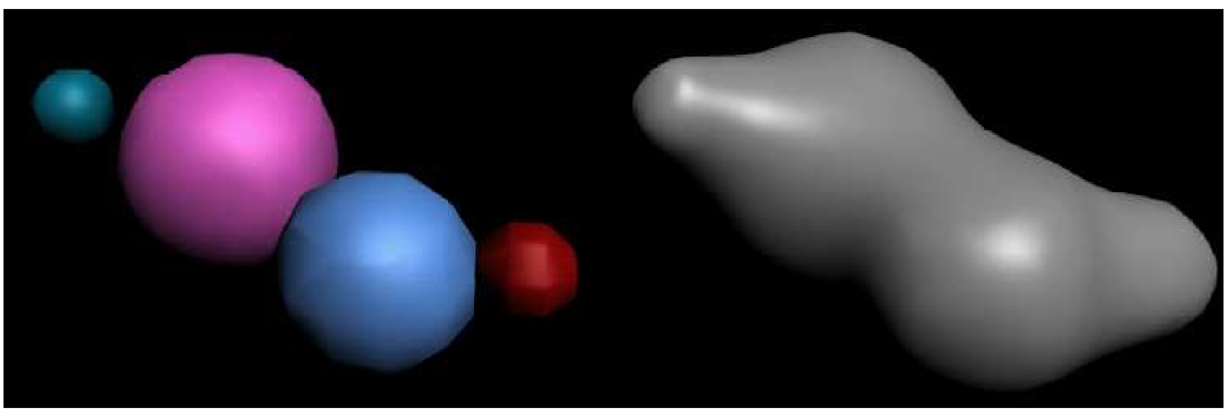

Fig. 11 Simulation of a physic model; Blobmesh

4.2 Structure analysis of the blob prototype

When the architectural design process was finished, the structural behavior of the shell was analyzed, the calculations done with the help of the program 'Marc Mentat'.
The calculations with the program showed a tension of 2 N/mm2. Concrete can only resist small tension stresses. That is why concrete is supplied with steel-bar reinforcement. The most traditional concrete structures are straight and can be reinforced in a simple way with traditional steel-bar reinforcement. The reinforcement of free forms in concrete is far more complicated.

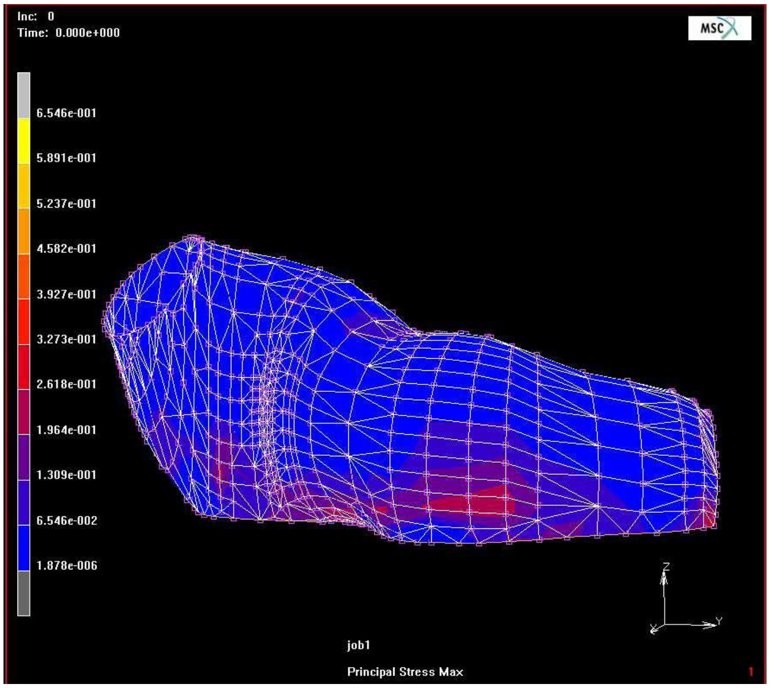

Fig. 12 Marc Mentat.
The diagram on the left shows where the tensile stresses will occur and how large they are. In the red areas of the diagram the largest tensile stresses are shown.

In the past this problem was solved with the help of the Ferro cement technique. In the realization of very thin concrete structures, large quantities of steel wire mesh and steel-bar reinforcement were used. Through the high content of steel in the concrete, the completely shell behaved like a homogeneous element that resisted equal maximum compressive and tensile stresses. Through the application of this technique different freeform concrete buildings have been realized in the 40's and 50's of the last century. However, this technique is very labor-intensive.

Another solution to this problem is the use of fibres in concrete. (fibre concrete) Fibre concrete consists of small steel or synthetic fibres mixed with concrete. This mixture can easily be applied in a mould. Through the small dimensions of the fibres, the concrete can be shaped in any form you wish. For forms like the prototype blob, steel fibre concrete is suitable. The reinforcement bars need no longer be adapted to the form of the structure. Because of the small dimensions of the fibres, the fluid qualities of the concrete can become utilized optimally. As well the reinforcement, the concrete can be poured in each form without adaptations. A condition for the application of fibre concrete, is that only small stresses are allowed. In the prototype blob this condition was applicable. On places where large stresses occur, the concrete has to be reinforced in a traditional way.

4.3 Form Analysis of the prototype blob.

As a result of the form analysis of the object, it becomes clear that the object describes in principle, 2 kinds of geometrical surfaces. Synclastic surfaces and Anticlastic surfaces.

- The Synclastic surfaces will be realized with the help of balloons. They serve as mould for the concrete construction. These balloons are composed of a number of patterns. The larger the number of patterns, the more precise a spherical shape is described. The patterns are printed on a PVC membrane with the help of a plotter. While welding the patterns, different so-called stamps can be used. In this case a relative short stamp is chosen because of the curvature of the inflatables. To see that these seams are completely airtight they are fixed with a special glue.
- The Anticlastic surface will be realized with cable nets. In principle, this is an application of the earlier described Ferro cement-bracing technique. The main difference is the use of form-active cable nets instead of steel cages and structures. The advantage of this is that this technique is less labor-intensive.

4.4 Construction of the prototype blob.

In the utilization phase the prototype blob has to be movable from one place to another. That's why the object is built on a concrete foundation plate equipped with hoist eyes. (See fig. 13)

Fig. 13 The foundation of the prototype blob.

In the following stage three balloons are blown up, placed in the right position and fastened with ropes / wires. The balloons are coupled with each other using an air hose. In this way they stay on sufficient pressure with one air pump. (See fig. 14)

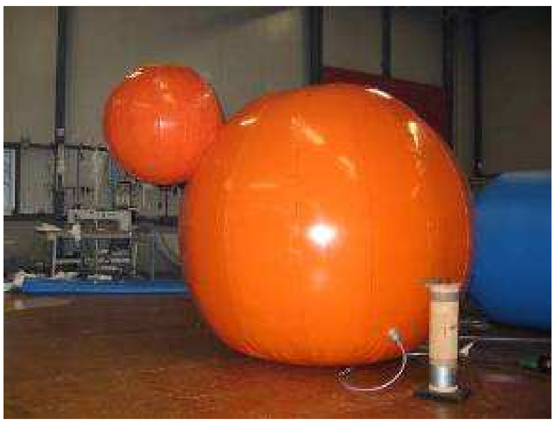

Fig. 14 Three fixed blown up balloons with the air pump.

The fastened balloons lie on their spot during the appliance of the wire mesh. The openings of the prototype blob are realized with steel rings. The wire mesh which is stretched over the balloons is fixed to the foundation using pouring eyes. (See fig. 15)

Fig. 15 The balloons covered with wire mesh and the steel rings for the openings.

Before spraying the balloons with shotcrete, the size of the wire mesh has to be brought down to a smaller size to ensure the shotcrete is sprayed though the openings of the wire mesh. The largest part of the wire mesh surface is positioned on the four balloons. In this way there is a closed base under the wire mesh and an additional finer mesh is not needed. The last steps before spraying the concrete are putting in the reinforcement and distance holders. The reinforcement is to improve the structural behavior. Calculations with the program showed a tension of 2 N/mm2. That's why we made use of steel bar reinforcements with a thickness of around 6 millimeters. Shrinking cracks are avoided by small polycarbonate fibers in the concrete. Spraying the concrete begins on the outside surface. The concrete is sprayed in two layers. The second layer is finished by rubbing and sponging the concrete. (See fig.16)

Fig. 16 Spraying the first layer of shotcrete .

After the concrete shell is rigidized, the balloons can be removed. Finally, the inside of the object is provided with cement screed. The total thickness of the skin is about 5 cm. (See fig..17)

Fig.17 The Result

5. Conclusion

The paper provides a method for making irregular shell structures in a feasible way:
A wire frame will provide more or less the minimal surface including the volumes inside the net influenced by the material and deadweight of the net. (fig7) The form to the net can be influenced by pulling or pushing local point(s) of the net. The combination of a pre stressed wire frame coveringinflatables rigidized by shotcrete, creating irregular shell structures is new. The method is patent protected and will be explored in the near future.

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