DESIGN TOOLS FOR INFLATABLE STRUCTURES

ROBERTO MAFFEI[*], ROLF H. LUCHSINGER[†] AND ALESSANDRA ZANELLI[*]

[*] Department Building Environment Science and Technology - BEST
Politecnico di Milano Via Bonardi 9, 20133 Milano, Italy
e-mail: roberto.maffei@mail.polimi.it, web page: www.robertomaffei.com

[†] Empa, Center for Synergetic Structures
Ueberlandstrasse 129, 8600 Duebendorf, Switzerland
e-mail: rolf.luchsinger@empa.ch

[*] Department Building Environment Science and Technology - BEST
Politecnico di Milano Via Bonardi 9, 20133 Milano, Italy
e-mail: alessandra.zanelli@polimi.it, web page: www.textilearchitecture.polimi.it

Key words: Inflatable Structures, Form Finding Process, Cutting Pattern, Parametric Design, Tensairity[®].

Summary. This paper shows different tools and approaches that can be useful for the definition of the design of pneumatic structures. Some of these tools have been applied for the design of a Tensairity[®] hull.

1 INTRODUCTION

"Form finding" is the process to generate the optimal configuration from the structural and visual point of view due to a given stress distribution and boundary conditions acting on a flexible structure[1].

Several software for form finding are available on the market and each of them present pros and contras. Considering the contra, the most complete and advance software for form finding and non linear behavior calculations require a strong background about finite elements analysis[8] and a lot of mathematics, too. Moreover, the outcome, most of the time, is not "ready to use" and its result must be carefully checked to avoid errors and misunderstandings. In other words, these software are powerful and can solve complex design but their results can be tricky too and that's the reason why the user should have a certain level of experience to came out with trustable results.

From the usability point of view, most of these software are not user-friendly: time and effort are necessary to interact with their interface. Considering the already large number of software an architect or engineer should know to carry on a project of architecture, a process of integrations of different "specific tools" accessible within the same domain would dramatically reduce the waste of time (for example saving the time of import/export procedures) in the design process and would enlarge the audience of designer ready to apply tensile principles in their projects.

From a technical point of view, some of these software require computers that can offer high performances because solving algorithms are time and CPU consuming. Some firms or design studios, for this reason, use to develop their own software or tools, focused on their specific task. These scripts are lighter than complete software and they are usually dedicated to a specific purpose.

Some commercial firms already offer toolbars that operate within CAD domains such as Autodesk Autocad® or McNeel Rhinoceros® (Rhino). However, the features offered by those tools are most of the time limited even if they can solve perfectly standard shapes with well known boundary conditions. The positive side of a "friendly interface" and the "lightness" of the tool is counterbalanced by the limitation in forms and restrains they can solve.

A further step on this process would be the integration of different specific tools and form finding "solvers" through the use of an unique and adaptable interface, easy to deal with and to personalize. That's possible, for example, using the plug-in "Grasshopper®" (GH) for Rhino. GH is a visual programming language. Programs, called *definitions*, are created by dragging components onto a canvas. The outputs of these components are then connected to the inputs of subsequent components. The GH environment provides an intuitive way to explore designs without having to learn to script[2]. Users can generate their own *definition* and "plugging" the useful *components*. These *components* can collect the geometrical input from the graphic interface of Rhinoceros and compute equilibrium or non linear analysis using the same algorithms developed by the most advanced finite elements software. In other cases, expert users can generate and define their own *components* based on algorithms they have developed (figure 1). Most of these "homemade" *components* are far away to be accurate but surfing the net and looking at the developments and growing of the GH's community, it's clear how fast improvements can be done[2].
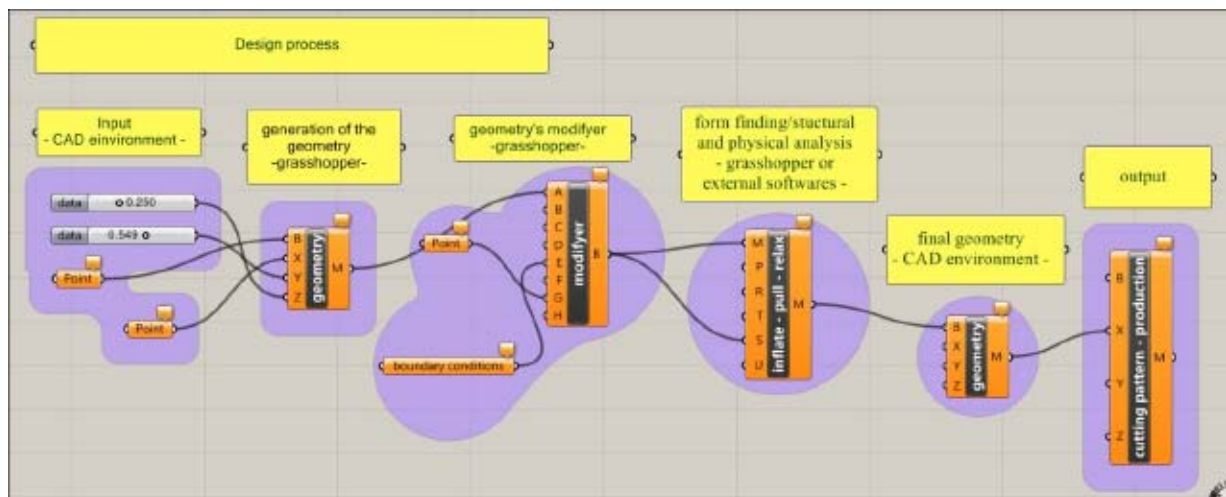

Figure 1: Design process with Grasshopper®

In this paper, several case studies about the form finding and the design process for different inflatable shapes, using GH and other plug-ins, will be presented. Special attention will be given to the design and manufacturing of a parametric Tensairity® hull.

2 DEFINITION OF SHAPES: TWO APPROACHES

The definition of the shape of an inflatable structure is not an easy task[5]. Not every shapes can be done with the inflatable technology: that's the case, for example, of sharp edges. On the other hand, some envelope, under the load of pressure can't reach, a well distribution of stresses: as a result wrinkles are produced. One of the goals of the designer is to avoid wrinkles in the structure, because wrinkles can't guarantee an effective behavior of the system as a whole and they can generate unpredictable deformation under loading. To generate a pneumatic structure, one should predict how a certain envelope will accommodate itself to reach its equilibrium under a certain inner overpressure level.

Pneumatic structures are form-resisting structures and their shapes follow specific equilibrium rules. Complex shapes can be done connecting and intersecting several basic geometrical shapes. Each of these basic geometrical shapes present circular or portion of circular sections. The definition of the exact position of these circular sections and, sometimes, their deformations due to the interaction with boundary conditions, such as inner or outer struts or cables, is the crucial task to design an inflatable structure[5]. The higher the number of circular sections I can define, the more accurate the prediction of the shape of the pneumatic structure will be. Unfortunately, in most cases, only few circular sections are known in advance, especially if the structure is complex.

That's the reason why two different design approaches for pneumatic structures can be identified. In the first case, the designer should look for the circles or portions of circles that will be generated by the inflation, set them as strict boundary-conditions and generate from them the final shape (figure 2). This approach requires time and extensive geometrical abstraction's capacities. Its results are accurate but complex shapes can hardly be done. In the second case, the designer should look for the envelope and then, using specific scripts, simulate its behavior under the load of inflation (figure 3).
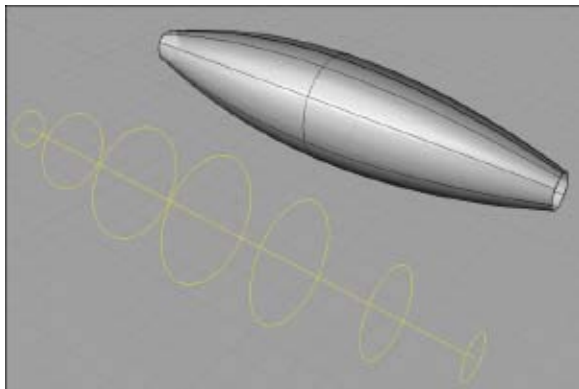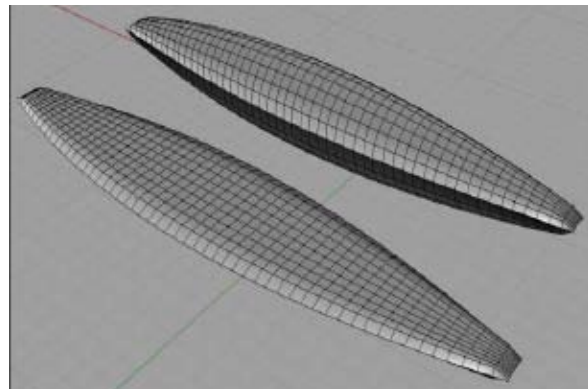

Figure 2: cross sections approach

Figure 3: envelope approach

In this case, geometrical intuition is not required. Any shape can be generated but the accuracy of the results has to be tested. The two approaches are different but complementary: the first one requires a clear idea about the final shape one has in mind; the second one focuses on the flat envelope before the inflation. The first one can be done with simple CAD systems or even by hand; the second one requires specific software and plug-ins (in this paper

the use of GH for Rhino will be considered). As we will see in the conclusions, most of the time, both approaches should be used: firstly the envelope approach will give the raw shape and will help to define the position of the circle sections; secondly, the cross-section approach will generate the final shape with better accuracy. The following section will describe the first approach; section four will investigate the second one.

3 CROSS-SECTIONS APPROACH

Any envelope, under the load of inner pressure, tries to accommodate most of its cross-sections in the shape of circles or portions of circles. According to different boundary conditions such as borders connections, inner or outer springs or struts, these sections deform and they become more difficult to be identified.
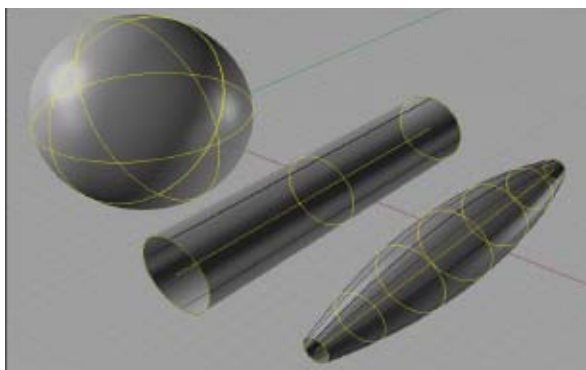

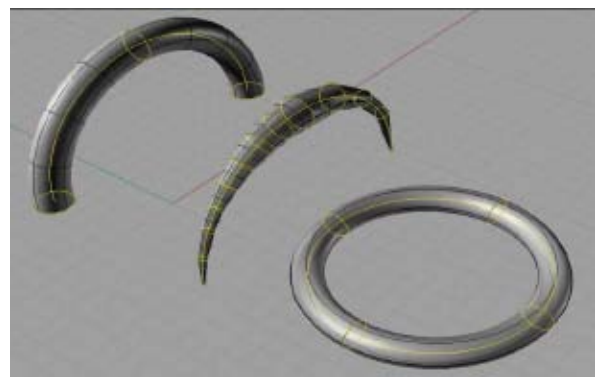Figure 4: basic shapes from points and linear axes

Figure 5: basic shapes from curved axes

The simplest pneumatic shape is the sphere: on it, an infinite number of circles with their centers on the center of the sphere can be identified. In a cylinder, infinite circular sections are placed, normal, along the axes of the cylinder itself. In the case of a spindle, the circles vary their radius along the length of the axes (figure 4). If the axes is not a straight line but a generic curve, more complex shapes can be defined. Cylinder-arches or spindle-arches are generated if the axes is an arc. In a similar way, a torus can be defined if circular sections are placed normal to a circle (figure 5).
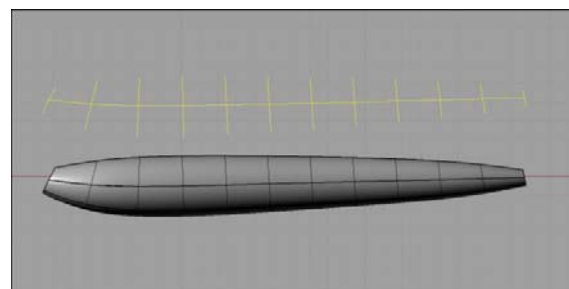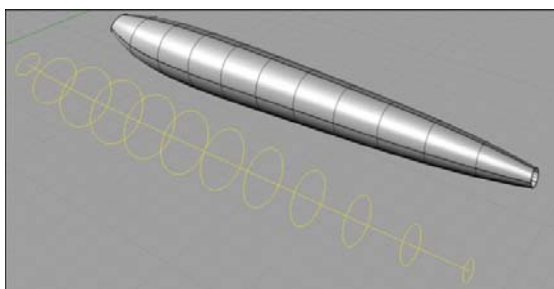

Figure 6 and figure 7: asymmetrical linear pneumatic element, perspective and front view

Symmetrical and asymmetrical elements can be designed with this approach scaling and rotating circular sections (ax in this case would be a generic curve or a "*spline*") in specific

points as shown in figure 6 and 7.

Starting from these simple considerations and connecting together primitive forms, a large number of more complex shapes can be obtained. The final configuration can be predicted by the simple combination of each primitive form as far as no extra deformations will occur in the connection points.

3.1. INPUTS AND OUTPUTS

In McNeel® Rhinoceros® environment is rather easy to define geometries and make them interact parametrically using the free plug-in GH. To generate any inflatable element with the cross-sections approach one should be able to define as input: 1) the axes of the element, with a start and end point (or length); 2) a series of circular sections (radius), normal to the axes; 3) other restrains such as inner or outer springs or struts. All these inputs can be drawn in two ways: 1) all dates and geometrical elements (.dxf) can be drawn in Rhinoceros® or with any CAD system: all these dates can be then connected to each other parametrically with GH; 2) all inputs can be defined already in GH and then connected to each other. The second approach may take more time in the definition of the boundary conditions but it is way better as far as the final structure will be fully parametric.
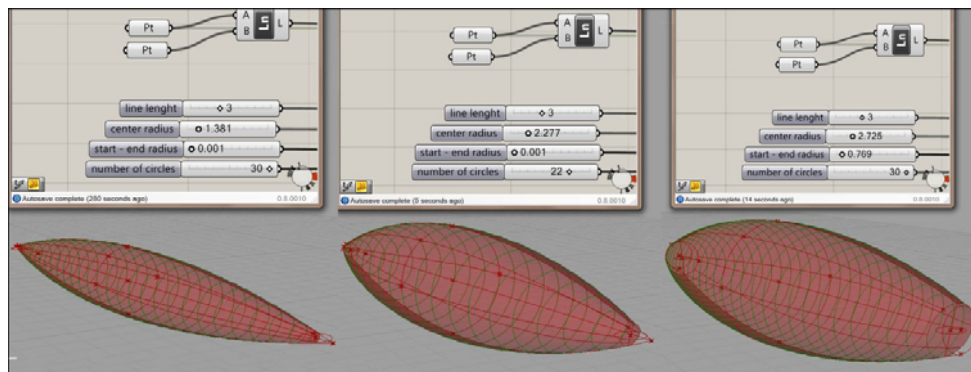

Figure 8: changing of parameters

This means that changing any of the parameters, the structure is automatically redefined according to the new given inputs (figure 8).

Outputs of these kind of definitions can be as vary as designer's imagination; anyway, the basic outputs are twofold: 1) the envelope (surface or mesh); 2) dimension of any restrains (cables, struts, springs). The envelope can be split in different parts through cutting lines defined by the designer and ready to be "flattened" using specific tools as shown in section five.

4 ENVELOPE APPROACH

Sometimes, it is not possible to identify in advance circular sections that can be set as fixed boundary conditions for the definition of the final shape of an inflatable. Moreover, in some cases, designers would like to investigate how an envelope would look like under inflation without passing through the construction of hand models. Hand models cost times and effort

180

and their behaviors are strongly dependent on their size, the properties of the materials used, the accuracy of the model itself and the definition of the cutting pattern for the production[6]. That's why the envelope approach would give an answer to those who would like to explore the world of pneumatics starting from the envelope itself. A process of trial and error would guide the designer to reach the final shape and maybe in the near future, it would help designers in controlling the whole inflation process, for example, of a folded pneumatic element. At the moment, inflation processes, for example for applications in space, are studied through complex finite elements analysis[7]. That's definitely not the tool architects or designer could apply for their purposes.

Sometimes, even some simple shapes can hardly be defined using the cross-section approach. A pneumatic pillow generated by the inflation of a flat rectangular peace of membrane, for example, is something that cannot be modeled accurately (especially at the ends) based on the cross-section approach (figure 9). In the case of a cushion with several holes, the identification of circular sections becomes quite difficult or even impossible (figure 10).
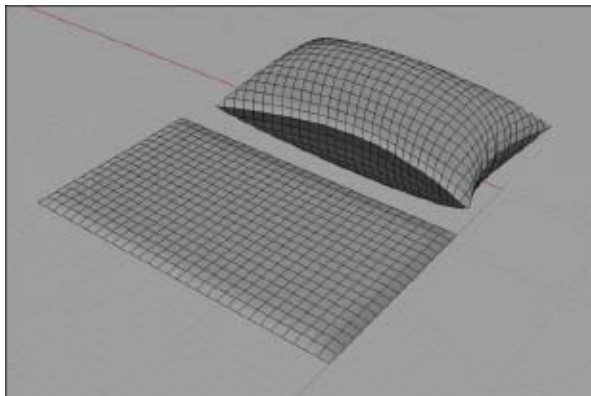
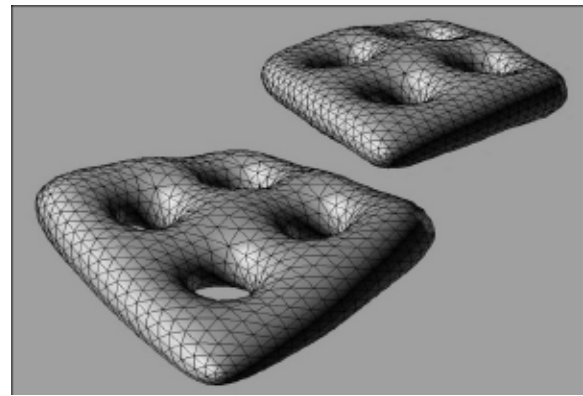Figure 9: inflated pillow from a rectangular mesh   Figure 10: pillow with holes, two configurations

The generation of the process of inflation of the meshes showed in the pictures above has been done through the use of a plug in for GH called Kangaroo Physics[®]. Kangaroo is an add-on for GH/Rhino which embeds the physical behaviour directly in the 3D modeling environment and allows a live-interaction with the model when the simulation is running. It is used for various sorts of optimization, structural analysis, animation and more[3]. Kangaroo simulates the physical behaviour applying the "particle system". "Particles are objects that have mass, position, and velocity, and respond to forces but have no spatial extent. [...] Despite their simplicity, particles can be made to exhibit a wide range of interesting behaviour. For example, a wide variety of non-rigid structures can be built by connecting particles with simple damped springs"[4]. How Kangaroo applies forces and simulate physical behaviours is not the goal of this paper: further information can be found in the manual[3]. Connecting Kangaroo physics with any triangular or quadrangular mesh through a *definition* designed with GH, it is possible to simulate how the envelope accommodates itself under the load of internal pressure. The definition can simulate the inflation of any mesh, in real time, with a relatively low consumption of CPU. The definition deforms the mesh applying a

181

uniform distributed load on both inner surfaces of the mesh keeping the total surface area of the envelope constant. The stiffness of the envelope can be changed: for low stiffness, the mesh behaves like a toy balloon or a soap bubble (figure 11); increasing the level of stiffness, wrinkles appear in the structure (figure 12).
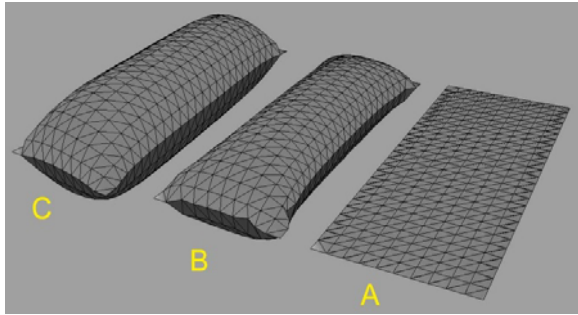

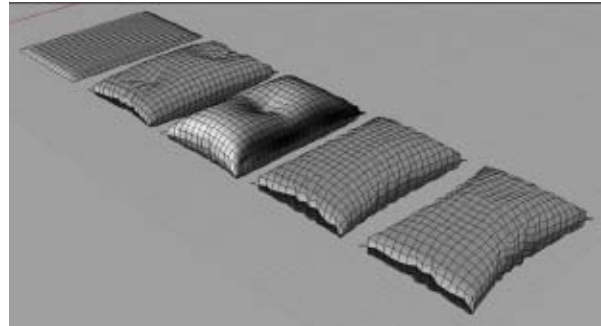Figure 11: stiffness influence during inflation process

Figure 12: different pressure and stiffness levels
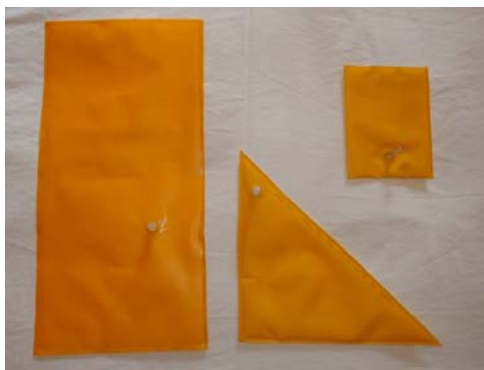
4.1 VALIDATION OF THE RESULTS
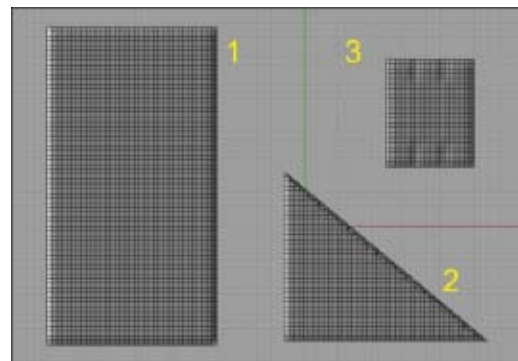

Figure 13: flat envelopes before inflation

Figure 14: flat meshes in Rhinoceros

Three different simple shapes have been built to validate the results of the inflation process using GH. A rectangle of size 47 cm*25 cm, a right-angle triangle of size 30cm*25cm and a second rectangle of size 13 cm*16 cm. The latter rectangle has been designed with two welding lines (every 4.5 cm) of 2 cm in length normal to the upper and lower edges between the two layers of the envelope. This design wants to generate deep wrinkles in some controlled points. All three envelopes are planar before inflation (figure 13). The reason why no cutting pattern has been done for these envelopes stems from the desire to check if this design approach could identify and predict if and where wrinkles would appear. The material used for the construction of the mock-ups is a light nylon fabric coated with polyurethane. According to the stiffness of the material, wrinkles would change the configuration and would appear at different pressure levels. As far as the definition in GH is not able yet to take into account material properties, a light membrane has been chosen in order to simplify the influence of the of the material in the deformation of the initial mesh.

Considering the case of the first rectangle (sample 1), the results of the inflation using GH

is quite promising. With an increment of the total surface of less than 1%, the inflated mesh presents, from a quick sight, the same shape of the mock-up (figure 15). Wrinkles' position is also quite accurate: biggest wrinkles appear close to each corner; other smaller wrinkles can be identified along the upper and lower edges (figure 16). Moreover the circumference at central section and the total longitudinal length after inflation have an accuracy of 5%.

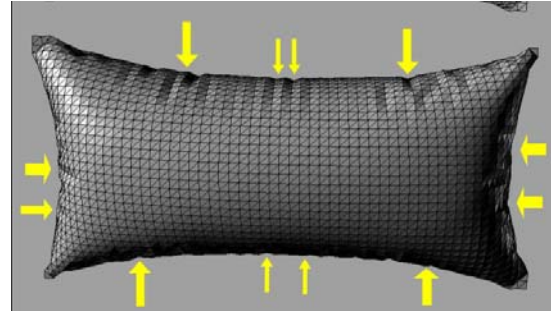Figure 15: mock-up envelope 1   Figure 16: mesh envelope 1

Concerning the case of the right triangle (sample 2), the size of the final envelope is increased by 1%. Looking at the final shape of the mock-up one can clearly see how two deep wrinkles in the edges close to the right angle appear (figure 17).
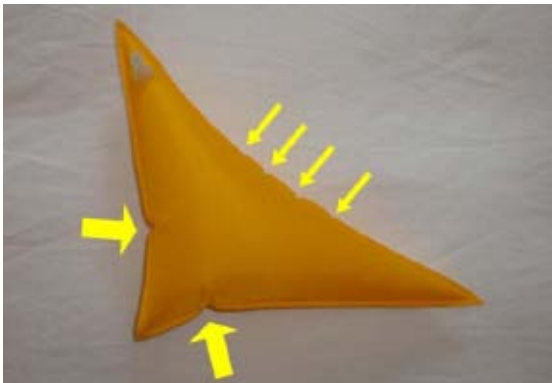

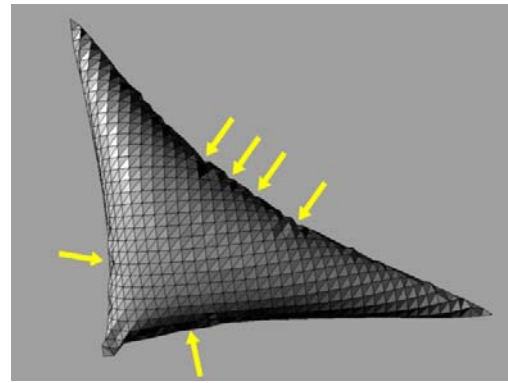Figure 17: mock-up envelope 2   Figure 18: mesh envelope 2

Along the hypotenuse, smaller wrinkles are generated, too. On the contrary, considering the inflated mesh (figure 18), wrinkles in the area of the catheti seem quite smooth whereas the ones along the hypotenuse look quite reasonable. Geometrical analysis shows that as in sample one, the main dimensions have an accuracy around 3%.

Investigating the behavior of more complex shapes like the one of sample 3 (figure 19), deep wrinkles are generated starting from the 2 cm welding; some of them go in two directions along the surface. Inflating the mesh, a similar behavior can be noticed. Anyway, the main difference comes for the fact that material and seam properties (i.e. stiffness, friction) are not taken into account at all: That's the reason why a rotation of the upper and lower part of sample two appears in the mesh envelope.
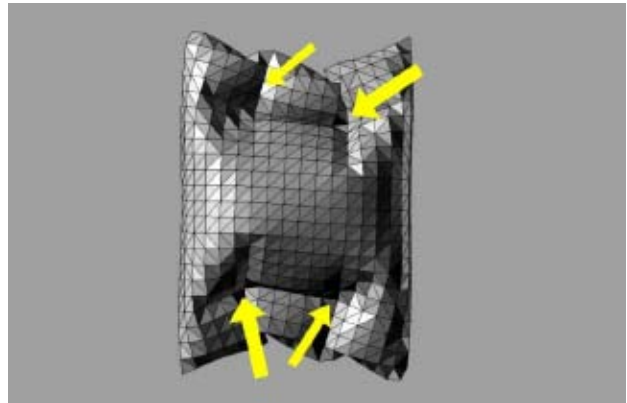
Figure 19: mock-up envelope 3

Figure 20: mesh envelope 3

From the geometrical point of view, the central circumference of the mesh envelope matches the length of the circumference of the mock-up built; on the contrary, the total longitudinal length decreases more than in the mock up case. This discrepancy probably comes again from the fact that no material properties and no interactions derived by the contact of the surface with itself is taken into account.

5   CUTTING PATTERN

The generation of the cutting pattern is the last step of the design process and it influences the manufacturing phase, the performances of the element under inflation and its aesthetical properties. An accurate cutting pattern produces a nice smooth shape once the envelope is inflated. To generate the cutting pattern, a series of cutting lines (that will become seams during the manufacturing process) are required. The arrangement of the cutting lines is the crucial part of an effective cutting pattern. In the case of a simple shape like an inflatable spindle arch, two main arrangements of seams are possible. In the first case, cutting lines are circular sections of the structure (figure 21). In the second case, seams follow the length of the arch, from one end to the other (figure 22).
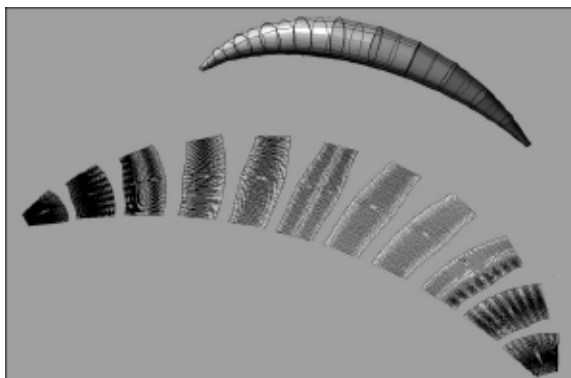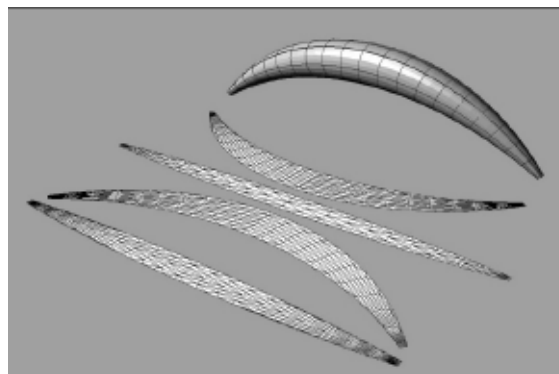

Figure 21: cross section cutting pattern

Figure 22: longitudinal cutting pattern

The result of the cutting pattern of the first arrangement is a series of strips of different lengths: their lengths is equal to the circumference of the sections at that point. The result of

the cutting pattern of the second arrangements is a series of curved or straight strips. Having as a result straight (or almost straight) seam lines would speed up the process of manufacturing as far welding will be straight too. On the contrary, the longitudinal cutting pattern generates curved and straight panels that have to be welded together.

The final result of an inflated spindle arch manufactured using the cross section cutting pattern is most of the time poor because the final shape will be a combination of straight segments (figure 23). On the contrary, having a longitudinal cutting pattern, the shape will be continuous and smooth (figure 24).
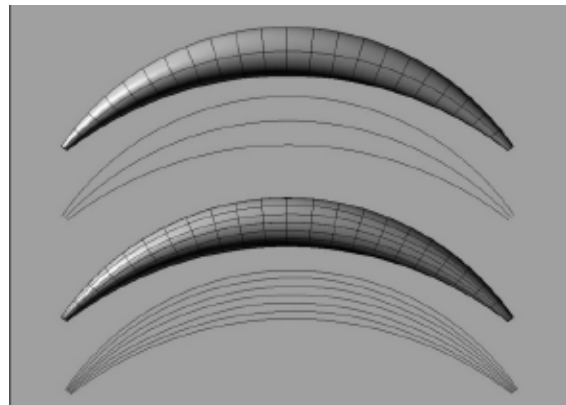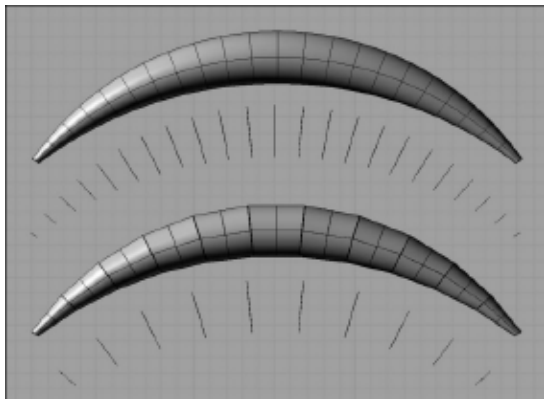

Figure 23: spindle arch, cross section cutting pattern

Figure 24: spindle arch, longitudinal cutting pattern

Terraflat® was the plug-in tool used in Rhino for the generation of the cutting pattern.

6   DESIGNING OF TENSAIRITY® STRUCTURES

Tensairity® are special structures[8] and they require adequate design tools, too. The design of a Tensairity® could take a lot of time and effort especially if one doesn't have a well defined and clear idea of what the final result should look like. In other words, once one design has been made, any change in its geometry (length, height of section, position and number of struts/cables) would require to restart the design process from the very beginning. That's the reason why a parametric design for Tensairity® is highly recommended. In the next paragraphs a simple parametric tool for designing Tensairity® elements will be presented.
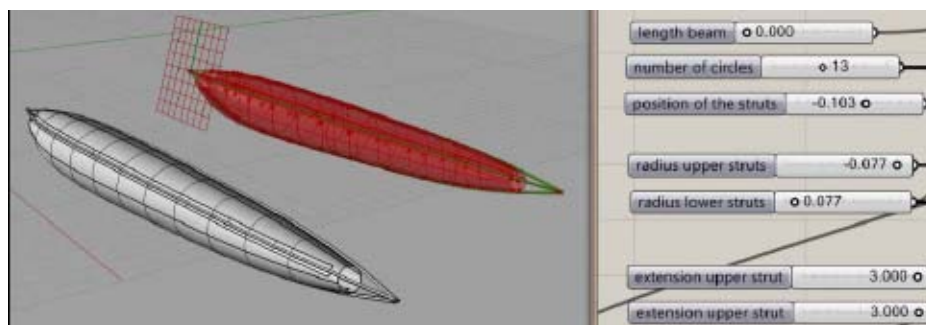

Figure 25: generation of the Tensairity® hull and some of the inputs

Five parameters have been considered crucial for the design of this kind of structure:1) the total length; 2) the height of the section at certain points (usually at 25%, 50 % and 75% of the total length) 3) the curvature of the element itself (to create straight elements or arches); 4) the number of struts or cables involved 5) the position of these struts of cables along the radius of the hull. Combining these parameters, a large number of Tensairity® elements can be designed, modified by changing each parameters (simply by changing the input values), adapting it to each specific design case (figure 25).

Output of the tolls are 1) the complete membrane, already divided into parts ready to be flatten with other software like Terraflat®; 2) length of Tensairity® cables and struts), 3) definition of pockets for struts and cables. The accuracy of the tool was tested by comparison with several built prototypes (figure 26 and figure 27).

Figure 26: spindle asymmetric tensairity, version 1

Figure 27: spindle asymmetric tensairity, version 2

7 CONCLUSIONS

Two design methods for inflatable structures have been presented in this paper. The cross section approach is the most used method so far and doesn't require any particular software tool. It has been shown how a parameterization of this approach through software like GH does dramatically improve and speed up the design process. This approach is useful for simple shapes or aggregation of simple elements. The definition of circular or segments of circular cross-sections is the main input. For complex shapes, these cross sections are difficult to be identified thus limiting this approach.

The envelope approach is useful when cross sections cannot be identified clearly in advance. It is also useful if one would like to test how a generic envelop would look like under the inner pressure load without any handmade models. The accuracy of the tools tested is still low and cannot be considered sufficient to be used in architecture. The main problems identified are two: 1) as far as wrinkles depends on the stresses in the membrane, these tools should be able to control the inner pressure too: in GH the value of pressure or overpressure is not accurate at present and it is not related to real pressure; 2) the material properties are not taken into account. Future development of the research should test the accuracy of the mock up built with other materials (i.e. a thicker membrane) and should try to take into account the presence of seams and valves.

However, thanks to a continuously growing open-source on line community improvements in the field are incredibly fast. It is possible that in the near future some of these tools will reach the same level of accuracy as commercial software on the market with the great advantage to be extremely user-friendly and much less CPU consuming.

To achieve the best result in designing inflatable structures both approaches are recommended. The cross-section approach can not be used for complex shapes but it can assure high accuracy. On the contrary, the envelope approach could give a raw idea about the shape any envelope would accommodate under inflation and can be extremely useful for complex shapes in which cross circular sections cannot be easily identified.

Cutting pattern generation plays the key role in the manufacturing of inflatable elements. Welding arrangements should be thought carefully to match the need of the construction phase. Specific tools like Terraflat® are now under development and work fine for most of the basic shapes. If meshes are too dense or if they are badly arranged, programs would not give an accurate result or, sometimes, cannot give result at all. Anyway, improvements are going fast and they are occurring during the time this paper was written, too.

In case of simple Tensairity® elements both approaches are effective and give accurate results. If the accuracy needs to be high, the cross-section approach is the most useful for this purpose. The help of the parametric tool of GH results in a dramatic speed up the design process.

8   ACKNOWLEDGMENTS

9   REFERENCES

[1] Bletzinger K., *Formfinding and Optimization of Membranes and Minimal Surfaces Formfinding with the Updated Reference Strategy (URS)*, Lecture notes, prepared for the Ph.D.-course: Advanced school on Advanced Topics In Structural Optimization, (1998).

[2] www.grasshopper3d.com

[3] www.grasshopper3d.com/group/kangaroo

[4] Witkin A.*, Physically Based Modeling: Principles and Practice, Particle System Dynamics*, Robotics Institute, Carnegie Mellon University.

[5] Lennon A., *Geometrical Mechanics for Inflatable Structures*, Fourth European Workshop on Inflatable Space Structures ESTEC, Noordwijk, Netherlands; (2008).

[6] Herzog T., *Pneumatic structures: a handbook for the Architect and Engineer*, Crosby Lockwood, London, (1977).

[7] Lou C. M., *Development and application of space inflatable structures,* 22nd International Symposium on Space Technology and Science, Morioka, Japan, (2004).

[8] Luchsinger, R.H., Pedretti, A., Pedretti, M. and Steingruber, P. *"The new structural concept Tensairity: Basic principles"*. In: Zingoni, A. (Ed.), *Progress in Structural Engineering, Mechanics and Computation*, A.A. Balkema Publisher, London (2004)