Making Blobs with a Textile Mould

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Summary. *In the last decade complex buildings i.e. with unregular curved surfaces have been designed. . The subject of this paper is the construction of those complex buildings. One of the main characteristics of a membrane structure is its geometrical complexity, which can be seen in multiple curved surfaces and complicated connection elements. Modern sophisticated computer technologies can be used to produce easily these complex three-dimensional shapes out of flat strips of fabric. Due to a lack of suitable production methods the expression of the natural stress flow in supporting and connecting (rigid) structural elements is difficult. This paper assumes that it is possible to achieve the architectural desired free forms by manipulation of structural membranes. To prove that it is possible to achieve the architectural desired free forms different cases are described in which this technique is used. The first case describes the design of an indoor Ski run. The second and third case describes the building of a lightweight stage covering and an art pavilion. In all the three cases physical models have been used in the design phase. The structural design of the membrane mould has been engineered with the program easy. The rigidized structures have been analyzed using different FEM programs for each case. The transformation of a form-active structure (membrane) into a surface-active structure has been researched to make domes ore dome-like structures.*

Key words: Blobs, textile mould, free geometry architecture, tensile structures, pneumatic structures, formfinding, structural optimisation

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1 Blobs

In 1994 K. Michael Hays [10] writes that in reaction to fragmentation and contradiction there is a new movement in architecture, which propagates a combination not only of forms, but also between different media like film, video, computers, graphics mathematics and biology. He recognizes that architecture is influenced by the development of an increasing complexity of information and communication is changed into information and media. This has lead to a development that is being referred to as blob architecture (Figs. 1,3). The characteristics of blobs are: smoothness, irregularity and a double curved skin.

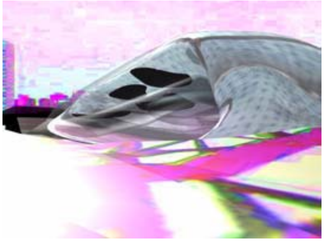

Fig. 1. by Michael Bittermann

Fig. 2. **Fig. 3.**

Modeling by means of nylon stockings and balloons

2 Blobs with a Textile Mould

The similarity between form active structures, like tent- and pneumatic structures on the one hand and blobs on the other hand is so striking that it is obvious to try to make blobs with techniques, that are being used for constructing tent- and pneumatic structures.

In the past numerous possibilities have been examined. Frei Otto for example has demonstrated the possibilities of influencing the form of pneumatic structures by stretching nets and cables over them. Another possibility of manipulating a tensile form is the combination of cloth and a pneumatic structure into a blob design. An example is the floating theatre at the Expo 1970 in Osaka designed by Yutaka Murata. One of the latest examples of transforming the shape of a pneumatic structure is the tensile structure of the Swiss pavilion (Figs. 4,5) at the Expo 2002. The edges of the structure are transformed by using bending stiff elements. The connection with nature is obvious if we realize that a human body can be seen as a membrane (the skin) stretched over bones (wire-frame) and muscles (pneumatic structure).

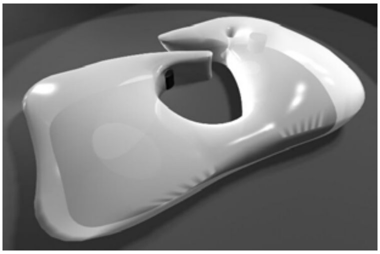

Fig. 4.

Fig. 5.

Nouvelle DestiNation Bundespavillon, Swiss Expo 02 (Eckert Eckert Architekten)

Fig. 6. Rigidized inflatable structure (A. Pronk)

3 Form-Active/Surface Active

In the open-air theatre in Soest a pneumatic structure was used as a mould. This mould was then rigidized, which resulted into a bent stiff beam that was combined with cloth. The result was a tensile structure. This technique was then studied. The purpose was to use this technique to realize complete buildings.

Heinz Isler has already demonstrated that it is possible to rigidize a pneumatic mould to construct buildings. The same principle is used in aerospace engineering for realizing antennas and space habitats. (In Soest the same principle is used to construct architectural shapes.) The surface of the building was not the result of the mechanics but the result of an architectural design process. At the Technical University of Delft and Eindhoven a group has been formed that has taken on the challenge of finding a way to realize blobs by means of transforming and rigidizing pneumatic structures. As a first study a model has been build that consists of balloons and a wire-frame that is placed in a nylon stocking (Fig. 2). It is possible to make many different forms with this technique. After modeling the shape a polymer resin is applied (Fig. 3). This physical model can be analyzed by means of a finite element computer program that looks at the active behavior of the surface of the structure. The input for the program is generated by a 3d scan (Fig. 17).

4 Stage Covering for an Open-Air Theatre

4.1 Introduction

This semi-permanent membrane structure covers the stage of the open-air theatre in Soest (the Netherlands) Fiber reinforced plastics are used for the production of a structural optimized and therefore lightweight and complex arch shaped structure. By using an inflatable mould the arch could be produced more economically (30% cost reduction). In the production the vacuum injection method is utilized for stiffening flexible fibers.

The owner of the Soest open-air theatre asked for a protection against bad weather for the stage. Therefore we suggested covering it with a lightweight membrane structure. A suspended membrane floats above the stage, so that visual relations with the natural environment are still preserved (Fig. 7). Outside the theatre-season the structure could partially be dismantled in this way the environment that is protected by national government is not visually disrupted. Two guyed columns are part of a dismantling system and could be used for hoisting the temporary membrane. The form of the spatial membrane is, beside the indirect support of the columns, the result of an arch. Because of this arch the protective area of the covering is increased and additional curvature in the membrane is improved (Fig. 8). In this way the membrane structure is a combination of two highpoint surfaces and an arched surface, the stage covering works like a tensegrity structure. The columns and arch transmit compressive loads. Both the Tensile loads and the stabilization of the whole structure are transmitted and organized by the prestressed membrane and cable structure.

Fig. 7. The stage covering for the Soest open-air theatre in the Netherlands (H. Werkman)

Fig. 8. An arched beam ensures an increase of the protective area and the curvature of the membrane structure

Due to its position in the audience's view and its proportions, the arch contributes in certain extent to the architecture of the structure. Therefore, special attention is given to the elaboration of the structural arch. The arch' dimensions exceed several times the thickness of the membrane and the cables. To avoid an abrupt change between the 'thick' arch and 'thin' membrane, a tapered arch section is desirable. The result is a conical arch. Because the mass of the arch would influence the membrane shape, a lightweight construction is necessary. This conical arch, which is characterized by geometrical complexity due to multiple curvature, and the necessity of a lightweight structure, asked for the use of an unconventional construction material and production technology.

4.2 Materialisation

Conventional construction materials like steel and aluminium and accompanying production technologies are not suitable for making lightweight multiple curved arches. The material properties and production methods of fibre reinforced plastics (FRP) matches the arch requirements. Some advantages of fibre reinforced plastics are: rigid and lightweight construction possibilities, fatigue resistance, chemical and corrosion resistance, freedom in design and form and the possibility to integrate parts. Important disadvantages are the cost prices of material, mould, production (labour) and engineering. In the case of complex shapes, for example a conical arch, approximately 50% of the production costs consist out of model costs. Therefore an effective way of cost reduction is to decrease the mould price.

4.3 Geometrical Complexity and Production Technology

Through the utilisation of a pneumatic mould the cost price of the arch is reduced with 30% (Fig. 9). In the production of the mould the same computer applications (EASY, FEM-based software) and production technologies are used as those used for the development of the membrane structure. After modelling and formfinding in EASY cutting patterns are generated and used for the production of the mould. The internal over-pressure ensures the rigidity of the inflatable mould. The general dimensions, like the distance between the supports, are controlled by an auxiliary structure (Fig. 10).

Fig. 9. Pneumatic mould supported by the auxiliary structure (Tentech/Buitink Zeilmakerij)

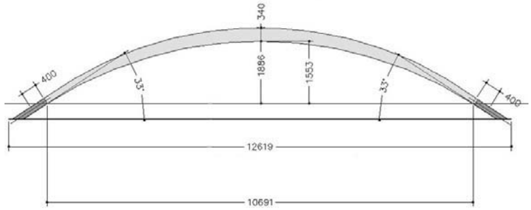

Fig. 10. General dimensions of the mould

4.4 Rigidizing Inflatable Structures

A rigidizable inflatable structure can be described as a structure that is flexible when inflated and becomes rigid after exposure to an external influence. Therefore it is not necessary o maintain the overpressure. There are several rigidizing techniques developed and more are still under development. They can be divided into three categories: thermosetting composite systems, thermoplastic composite systems and aluminum/polymer laminate system. Advanced rigidizing systems used for space applications are designed for specific structures and may be very expensive. In civil engineering, vacuum injection, which is a thermosetting composite system is a feasible way of rigidizing membranes.

4.5 Structural Optimisation

The structural engineering of the membrane structure is done with the use of the software package EASY, which is based upon the finite element method (FEM). To examine the shape of the structure and its reaction to external forces, the structure is first modelled with an arch set up as a spatial truss with a defined stiffness. Then this model is used for the structural analysis of the complete structure, consisting of a membrane and supporting cables and columns. Also the deformations due to extreme loading (wind and snow loads) are examined.

In order to be able to produce the synthetic arch the stiffness has to be determined. The pre-stress in the membrane and boundary cables causes an axial compression in the arch. Hence the curve of the arch will increase. The arch consists of synthetic fabrics rigidized by injecting resin into this fabric. By varying the use of material (e.g. thickness of the layers, layers of different materials) a range of E-moduli can be obtained. Also the moment of inertia is a variable. Therefore a variety in stiffness and bending resistance is possible. As said before, in order to find the desired shape the initial arch is designed having less curvature than ultimately was needed. - an E-module of 210 GPa (210.000 N/mm^2, comparable to steel) is used. The initial moment of inertia (Iy) was set at $855{\cdot}10^4$ mm^4, resulting in stiffness $1.8{\cdot}10^{12}$ Nmm^2. First the deformations of the arch under pre-stress are calculated. The pre-stress in the membrane and the boundary cables cause the arch to deform and result in an increase of curvature.

EASY-BEAM is used to determine this initial curve. Then the stiffness is used to calculate the composition of the synthetic arch, (a specific E-module with needed I_y.)??

To be able to be more material-efficient a second step is taken. By adjusting the E-module from 210 GPa to 60 GPa a new stiffness is found ($EI_y = 5.14 \cdot 10^{12}$ Nmm^2). The initial curve of the arch is also adjusted to its new stiffness. Deformations of the curve under pre-stress are calculated, as are the deformations under extreme loading. These deformations turned out to be more than desired.

A third step had to be taken. The stiffness had to be increased considerably. This is obtained by a change in the moment of inertia (I_y). In the first step of the design the diameter of the arch was determined at 200 mm. By enlarging this diameter to 360 mm a factor 20 of increase in Iy is achieved (also a change in layer composition was introduced). Because of architectural consideration and in order to economize the use of material even more Iy is varied within the arch. This is translated in a tapered cross-section, with a decrease in diameter towards the ends of the arch.

Fig. 11. Bending for power, a pole vaulter using a beam's bending stiffness and deformation

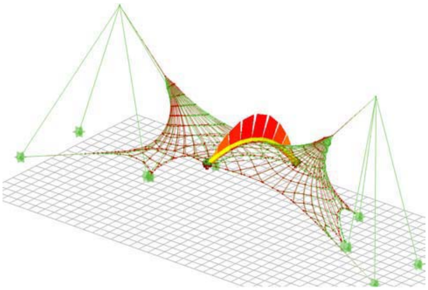

Fig. 12. Bending forces in beam-elements of conical arch, calculated in EASY-BEAM

In this third model Iy varies between $16170 \cdot 10^4$ mm^4 in the middle section to $8170 \cdot 10^4$ mm^4 at the ends. The deformations under pre-stress and extreme loading are checked and are within the design boundaries.

These insights resulted in a tapered glass- and carbon fiber beam, with its diameter varying between 150 to 360 mm.

4.6 Vacuum Injection

For the production of the arch the vacuum injection method is used to impregnate the resin in the woven fibres (Figs. 13–15). Around the pneumatic mould alternately layers of fibres and resin are placed. To create a closed system the whole package is wrapped with some airthight and protective foils. In the closed system a pressure differential is applied that impregnates the fabric with resin. The pressure differential of the technique is obtained by means of a vacuum. The injection has to take place within the cure time of a resin. The following formula (1) expresses the filling time (t_{fill}) as a function of the porosity (φ) and permeability (K) of the reinforcement, viscosity (ν) of the resin, flow distance (l), and applied pressure ($\mathit{\Delta} P$).

$$t_{\text{fill}} = \frac{\varphi \cdot \nu \cdot l^2}{2 \cdot \kappa \cdot \mathit{\Delta} P}$$

The objective is to design a channel layout that ensures full wetting of the fabric at each location. Three distinctive injection strategies for a three-dimensional object can be followed, viz.. edge injection: downward, upward and sideways. Downward injection is sometimes disadvantageous because bubbles will be entrapped more easily and there is the increased risk of dry spots due to race tracking by the runner channels. The choice between the other two injection strategies depends on the geometrical shape of the product. Factors that are of influence are the number of inlet ports and the total injection time that, when minimal, are both at an optimum. In this case upward injection is used.

Fig. 13.

Fig. 14.

Fig. 15.

Production of the conical arch, by using the vacuum injection method. Both glass and carbon fibres are applied (photos: Rep-air Composites)

5 Indoor Ski Run

After the case of the open-air theatre students carried out several studies, Henno Hanselaar has carried out a very interesting one that shows the possibilities of the structures. He designed an indoor ski run with blob appearances and analyzed the mechanical behavior of this structure. The design has been made with the aid of the computer program Maya 4.0. This program is designed to make virtual animations, which are used for example in video games. It is also easy to design blobarchitecture and kinetic buildings. A three-dimensional site was drawn with the help of geodetic information from the local government.

Two lines were drawn on the ground of the slope that acted as the edges of the shell structure. Profile lines were drawn between the ends of these lines (they will function as rails) and on arbitrary distances between the ends of these lines. With the "Birail 3+"-function Maya generates a surface between the drawn profile lines. The surface can easily be transformed by changing the profile lines. The "Rebuild"-function generates an even smoother surface. When the final shape is obtained, the drawing can be exported as an Iges file type.

5.1 Surface-Active Analysis of the Mechanical Behavior

This file type can be imported in the computer program DIANA. It is the FEM package that is used to make a structural analysis of the rigidized shell. For pre and postprocessing DIANA makes use of the FEMGVX program. In the main menu of FEMGVX there are two options. The first is Femgen. This can be used for generating a 3d model and modifying the properties. The second option is Femview. With Femview the calculation results can be viewed. The building of the model has been done, as described above, in Maya.

5.2 Conclusions from the Structural Calculations

After all the results of the structural analysis have been processed the next phase was the evaluation and the possible material adjustments. If it appears that certain values are not satisfying a different solution has to be found Most striking is the

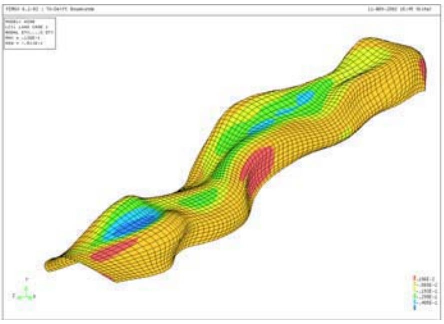

Fig. 16. Model in DIANA

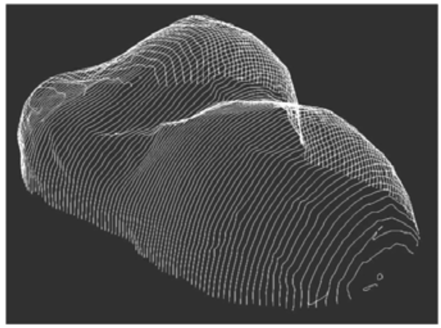

Fig. 17. 3D scan of Blob oject

large deflection of the system. But due to all the irregular bent surfaces there is no reference for the deflection. In this case a deflection of for example 400mm or 800mm cannot be seen. The structural system partly functions as a shell. At places where there is a transition from one curvature to another the outer forces are transferred by means of a bending moment. This is of course a bad situation for a thin walled structure. There are different solutions for this problem. From the solutions that were thought of the option of varying the wall thickness was chosen.

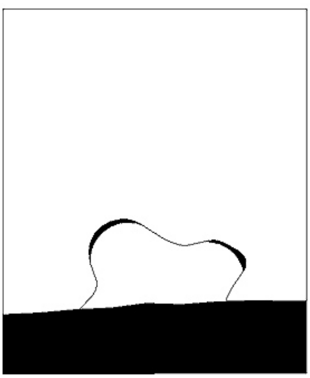

Fig. 18. Wall locally strengthened around problem area

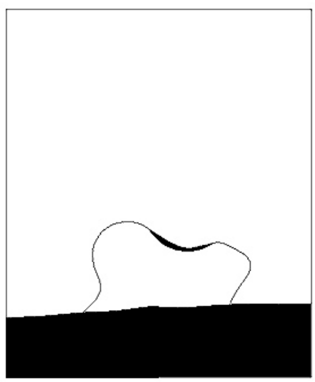

Fig. 19. Wall locally strengthened in problem area

5.3 The Form-Active Analysis of the Structure

The form of the indoor ski run was analyzed by means of describing the form by sections. To achieve the designed form there are a number of possibilities for the inflated structural elements that are put under the skin. At first the cross sections in width direction are shown. Next the different inflated structural elements are explained.

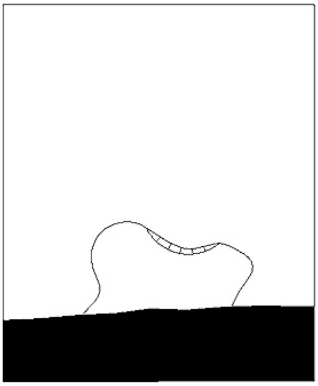

Fig. 20. Support construction placed under the roof

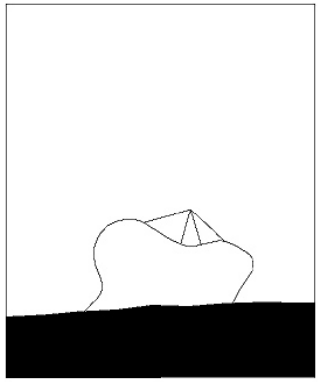

Fig. 21. Support construction placed on top of the roof

The width cross sections are more or less sinclastic. At several spots there is an anticlastic curvature. This indicates that there will be no structural inflated element underneath. The tension in the skin in longitudinal direction will have to apply the anticlastic curvature (Fig. 23). The longitudinal sections also show a global sinclastic shape and locally anticlastic curvature. This has to alternate with the width anticlastic curvature (Fig. 22).

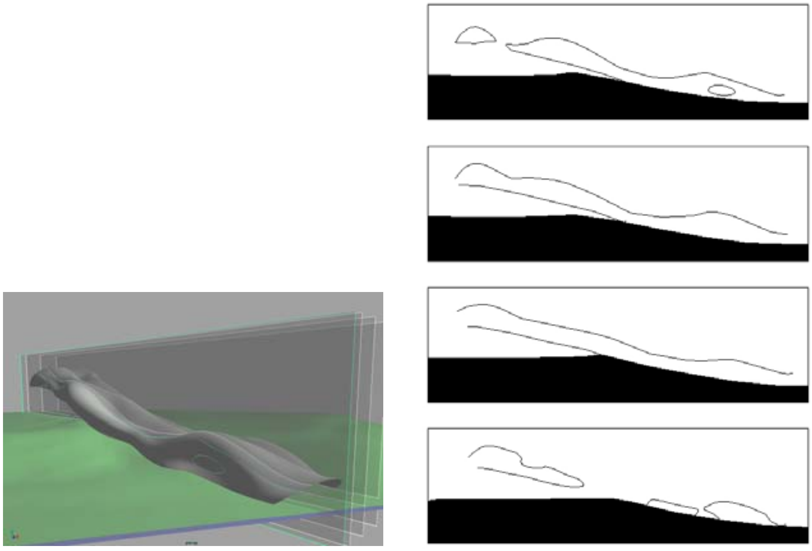

Fig. 22. Longitudinal cross sections

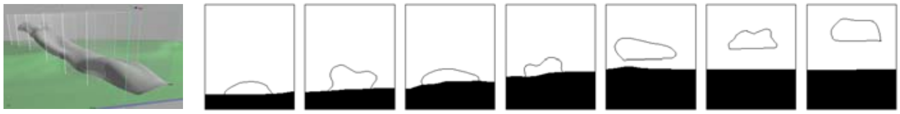

Fig. 23. Width cross sections

5.4 Manipulating Inflated Elements

The possibilities to fundamentally change the form of an inflated structure are limited. The form can merely be influenced. The curvatures are always existent and that is also the intention. There are simple examples from daily life where inflated structures are used and deformed. For example a car tire has a flat outer surface. In the rubber of the tire steel rings are embedded to prevent the tire from having a round cross-section (Fig. 24). An airbed is also an example where the form is influenced. There are partitions that hold the upper and lower side together when the airbed is inflated. These partitions make the cavities that exist in an airbed. In this way different sorts of shapes can be made with the aid of pneumatic structures. A number of possibilities to influence pneumatic forms will shortly be described.

Pressure Surfaces

By pressing two sides of a pneu with the aid of 2 so-called pressure surfaces, the pneu gets an elliptic shape. At the contact surface with the pressure surfaces, the pneu will follow the form of the pressure surfaces. The same effect appears when two pneus are pushed against each other. The contact surface is in this case flat (Fig. 25).

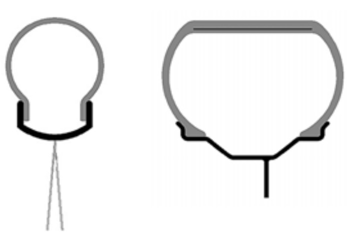

Fig. 24. Cross-sections of a bicycle tire and a car tire

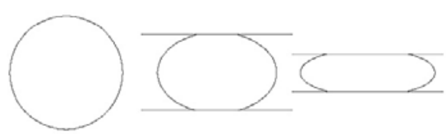

Fig. 25. Pneu with pressure surfaces

Tension Cable

By tightening a tension cable around a pneu, the pneu can be laced up. At the position of the tension cable a sharp line appears (Fig. 26).

Partition

By applying a partition it is possible to get the deformation to follow a certain line. This is the line of the partition. For example in the air mattress the partitions are there to hold the upper and lower side of the air mattress together (Fig. 27).

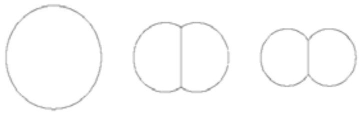

Fig. 26. Pneu with pressure surfaces

Fig. 27. Airbed with partitions

Combination of Internal Pneus and Outer Skins

Fabric material is highly suitable to make negative curves. By combining an outer skin with internal pneus, positive as well as negative curves can be made. The following cross-sections can be made (Figs. 29–31).

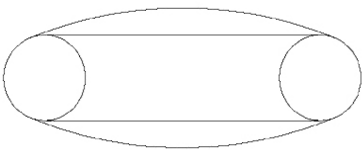

Fig. 28. Combination of two pneus (torus)

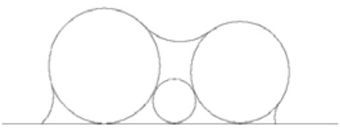

Fig. 29. A small pneu is used as a distance holder

Combination of Two Pneus

In this case a pneu is wrapped around a torus (donut shape). The torus holds the pneu in its place during the inflation. In this way a reasonable flat form like M&M's can be achieved (Fig. 28).

5.5 Variety of Pneu Combinations

In Maya a number of combinations of different pneu forms were researched that are necessary to realize the form of the indoor ski run. Three alternatives have been made. In the alternative that was chosen two trunks can be recognized. During construction the free ends, at the top and at the bottom of the ski run, will be stiffened and thereby holding the tent cloth. It is possible that the form of the pneus deviates from the original design form. This can be seen in Maya where the dark gray areas are the deviating pneus (Fig. 33). The deviation is between a few centimeters and a decimeter. To construct cross-section 6 a number of pneus have to be placed on top of each other (Fig. 32).

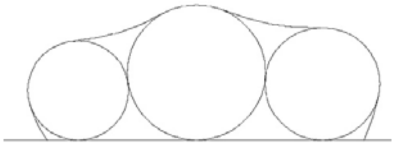

Fig. 30. To create a declining facade the tent cloth has to be fixed under the pneu

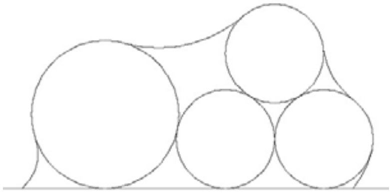

Fig. 31. To create a declining facade the tent cloth has to be fixed under the pneu

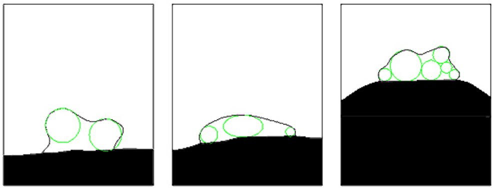

Fig. 32. Cross-sections 2, 3 en 6 with pneus

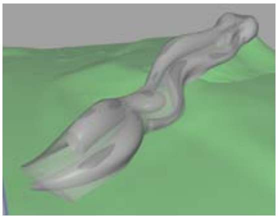

Fig. 33. Alternative 3

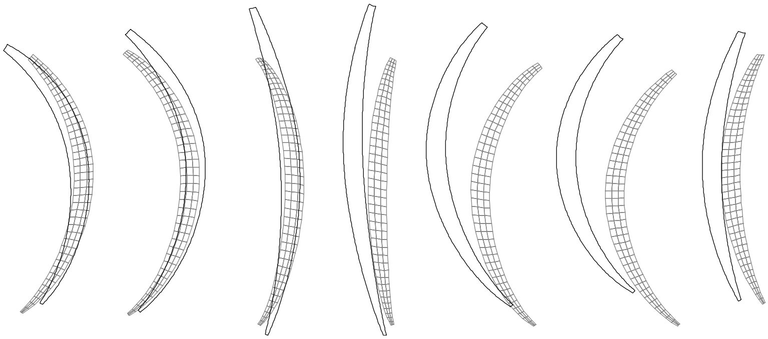

Fig. 34. Top view of 3D and 2D

5.6 Scale Model

To verify whether the proposed technology is a sensible way of working, a part of the ski run is made as a scale model. To be sure that the result of the model was close to the designed form, cutting patterns were made from the inflated structural elements. The different cutting patterns were stitched together and made airtight. Patterns from a banana, an M&M, 2 types of trunks and a part of the outer skin are made. All the different elements are grouped on the ground plan made out of cardboard (Fig. 35). The skin is put over the inflated elements and rigidized (Fig. 36).

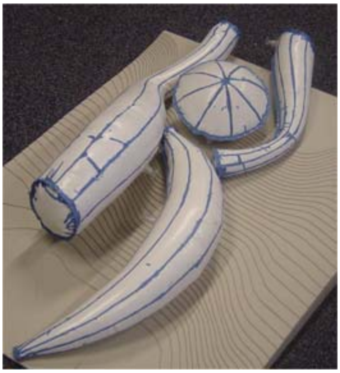

Fig. 35. Inflated structural elements

Fig. 36. Rigidized skin of Ski Run

It is hard to create geodesic lines on inflated elements because of the sinclastic curvature. There are numerous solutions for the geodesic line algorithm. Therefore the straight model out of Maya is used. An inflated element is made out of a mesh. This element is divided into separate strips. The strips follow the curvature of the element. The Ski run has quite strong curved inflated elements that results in strongly curved 3D patterns.

Because the 3D strips are not according to geodesic lines, the resulting 2D strips are very curved. When it would have been a real-sized structure, it would not have been very economical to use these kind of cutting patterns. In this case it only concerned a scale model and waste of material was not that large. For flattening the 3D strips the EASY Flatten module from the TECHNET Company was used.

5.7 Concluding Remarks

The study of a blob structure as a cover of a Ski run has resulted in a very convincing structure(in what way?). In a controlled way a design of the outer skin is made supported by inflated elements. After rigidizing the skin (by means of concrete) it is very well possible to solve occurring problems in the structural system. The section analysis of the inflated elements suggests a possible way of supporting the outer skin. Missing link here is the numerical analysis of the total system, outer skin combined with the inflated elements. This is still what has to be done. Then also will be investigated what the effect will be on the shape during the application of the rigidizing material. This study must be seen as a first step on the way of a new design and production method of Blob blowing structures.

6 The Art Pavillion

This case describes the concept and engineering design for an art Pavilion in Eindhoven Holland. The surface of the pavilion is made out of Glassfiber-reinforced Polyester. The mould of the structure is made of a PVC coated Polyester membrane.

The manipulation of form-active structures makes it possible to use membranes as a mould to make a surface-active structure. The engineering is divided in two parts. The first part describes the way the artist (Jurgen Bey) made his model and how we used this model as a starting point for the engineering.

The pavilion will be used for art exhibitions, filmprojections on the screen, as street lighting and as a piece of art. The general theme of the activities in and around the pavilion is the influence of technical innovations in art. The pavilion has two positions, vertical and horizontal. To put the pavilion in upright position, aircushions are used to raise the pavilion from a horizontal position to a vertical position (Fig. 37).

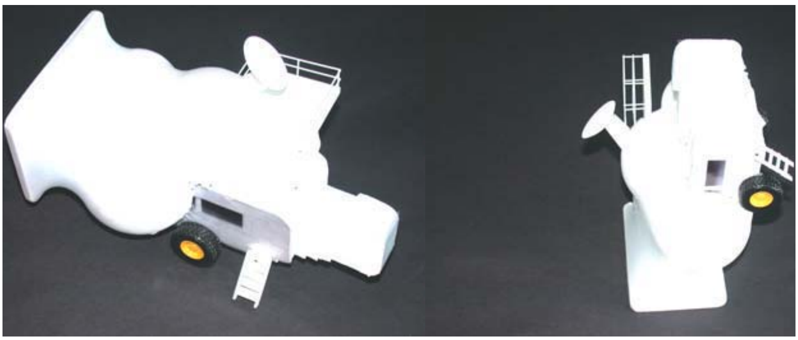

Fig. 37.

The artist was made familiar with form-active modelling. The design the artist had to conceive should be able to be realised as an inflated inner fabric that supports a tensioned outer fabric. This is the so-called Blowing Structure Method. The first design sketches were in 2D, the final design only existed out of a 3D physical model, made according to the Blowing Structure method.

From the model that is shown above (Fig. 37) a 3D scan was made. It was represented as an IGES file which made it possible to generate cross sections. This digital model with cross sections was used to analyse the form the inner and outer skin. The first form analyses were done in the program Rhino. Here the size and position of the inflated elements were derived from the 3D scan. The inflated elements were imported into the program EASY of Technet GMBH. To be able to form find a fabric over the inflated elements, a new module for the program was developed. This program is called Conformer Alpha and is based upon a sliding support system and bary-centric coordinates. This makes it possible to investigate the interaction between the inner inflated elements and the outer tensioned surface. Both inner and outer surface will need to be translated into cutting patterns for production.

Fig. 38 shows the order of the inflated elements. Fig. 39 shows the cutting patterns of the outer membrane. Fig. 40 shows a rendering of the tensioned outer skin and the inflated inner elements. Fig. 41 shows a view of the Conformer Alpha program with a part of the inner and outer skin.

The second part of the engineering was the behaviour of the surface-active structure and the materialisation. The 3D scan made from the model shown in part one

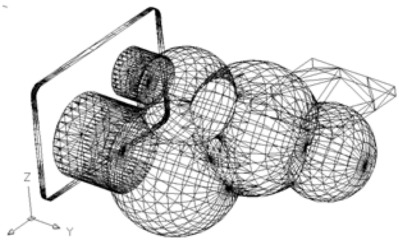

Fig. 38.

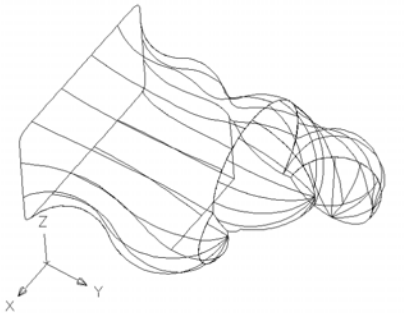

Fig. 39.

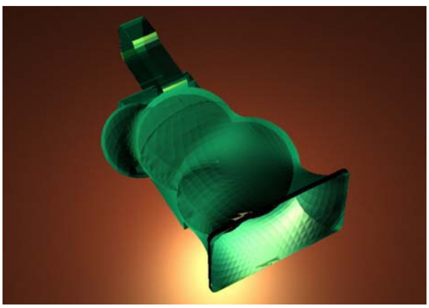

Fig. 40.

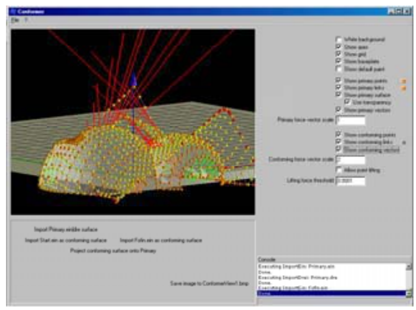

Fig. 41.

was also used for the structural analysis. This was done with the Finite Element program Marc-Mentat. Marc Mentat is able to import the 3d scan in STL format. The STL file consists out of triangular elements. In Marc it is possible to calculate with triangular elements but in order to calculate with a thick shell element, quadruple elements were needed. We didn't succeed in transforming the triangular elements into quadruple elements automatically. Therefore we had to redraw the mesh of the model by hand in Autocad. The benefit of the program Marc is that if the model works it is quite easy to calculate different types of materialisation for the skin of the pavilion. Another benefit is that the calculation time of the model is short in comparison to other Finite Element programs. The results are shown in the Figs. 42–45.

The pictures show the way the skin of the pavilion is divided in translucent and non translucent parts. Two factors determined this outcome. The first and most important was the structural behaviour of the pavilion. The second factor was the artistic input of the artist (Jurgen Bey). The yellow and orange parts are translucent, the other parts are non-translucent sandwiches. Parallel to this process different kind of materialisation experiments were made. We did al kind of materialisation experiments. For example in one experiment the behaviour of ropes in a polyester composite structure has been studied (Fig. 46).

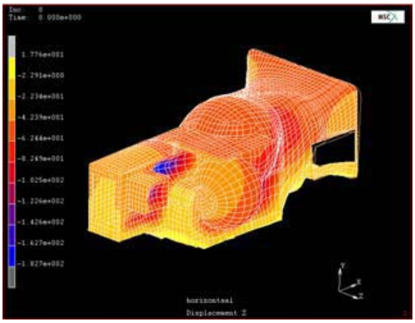

Fig. 42

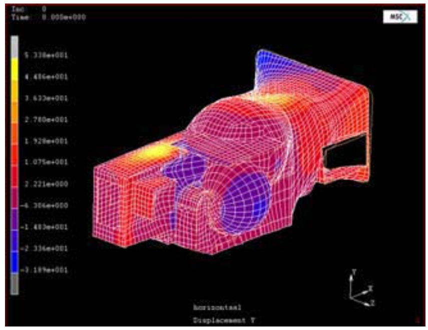

Fig. 43

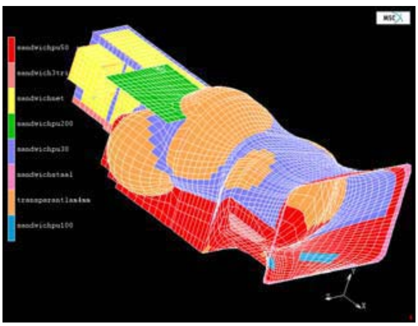

Fig. 44

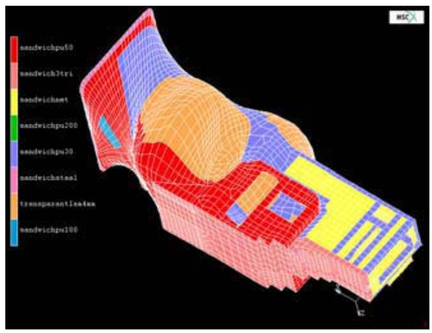

Fig. 45

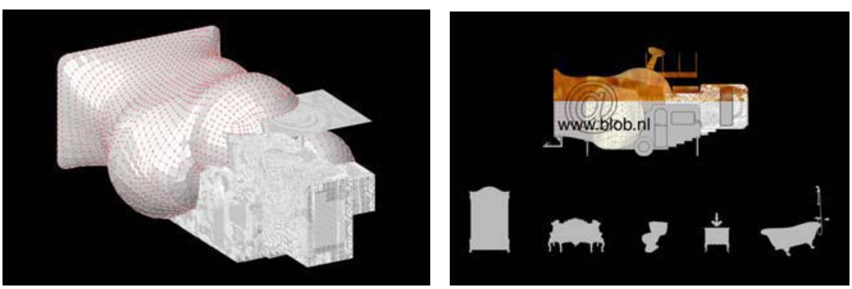

Fig. 46. Artist impression of the pavilion by Jurgen Bey

7 Conclusion

Modern sophisticated computer technologies offer new possibilities in designing free-geometrical architectural forms and geometrical complex structural elements. Pneumatic and tensile structures, in combination with bent stiff elements, play a great role in the development of non-rectangular shapes, due to their minimal dead load and great freedom of shapes. Examples are the moulds, which have been used, in the described cases of this paper.

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