ARCHITECTURAL DESIGN OF MEMBRANE LIGHTWEIGT STRUCTURES AND THE CONSIDERATION OF BUILDING COSTS

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ABSTRACT

In the context of membrane architecture it is a necessity that design teams of people with different expertise collaborate in an integrated design process. Knowledge in geometric design, engineering, installation, and costing as well as understanding of their correlation is fundamental for the success of membrane projects.

Especially cost estimation is often neglected in the early design stage. As a consequence decision makers cannot reason over the realization of a project until very late. The result is, time and money are spent without knowing the future of the project.

For their intentions and ideas to be realized, it is crucial for designers to have knowledge about the expected costs and the economic influence of various design parameters already at the very beginning of a project.

A software tool that gives the designer an instant cost estimation of the current design could provide valuable knowledge about how to optimize the costs and bring the original design intention into reality. Surveying and quantifying the parameters within the designer's sphere of influence was the basis to create an interactive tool integrated into the "Formfinder" design software for membrane lightweight structures.

This paper discusses those parameters the designer can control in this early stage of a project. The results of cost estimations of membrane roofs with different constraints will show their influence on the project costs. Furthermore a short description of our software tool will be given.

Conference TOPIC / CATEGORY
Invited Session 50: "Detailing – Case studies – Installation Process"

1 Introduction

The main difference between designing rigid or form-active structures is the approach to find the geometry required for a certain purpose. In general one can say: rigid structures are shaped; form-active structures are derived.

Conventional (rigid) structures are given a specific shape or geometry. Spans, dimensions, and materials are chosen to be checked mathematically in relation to given load cases. If the proves fail, either the geometry, sections, or materials have to be changed. This iterative process continues until an acceptable result in ULS (= Ultimate Limit State) and SLS (= Serviceability Limit State) is achieved.

The form-finding of tensile surface structures on the other hand starts with the definition of the layout of an area to be covered as well as the arrangement of fixation points and boundary conditions (such as stiff or elastic edges, or stress ratios between warp and weft). Within these the membrane is supposed to find equilibrium. One layout of boundaries allows only for one mathematical solution, meaning one particular membrane shape. Every alteration of the arrangement results in a new variation of geometry. [2]

Therefore designers should be aware of the potential they have in hand to control the (commercial) success of a membrane project. Right after the project idea the first steps are the most important and have a major influence on the following design process. In the beginning the architect has to deal with a lot of uncertainties. At first the knowledge and the degree of detailing are very little and the risk for the project not to get realized is very high. The more time passes the more knowledge is gained and the risk of failure reduces.

2 Study

To visualize the relation between optimization of geometry and the resulting costs, design studies have been performed on a four-point sail. Every single variation of the base geometry ran through a complete predesign of all main construction components, such as membrane, edge cables, struts, guying cables, foundations, and anchors. In a next step the individual project costs were estimated and the gained values were visualized in figures for further analyses.

The three independent studies included the following:

1. Variation of the membrane curvature
2. Variation of the edge cables curvature
3. Variation of the inclination of the guying cables

2.1 Geometry

For easier understanding of the effects of altering the geometry the most simple roof type was used – a four-point sail.

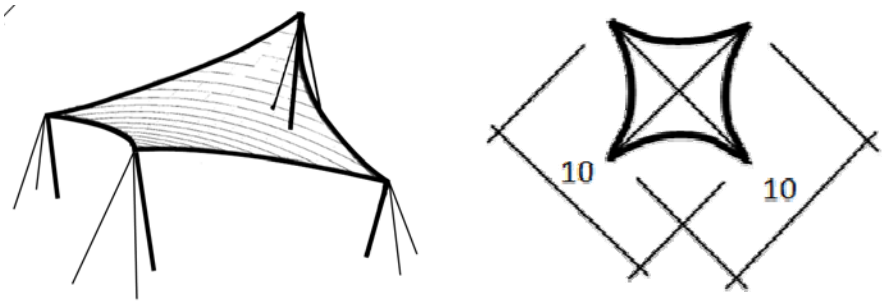

Figure 1. *Layout of standard sail*

2.2 Study 01 – Variation of membrane curvature

The membrane surface of the base roof is designed with an arch rise of 10%. In this study the curvature of the membrane was altered from 3-20%. As an additional precondition the minimum clearance of the sail at the highest point was set 3m. As a result the height of the corners changes from model to model.

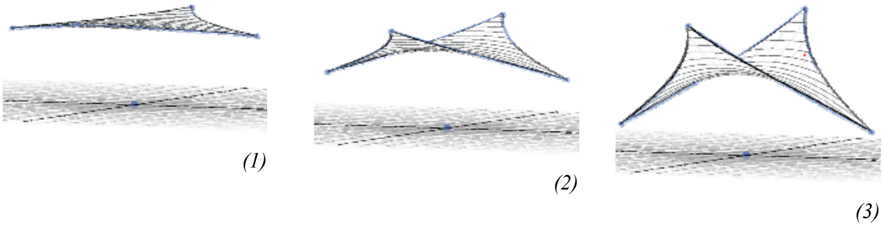
(1)
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Figure 2. *Study 01 – Variation of membrane curvature (1) 3%; (2) 10%; (3) 20%*

2.3 Study 02 – Variation of edge cable curvature

In this study the effects of different curvatures of the edge cables were analyzed. Starting with the base roof, the considered range of the arch rise is 3-20% of the fixation point distance. The clearance and the lengths of the struts remain the same in all models.

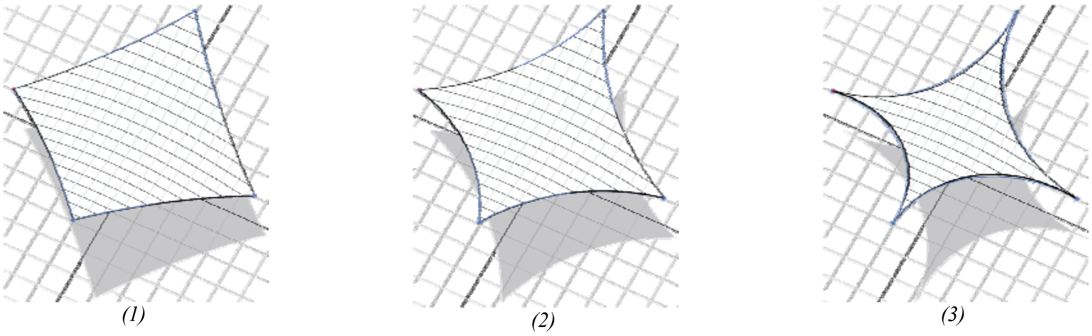
(1)
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Figure 3. *Study 02 – Variation of edge cable curvature (1) 3%; (2) 10%; (3) 20%*

2.4 Study 03 – Variation of inclination of guy cables

On basis of the reactions of the standard roof, the angles of the guy cables against the vertical were altered. The angle between the strut and the guy cables varies from 7.5 – 57.5°.

Figure 4. *Study 03 – Variation of inclination of guy cables (1) 45°; (2) 25°; (3) -5°; (4) restraint column*

3 Study 01

To visualize the effects of altering the membrane curvature the following figure gives an overview of the development of the bearing loads (*red* and *green graphs*) and the forces in the edge cables (*purple graph*). To meet the precondition of avoiding ponding, the prestress (*blue graph*) increases with the diminishing curvature.

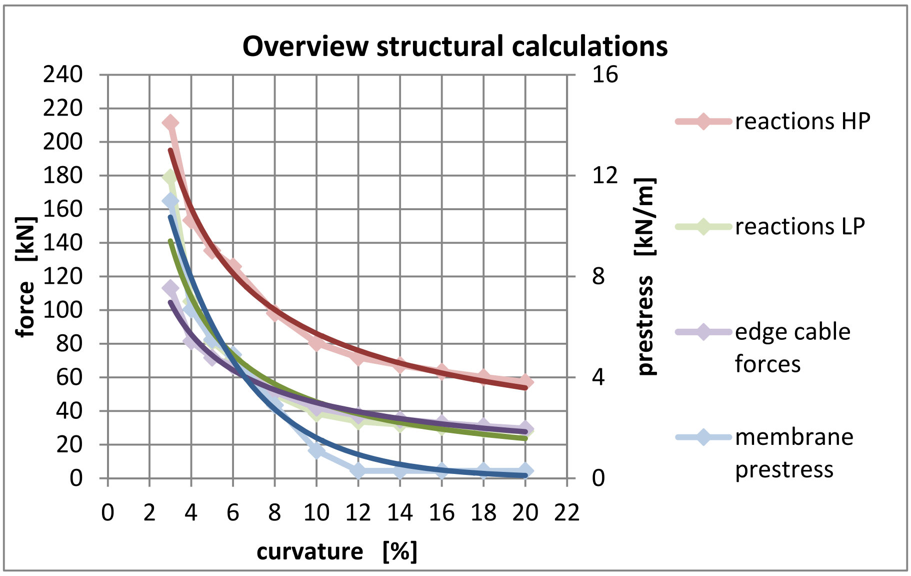

Figure 5. *Study 01 – Overview structural calculations*

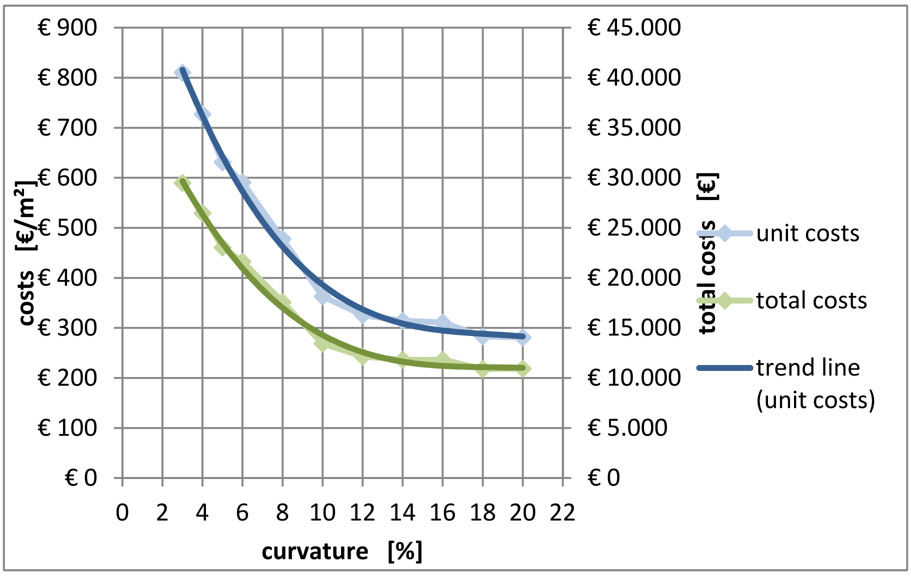

Figure 6. *Study 01 – Cost calculation*

As generally known, a reduction of membrane curvature causes bigger internal stresses and reaction forces (Figure 5). Taking the standard sail as a point of reference, the results show, when the curvature increases from 10 to 20 percent ($\Delta = 10\%$), the reaction forces decrease only by 25 percent. Almost the same variation occurs when the curvature is reduced from 10 to 8 percent ($\Delta = 2\%$). At the extreme end of the investigated range (curvature = 3%), the reaction forces are 175 percent higher than at the base geometry.

As expected, the less the membrane is curved the higher the total costs grow. The unit costs change almost in parallel to the project costs.

4 Study 02

In Study 02 the altered design parameter is the edge cable curvature. Figure 7 summarizes the development of the bearing loads (*red* and *green graphs*) and the edge cable forces (*purple graph*). In contrary to Study 01, here the prestress (*blue graph*) rises with the increasing curvature.

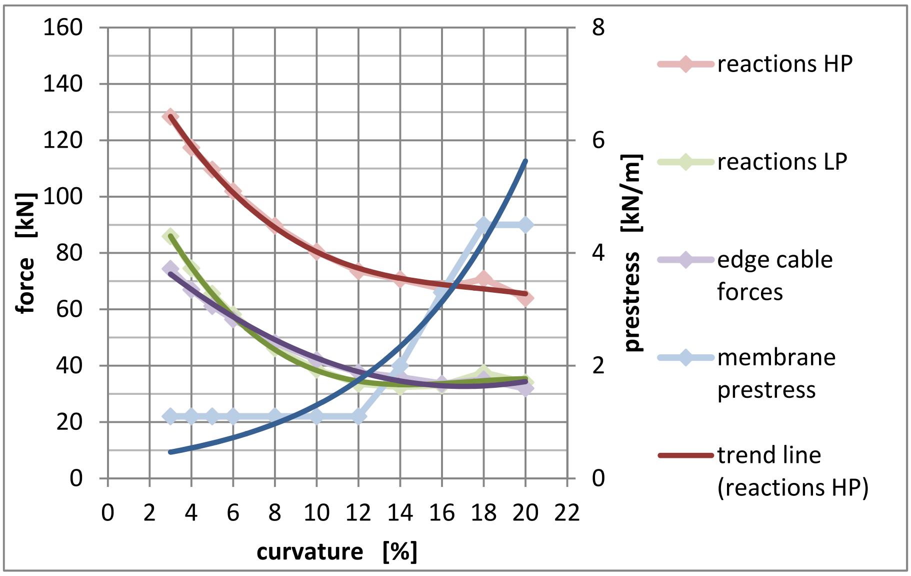

Figure 7. *Study 02 – Overview structural calculations*

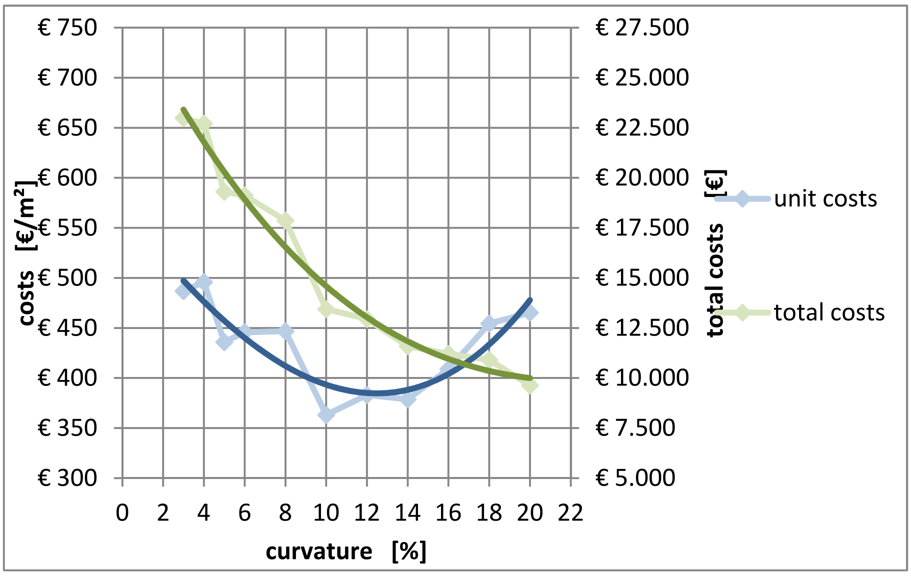

Figure 8. *Study 02 – Cost calculation*

Throughout Study 02 the location of the fixation points remains identical to the base geometry. The most obvious effect of reducing the edge cable curvature is a bigger membrane surface. Furthermore the edge cables become stressed more and consequently the reaction forces increase. Having the same membrane curvature in all models, bigger arch rises at the borders reduce the membrane stresses. As a result the sail requires higher pretensioning the more the edges are curved.

The variation of the edge cable geometry has a major impact on the development of the covered and the membrane surface area. While the progression is almost linear over the whole range, the membrane surface of the biggest sail measures 2.3 times the smallest.

Looking at the data of the structural calculations (Figure 7) the progression of the forces eases at a curvature of about 12 percent and does not vary much until 20 percent. Although the total costs grow from high going to lower edge curvature (caused by higher reactions forces), the development of the unit costs is misleading (Figure 8). Dividing the costs (having a polynomial progression) by the surface area (almost linear development) results in a U-shaped graph. First the unit costs follow the total costs but at 12 percent curvature the chart comes to a turning point. From this point on the unit costs grow again. The reason is the membrane surface decreasing faster than the costs.

In reality this situation is more of a theoretical kind. The roof geometries of the last models (with strong curved edges) do not seem reasonable from an architectural, practical, and economical point of view. In reality strong curved edge cables will be used for architectural reasons or if local stress reduction is required.

5 Study 03

The following diagram indicates the progression of the strut forces (*blue graph*) respectively the forces in the guy cables (*red graph*) and as a result the required size of concrete foundations (*green graph*).

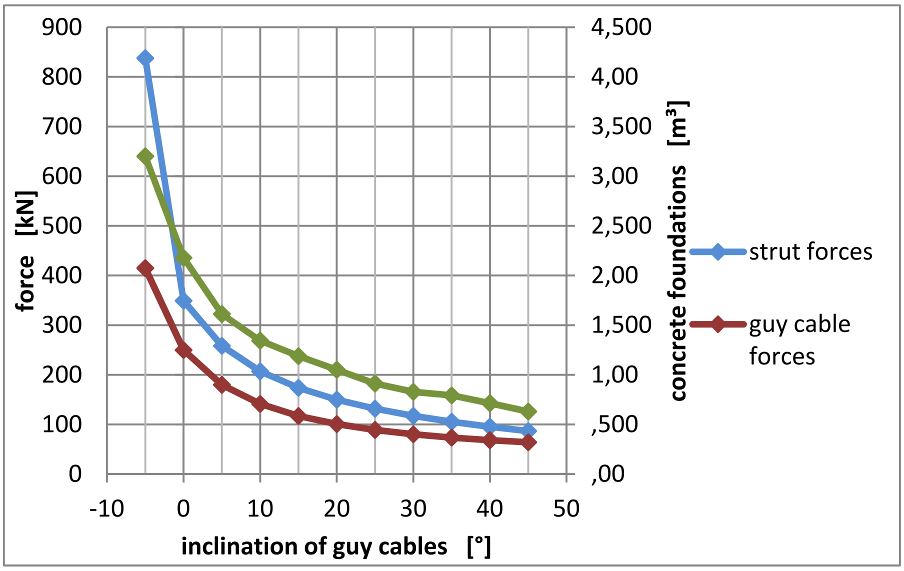

Figure 9. *Study 03 – Overview structural calculations*

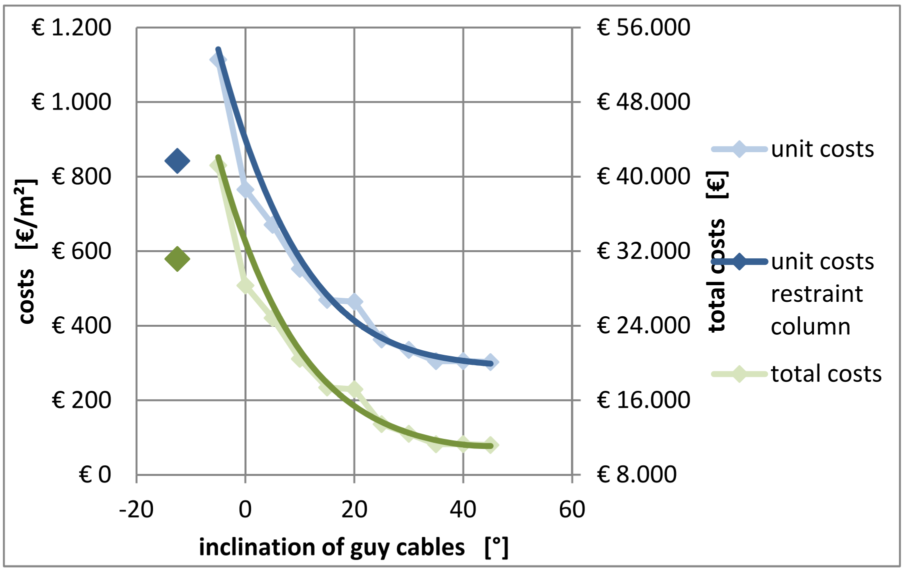

Figure 10. *Study 03 – Cost calculation*

As only the strut and guy cables were considered in this study, Figure 9 only shows the progression of the reaction forces and the corresponding size of the block foundations. The strut is constantly inclined at 12.5°. Therefore the angle between the strut and the guy cables varies from 7.5° to 57.5°. As expected, the smaller the angle, the higher become the reaction forces of guys and struts. In the range from 57.5° to 37.5° the forces develop almost linear. While the investigated inclinations augment in steps of 5°, in this range the internal forces grow by about 10 percent from model to model. From 37.5° up to 7.5° the augmentation is more exponential. The size of the block foundations evolves accordingly.

The effect of a variation of the enclosed angle between guy cables and struts is best seen when related to the costs (Figure 10). The visualization shows a development according to the progression of the forces. The single points on the left give the derived values for a support solution with restraint columns. It is interesting that the costs of sails with very narrow strut-cable-arrangements top the ones of restraint column solution. In this case architectural reasons may still be controlling. At an enclosed angle of 7.5° the required steel profile is a CHS 168.3/6 (buckling stresses authoritative) while the restraint column has to be a CHS 406.4/12 (bending stresses authoritative). As explained in the presumptions the more disadvantageous high point (h = 4m) was dimensioned and taken for all fixation points. The conclusion is that restraint columns are only reasonable up to a certain column length.

The costs certainly mirror the progression of the forces.

6 Perspective / Outlook

The idea for the topic of this study is based on the fact that there are plenty of different cost estimation (software) tools for conventional rigid structures on the market. All of them needed a certain degree of detailing for more or less reasonable results. Yet, there is no such tool for form-active structures. Some design guides give advice regarding geometry and detailing based on research and on practical experience. Only the relation to the costs is not discussed in any of those.

As mentioned in the introduction it is valuable to know about the efficiency of a structure (regarding the load transfer). However in reality the costs are the most authoritative *design parameter*. Very often architecture is driven by the available budget. Maximization of profits usually is the main aim. Concerning textile architecture aiming for a cheap solution may not be an issue. Deciding for a membrane roof already implies, an architectural solution is desired for the intended purpose, meaning tensile structures are usually not the cheapest one. Anyhow, regarding sustainable design a meaningful utilization of resources is to aspire at all times.

This study should lay the basis for a series of investigations and studies on design parameters and how the optimum costs can be achieved by considerate amendments. The intention is to extend this research to other types of geometries as well as to other stages of the project. This thesis even leaves space for further investigations on the four-point sail. Additional fixation points, rigid edges, use of other materials and products, or special design elements (like loops) are additional design parameters and their effects can be interesting for everyone involved in membrane design.

The idea is to collect data and to publish the results in a *real* design guide. In schools design is often seen as a combination of appearance and function of a product. Reality shows that the commercial aspects, costs and return on investment, are at least as important. This design guide should focus on all of these aspects. *The wheel will not be invented anew* but established knowledge will be extended by and associated with new aspects in design.

Furthermore the data gained should be used in a software tool that gives designers an instant cost estimation of the current design. An interactive tool integrated into a design-software for form-active structures, such as the *Formfinder*, would allow for a significant simplification of the calculation process. Reduced complexity increases the understanding of the cost-driving parameters. A first version of this software tool which is not released yet visualizes these cost factors and can support designers to keep their own design by providing a set of positive arguments to convince decision makers of the design intention and the design concept.

We believe, comprehensive research on this topic can make a major difference. If more and more people involved in membrane design understand the complex relation between design and costs, the number of realized projects will increase significantly. Eventually this could encourage the whole industry and make membrane architecture more common.

References

[1] GIRALDO, M., *Design Parameters of Membrane Structures and their Influence on the Costs*, master’s thesis, TU Vienna, Vienna, 2012.

[2] FORSTER, B., MOLLAERT, M. (eds.), *European Design Guide for Tensile Surface Structures*, TensiNet, Brussels, 2004.