MEng Membrane Lightweight Structure

HYBRID STATICS

Advantages of Hybrid Versus Separate Structural Calculation in Lightweight Structures Engineering

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Vienna, 14 August 2019

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Affidavit

I, **ANDREAS MICHAEL BAUMANN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "HYBRID STATICS - ADVANTAGES OF HYBRID VERSUS SEPARATE STRUCTURAL CALCULATION IN LIGHTWEIGHT STRUCTURES ENGINEERING", 212 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 14.08.2019

Signature

Acknowledgements

First of all I would like to thank Dieter Ströbel from Technet. When I met him once, he gave me a flyer of the Master's Degree Program Membrane Lightweight Structures at the Vienna University of Technology. Immediately I decided on this study because I somehow waited for exactly such an opportunity without being actually aware of it. From the very beginning of my professional life I have been absolutely captivated by the slenderness, beauty and grace of lightweight structures, which may not be so common for a structural engineer. I have realised the unique opportunity to deepen and extend my knowledges in this field in order to have better opportunities and to develop myself further in lightweight construction.

I would like to thank the initiators of the course and the Vienna University of Technology for the organisation and for the good training and advice, as well as for having been given the opportunity to establish great contacts in this field.

All my gratitude to the excellent lecturers who gave us deep insight into their experiences and knowledge and supporting us in acquiring the necessary basics and applying the skills in a practice-oriented manner. In person I would like to thank Julian Lienhard, who for me was most helpful due to his very profound and excellent engineering background, his knowledge and skills, since the engineering part is my profession as well.

I thank Frei Otto for his life's work. Without him, the lightweight world would not be where it is today, and we in this field would not do what we do today. Jürgen Hennicke, who worked with Frei Otto all his life, gave us so much insight into projects and developments of decades. I thank you for your inspiration also when talking about Frei Otto. It felt so close as if it came from himself. In Jürgen, Frei Otto established a person keeping his work, mentality and passion alive. Hence, Jürgen passes on his knowledge, experience and passion to the next generation.

Many thanks to Gerry D'Anza, who kindly allowed me to use in this thesis the projects of the festival tents on which we worked together in a design phase.

Last but not least, all my gratitude to the fellow students coming from all over the world, from Mexico to Hong Kong respectively South Africa. For me it felt like a close circle of friends from the very beginning. We have spent so much fantastic time together, have cooperated excellently, have helped each other fabulously and will continue to do so in the future. That will remain. This experience gave me the conviction that all cultures of the world can be on good terms with each other. The only thing needed is the will, the respect and the open-mindedness towards all. So let us all keep open-minded. "*It is more difficult to crack a prejudice than an atom.*" (Albert Einstein)

Abstract

Lightweight structures as they are today not only need good inspiration, but also good engineering using sophisticated technologies. This thesis should give an insight into the differences that arise when calculating lightweight structures hybrid in holistic models on one hand or separate on the other. In the best case, this work allows the reader to develop a sense of what the differences are between the two opposing approaches when working on a particular project. It certainly cannot feel as good as collecting own experiences when making personal comparisons in special cases, but it should give an overview. Evaluations, graphs and visualisations provide insight into what it means to pursue the one way or the other, where the possibilities are, but also the risks that may arise. Basic principles are presented and the topic is examined in practice on the basis of a specific practical project. A feeling should be delivered to the reader for when the consequences of the design of a structure is not that immense when calculating conventional, and when hybrid calculation is essential.

In the context of this thesis by hybrid is meant having a structure consisting of different types of structural behaviour. In this case, on one hand having lightweight components such as membranes, meshes, cushions, cable nets, etc., which can only take tensile forces, and on the other hand a supporting structure which can take further internal forces like compression and bending. Calculating separate means that lightweight components like membranes are calculated stand-alone in one model without the supporting structure. Afterwards the support forces from the lightweight calculation model are – better or worse – applied to the model of the pure supporting structure, dimensioning this then. In the hybrid approach the overall model is calculated and dimensioned in one holistic model.

Since the possibilities of hybrid calculation given today with the software available on the market, hybrid calculation has already become relatively unproblematic. Nevertheless, very often and not to say mostly according to the authors' experience, the hybrid calculation is not used resulting in a series of bad consequences.

The differences between the two approaches should be considered. What are the engineering implications? What are the cost impacts? What are the safety issues? What impact do the differences have on possible designs when following the one strategy or the other? As this thesis should be less theoretical than practice-oriented, it also examines the impact on companies operating in the market pursuing the different strategies. In particular, the negation of the hybrid approach can be decisive to win or lose projects in the global competitive market.

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1 Introduction

The fascination of lightweight structures coming in their slender, graceful and aerial appearance captures the attention of the spectators since their first implementation. The modern, computer-aided era brings more and more possibilities, creating fabulous, lightweight and eye-catching structures enabling the achievement of designs that even surpass what was able to be built only a short time ago. Forms, creations, entities are possible that have recently been no more than a dream.

Unfortunately, the possibilities offered are often not fully exploited. It is not fully made use of what modern computational methods can achieve. One of these possibilities, which are often not used yet according to the experience of the author is the hybrid calculation of lightweight structures. By hybrid calculation in this context is meant the structural calculation of complete structures in one model, structures that consist of parts of different load-carrying behaviour which affect each other.

The meaning of the term hybrid in construction can be interpreted in different ways. Martin Bechthold defines two of the most important meanings in the context of lightweight structures. As one of those he mentions lightweight structure elements together with conventional ones: *"Hybrid approaches (…) Many are simply curved envelope forms with only secondary structural functions, while primary frameworks on the inside deal with all structural loads."* (Bechthold, 2008). The classification "only secondary structural functions" needs to be handled carefully, since there are mostly effects on the primary structural components, more or less depending on the structural system. Membranes today are often an essential part, a key component of a structure. An example is the Amphitheatre Bilkent University in Ankara, Turkey (Figure 20; Figure 21). In this project, main load-carrying arched trusses are carrying the wide-spanning membranes in-between. Those membranes are a clear integral part of the structural system, not only a cladding as secondary construction components.

The other meaning refers more to a component or a complete structure as a whole, which in its overall load-carrying behaviour lies somewhere between lightweight structures and conventional ones. Bechthold states about these:

> *"Hybrid systems are surfaces or grids that are curved and even doubly curved, obviously structural, yet do not feature the efficiency one would expect from a rigid shell. If curvatures are very modest compared to the span, there are usually significant bending moments that need to be addressed. (…) An example (…) Island City Central Park GRIN GRIN, (…) the concrete roof with its swooping curves is too gently curved for*

membrane action to dominate. (...) the system is a hybrid between a shell and a slab in bending." (Bechthold, 2008: 14)

Figure 1: Grin Grin Park, Island City Fukuoka, Japan (website architecturerevived.com)[1]

Another structure of this type is the roof of Jewel Changi Airport, Singapore. Here, the author was the structural engineer during sales and also for the execution engineering for the executing company, so he knows the structural behaviour in detail.

Figure 2: Jewel Changi Airport, Singapore – Rendering (website www.straitstimes.com)[2]

[1] http://www.architecturerevived.com/grin-grin-park-island-city-fukuoka-japan – retrieved on 24 February 2018

[2] https://www.straitstimes.com/opinion/bold-steps-needed-for-spores-aviation-sector-to-keep-flying-high – retrieved on 26 May 2018

The structural system of Jewel consists of conventional rectangular hollow sections in a triangular grid comprised of rings (Hoops) and diagonals (Bias) in both directions.

Figure 3: Jewel Changi Airport, Singapore – Physical model (website www.twitter.com)[3]

At the perimeter, the roof structure is primarily supported by the building structure of level 5 and at its apex by columns. No further supports at the inner oculus opening with its 40 m high waterfall. The inner part of the roof construction evolves a significant lightweight structural behaviour, although it is anything but light. The components used are capable of transferring all internal forces and not only axial forces. Roughly at the column location at the apex the roof structure – simplified described – establishes a compression ring and roughly in the middle between this compression ring at the apex and the oculus a tension ring. The diagonal members also predominantly receive axial forces. Thus, the structural behaviour of the described is to a high degree the one of a lightweight structure. At all locations there are more or less bending moments, locally enormous, especially where the single-layer shell is supported by the columns, but the author clearly classifies the structural behaviour as somewhere between a tensile structure and a conventional one. The part of the roof between columns and perimeter is also of hybrid load-carrying nature. This part of the roof evolves to a high degree the structural response of a gridshell on the one hand and a conventional one with characteristic bending moments on the other side.

A third type of hybrid should also be mentioned. This consists of different types of lightweight structures, as is the case in many tensairities. These usually combine air beams, cables or belts and sometimes also compression elements, all of axial forces load-carrying nature.

[3] https://twitter.com/henrywoona10/status/541432532030349312 – retrieved on 26 May 2018

This paper deals with the first type of hybrid structures. Structures consisting of two different types of structural behaviour. One of real tensile structure and a supporting one of conventional nature, able to deal with all internal forces. Both interact and thus form the hybrid system. The other types of hybrid structures should not be part of this work.

In the following, the lightweight part of a structure is simplified called membrane unless of special importance and stated otherwise. This could also be a mesh, a cable net, a cushion or the like.

The main topic of this thesis is the investigation of the differences resulting from the two opposing methods of hybrid and separate calculation. The core of this work is the >Potential of Optimisation of Hybrid Against Separate Calculation<, so the original title of this thesis. In the course of the work, other aspects such as safety, optical appearance and others were also included, and the final title was chosen. Nevertheless, the core subject remains the optimisation potential of the hybrid or vice versa the degree of unnecessary over-dimensioning of the separate calculation, since the author sees this as perhaps the main task in his profession as a structural engineer for an executing company. Safety should not be classified as less important, as this is always above everything and not discussable. On the contrary, safety is another strong argument for the hybrid approach, which is also pointed out.

1.1 Motivation

This work was motivated to a high extent by the experience of the author being so often dissatisfied with the experienced attitude in the industry still not using the possibilities satisfactorily and developing them further, not exploiting the possible by using the available tools and exploring new pathways and thus finding solutions that are feasible hybrid but not achievable by means of separate calculation. The author even experienced to his deepest dissatisfaction companies owning a software capable of calculating hybrid used it solely for patterning, hence, structurally calculated separate renouncing the use of the hybrid-capable software. To explore and demonstrate the implications of abandoning the possibility of calculating lightweight components together with their supporting conventional structure hybrid is the main motivation of this work. Besides this, it is also the highest motivation of the author to build slender and aerial on one hand, and also cost-effective and competitive on the other. The reader should be given an insight and some feeling for the issue of hybrid versus separate calculation of a project. And it should present the reader some insight and examples, how to investigate the effect to find the differences for a particular project and what could be achieved when switching to hybrid calculation.

1.2 The Issue

The core topic to be investigated in detail here is how this special type of hybrid structures, such as membranes supported by a conventional structure, interact under load as they both form part of the whole system. When, for example, a membrane field of a structure is loaded and the supporting structure to which it is attached deforms, then this deformation usually has a positive statical effect in terms of an increase in the sag of the membrane and thus a decrease of its internal forces. Among other reasons, due to this effect the membrane and the supporting structure are strained less caused by the reduction of the tensile forces as a result of the deflections. If this effect is not covered by the structural model, the membrane and the supporting structure are mostly over-dimensioned. An over-dimensioning exemplarily results in:

- More massive, less slender components, spoiling the lightweight character and the attraction of an architecture
- Higher costs than necessary
- Additional members required by the need of reinforcing the structural system, exemplarily by additional members required to make the separate model of the substructure work statically. Those additional members increase the costs and reduce the attractiveness of a structure further
- Reduction of the chance for a company to win a project in a tender

However, the mentioned effect of the change of shape under load and the resulting force change can also be unfavourable, which can lead to damage and, in the worst case, endanger human life. This is the case, for example, when membranes span between trusses. Membranes of the same type but of different size, speaking of the structural span (for visualization refer to e.g. Figure 27). A positive effect of the deflecting trusses is there for a wide-spanning membrane due to the increase of its sag caused by an inwards deflection of the arches under load. However, this deflection has a negative effect on a neighbouring, less wide-spanning membrane, as the sag of this decreases, leading to higher forces. Therefore, a separate calculation will result in membrane forces being too high for the wide-spanning membranes but too small for the less wide-spanning and thus leading to an under-dimensioning. The same effect occurs for example with edge cables and their connections. Therefore, the separate calculation is very often also a safety issue.

Not part of this thesis, but mentioned briefly, should be other accompanying aspects important for an adequate hybrid structural engineering such as load application, especially complex wind loading. This is also a very crucial issue particularly for lightweight structures, as due to their complex shapes, wind load determination is even more complicated than with conventional, less complex architectures. In the lightweight construction industry, wind tunnel studies are often not carried out because they are considered too cost-intensive or due to tight schedules. Subsequently, another culprit of over-dimensioning is identified here. A very good and modern wind load determination approach, when wind tunnel studies are not carried out, is also located in the computational field, the CFD[4] calculation for wind load determination per computational simulations. CFD is another promising approach that can help hybrid statics calculate accurately, avoid over-dimensioning, build slender, be cost-effective and keep a company competitive. At best, the results of the CFD wind load calculation are directly transferred electronically to the structural system via an interface in order to not only precisely determine the loads, but also to be able to make very precise use of these advantages in structural engineering. More about CFD is discussed in Section 7 Conclusion and Perspective.

Also not part of this work should be the investigation of the influence of important topics such as the accuracy of load application and the influence of divergences. Such investigations could be carried out in the same way as the comparative calculations in this document. This topic is also a very important point with regard to accurate engineering and the avoidance of over-dimensioning, but should be the subject of other studies. The best possible load application, especially in the case of complicated wind loads on complex shaped lightweight structures, is achieved by electronic data transfer from a wind tunnel study or a CFD calculation to the structural model. Especially for smaller projects the wind load application is very rough and follows standardised types as specified in codes or papers like the European Design Guide for Tensile Surface Structures [4]. This is acceptable in many cases, but often results in further over-dimensioning or even incorrect calculations and defects.

Furthermore, not part of this thesis should be the different mathematical methods in computational modelling, form-finding and calculation of lightweight structures such as the Dynamic Relaxation Method, Updated Reference Strategy (URS) or the Force Density Method. Investigations of and comparisons between these methods or even a comparison between the programs of the different software manufacturers following the different approaches should be the subject of other works.

[4] CFD = Computational Fluid Dynamics

1.3 Research Problems

One problem in the course of this thesis was that very little documented research on this particular topic is available. Despite the fact that the branch is well aware of this issue and that the effects are often mentioned and discussed, real research of this nature is very limited.

Especially software manufacturers in this field sometimes mention comparative figures, but do not go into further details when it comes to providing comprehensible evidence or examples for such investigations or even figures. It is rather a whispering behind the scenes, which cites figures of cost savings or optimisation potentials "from x% to xx%".

Another difficulty in the course of this work was that it is impossible to offer the user a turnkey solution, a manual. The problem is too multifaceted and complex considering all possible structures, their boundary conditions and load-carrying behaviours. Each structure is different and requires its own engineering investigations. Master solutions that are easy to use in a specific project are simply not possible in non-standard structures.

1.4 Objective

The aim of this thesis is to give the reader an introduction to the impact of the decision to calculate either separate or hybrid. The objective was to provide a sense of what this means, if it is worth or even crucial calculating hybrid and when it may be acceptable to remain conventional and thus to evaluate how big the impact is in terms of optics, costs, possibilities and risks. Since many in the construction industry underestimate the impact, the examples and their comparisons should establish a strong and ever-present awareness of the issue through remarkable and impressive results.

1.5 Structure of the Thesis

This master thesis is structured in the following sections:

- Chapter 1 gives an introduction. It includes the motivation of the author, the definition of the research subject, the problems encountered and the goal to be achieved.

- Chapter 2 illustrates the state-of-the-art in this topic. It provides literature references and shows how the topic of this paper is dealt with in the industry today.
- Chapter 3 handles the methodical approach of the investigations and describes the procedure of investigations conducted in Chapter 5.
- Chapter 4 presents general influencing factors, describes the degree of influence between the two approaches depending on the boundary conditions, presents exemplary outcomes to which the respective procedure may lead and discusses topics such as the philosophy "on the safe side" or the requirements of Theory Third Order.
- Chapter 5 introduces the basic principle of this topic, fundamental examples and the practical project of >The Sea Star< and lists the boundary conditions so that the examples are comprehensible by listing dimensions, material properties, loads, boundary conditions and the like of the examples investigated.
- Chapter 6 summarises the results of the investigations. The findings are discussed.
- Chapter 7 finally presents the conclusions of the investigations and discussions. It shows the perspectives seen in this field together with the developments, opportunities, future possibilities of emerging technologies and the accompanying arising inspirations.

2 State-of-the-Art

As already mentioned in Section 1.3 very little documented material of research is available on the subject of this paper. For reasons of integrity and seriousness, numbers of possible optimisations only heard as rumours or guesses are not mentioned.

A few researches in this field have been found, although most of them have only a marginal relation to the core issue. Others contain only a few numbers.

2.1 Literature Review

Holger Alpermann and Christoph Gengnagel from the University of the Arts Berlin presented the research of a special hybrid structure on the Structural Membranes 2011. The topic of their lecture was "Membrane restrained columns" [1]. The presentation showed how membranes as structural elements that connect and stabilise three-chord curved columns can increase the compression capacity of the hybrid.

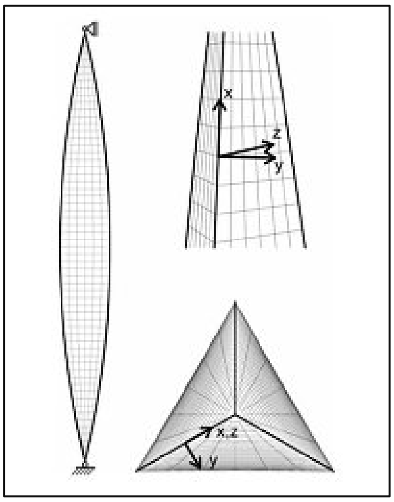


Figure 4: Three-chord column with membrane reinforcement ([1])

This composite column-membrane hybrid structure is a development of a structural component that is certainly much stronger than the three-chord column without stabilising elements connecting them. But due to its character in developing a new kind of structural compression element and less in investigating differences in calculation procedures, it should not be considered more in detail here. For such a type of compression component it is not really useful to compare separate and hybrid calculation, as normally one would not build such an element without the stabilising membranes or other interconnecting elements.

During the studies at the Vienna University of Technology, the software company Technet presented an example comparing separate and hybrid calculations. The project named "Galets Swiss Expo" is located in Neuchâtel, Switzerland. In this example, a large cushion is installed in a circular structural frame. Technet calculated this example separate and with their software EASY hybrid. The reduction of deflections by hybrid calculation, also taking into account the gas volume of the cushion according to the gas laws, was 50% and the maximum bending moment 40%, as shown in Figure 6.

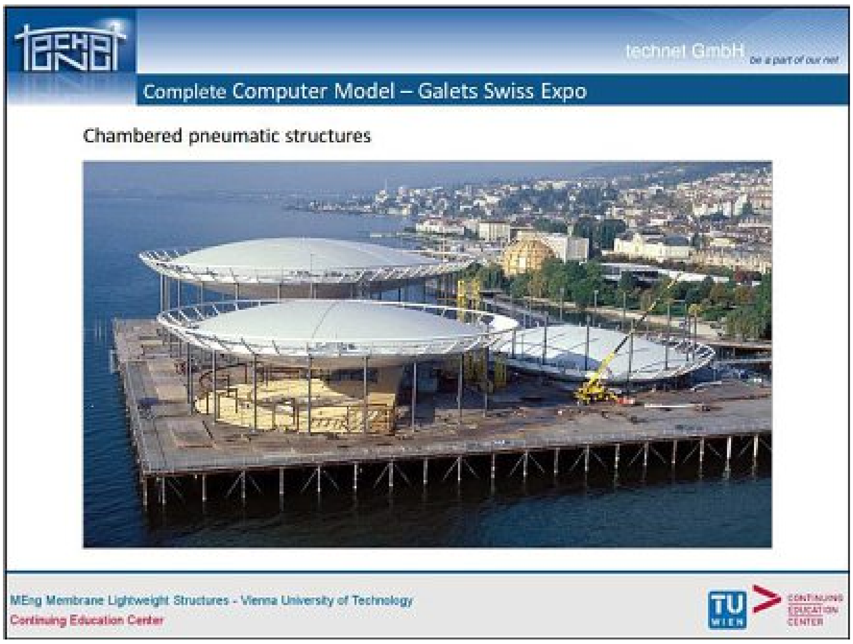


Figure 5: Galets Swiss Expo (Technet GmbH – Course material TU Vienna)

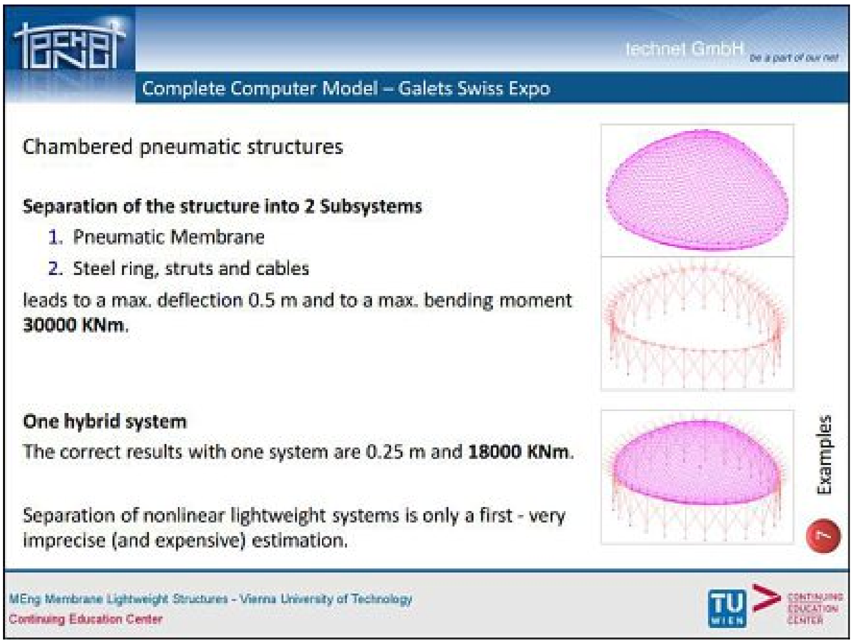


Figure 6: Galets Swiss Expo – Results separate/hybrid (Technet GmbH – Course material TU Vienna)

2.2 Available Equipment

Modern software technologies already offer great possibilities to realise very lightweight, slender and cost-effective structures by using membranes as an integral part of the structural load-carrying system. Exemplarily wide-spanning arches together with membranes in-between allow huge, slender and cost-effective structures. A construction of this kind is a hybrid in primary structural sense. The membranes carry the loads they receive and furthermore stabilise the wide-spanning arches These can be built much more slender and without additional components, which would require separate calculations. A project of this kind is the roof over the Chemical Research Centre in Venafro, Italy in Section 4.4.

With the current computational possibilities, the necessary high-performance hardware available together with sophisticated software solutions, structures can be calculated hybrid efficiently. The previously so-called lightweight/conventional hybrid system can be calculated and dimensioned slender. There are several software solutions on the market that can deal with such systems and even more. Further information on this can be found in Chapter 7 Conclusion and Perspective.

2.3 The Different Attitudes of the Users Today

Sadly, many in the market still do not use the possibilities of software solutions capable of calculating structural models hybrid. According to the experience of the author, many even have the possibilities to do so, have such software, but only use it for patterning, not for hybrid statics. One reason for this may be that people are often reluctant to change and want to stay in the familiar workflows. Or it is the lack of time or opportunity to learn new technologies and tools.

Others, using the new technologies, have clear advantages in terms of competitiveness. And not just for that, but also in terms of issues like safety in construction.

2.4 Procedures Used Today

This chapter outlines the most frequently used workflows of today. There are certainly variations and sub-types between these. The order of the following list is descending, from the most accurate to the least. The list may not be complete, there may already be further ones or surely will evolve in the future.

2.4.1 Hybrid Calculation; Load Application per Wind Tunnel Study or CFD; Electronic Load Transfer

The most accurate method nowadays is to build and calculate a model of hybrid characteristics, consisting of interacting structural components with different load-carrying behaviour, in a hybrid-capable software and dimension everything accordingly. The wind load is determined by CFD calculation and the resulting loads are transferred via interface to the structural analysis software in order to achieve the most accurate load application possible. More about CFD can be found in following chapters.

When following this procedure, it is fulfilled respectively achievable:

- the interactions of membrane and supporting structure are covered
- the rule to model a structure as accurately as possible is complied
- to calculate structures of high deflection according to Th. III. O. is followed
- most cost-effective project realisations are achievable
- aerial and slender structures are the outcome
- reduction of the risk of damage and risk to human life
- highest degree of sustainability and eco-friendliness

A variation of this method is the coupling of a wind tunnel study using a large number of pressure sensors with an electronic transfer of the wind load results to the structural model. It is even more precise when details like connections within the structure and support details are also included in the overall system to reflect the true conditions of such influencing factors. Factors like these can and often do have a significant impact on the results. One of these important influencing boundary conditions is the spring stiffness of supports.

This procedure is considered to be the most accurate of today, as Section 7 gives an outlook on the development of technologies and what may be possible in the future, which by far will surpass the accuracy and possibilities of today.

2.4.2 Hybrid Calculation; Manual Load Application

Wind load results from a wind tunnel study are available for this procedure. Alternatively, CFD wind load results are given and accepted by the approval authority, which is still often not the case nowadays. Even if CFD is not accepted for construction, a bidder's engineer can use CFD calculations to be less conservative and more competitive in the bidding process.

When the load application in the structural model is done very detailed, using many wind zones and being very accurate, e.g. using background layers of wind load zone images in the static software enabling the zones to be transferred very accurately, then a very close accuracy compared to the dimensioning in hybrid calculation with load application via electronic interface is possible. If CFD is not accepted, then the wind tunnel study together with this procedure is the most accurate and one which is always approved today.

A division of these two methods, loads from a CFD calculation or a wind tunnel study, should be avoided here, as it is not possible to say for certain which would be more accurate in which case. Furthermore, it should also be pointed out that CFD should be handled very carefully. Without being very experienced and skilled and having the opportunity to adequately verify the results of a CFD calculation in order to ensure the accuracy of the results, this should not be pursued as this matter is very complex and the results of CFD simulations can easily be far from reality. The results that a computer delivers is only as good as the user operating the computer, especially on such a complex matter.

2.4.3 Separate Calculation; Electronic Transfer of Forces between the Models

The next less accurate method is to calculate the membranes separate and then transfer their loads electronically to the model of the supporting structure by using tools. This method offers at least the advantage that the load with which the membrane strains the structure is applied much more accurately than with rough manual load application (Section 2.4.4). When having to follow this procedure, the structural engineer has the possibility to add some surcharge in order to be sure about the final calculation. As a result, in most cases an over-dimensioning will be the outcome. Experienced engineers may reduce this over-dimensioning by covering the effects of positive hybrid interactions according to experience. A further discussion about the strategy of giving some surcharge to be safe is conducted in Section 4.5 “On the Safe Side”.

The negative aspect of this procedure is that the interaction between the parts of the structure is no longer covered. In best case, spring stiffnesses are taken into account for the separated components. However, this can only be a rough approximation and far from being as accurate as a hybrid calculation.

2.4.4 Separate Calculation; Manual Transfer of Forces between the Models

Today, a common practice is to calculate membranes separate in one model, often in another software, which is usually a complex and time-consuming finite element software. The edges are defined fix and the very complex support forces are applied in a simplified manner to the structural model of the supporting structure.

A high degree of complexity, even regardless the interaction with a deflecting substructure, is the nature of membrane support forces. Figure 7, taken from a separate finite element calculation of a simplified cushion shows the complexity of the support forces. This figure shows only the global z-directional (T3) support forces of a trapezoidal cushion with the three short sides flat in one plane and its long side forming an arch out of plane in z-direction. The forces in this picture are only one of three components. Of similar complexity are the x- and y-directional forces. This example points out a further problem. Such calculations are often carried out not following another hybrid calculation topic, the inclusion of the gas laws in cushion structural calculations. Section 5.2.3 goes deeper into this topic.

It is not only very time-consuming and complex to apply such support forces to the model of the substructure, especially when there are many complex components like the cushion below. It also seems clear that it is simply impossible to apply such loads manually in an adequate manner and dimension everything properly. Load application much “on the safe side” (more on this term in Section 4.5) is very likely.

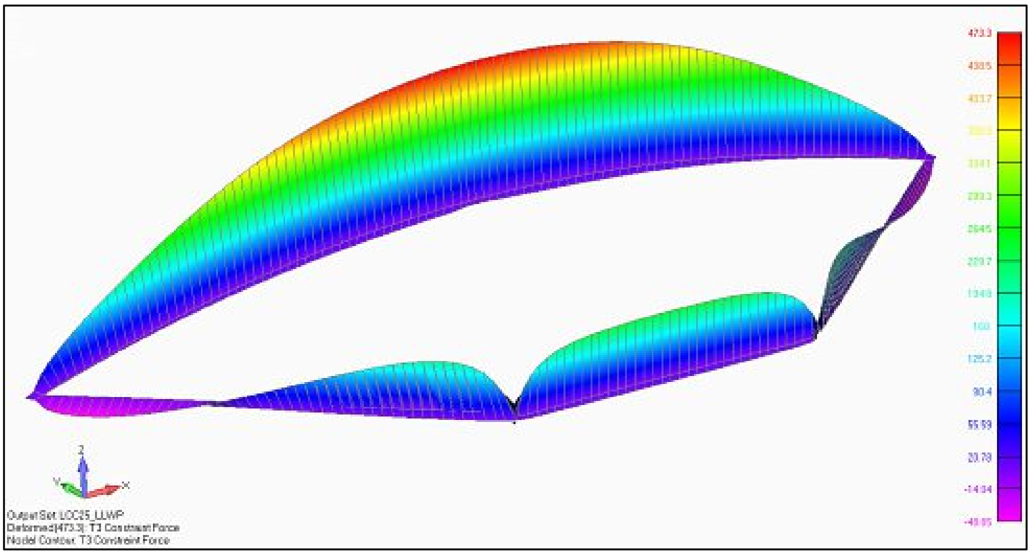


Figure 7: T3 (z-directional) support forces of a trapezoid cushion,
FEMAP for NX Nastran (by author)

Figure 8 is another example depicting the local x-, y- and z-directional support forces of one membrane at one component in one load case of the presented practical project >The Sea Star<. Figure 9 shows the load application of one support force in one direction on one component in one load case in the STR model of >The Sea Star<. It should be clear that simplified load applications by hand are most likely far from reaching an acceptable level of accuracy. Sadly, this is often practiced in the industry.

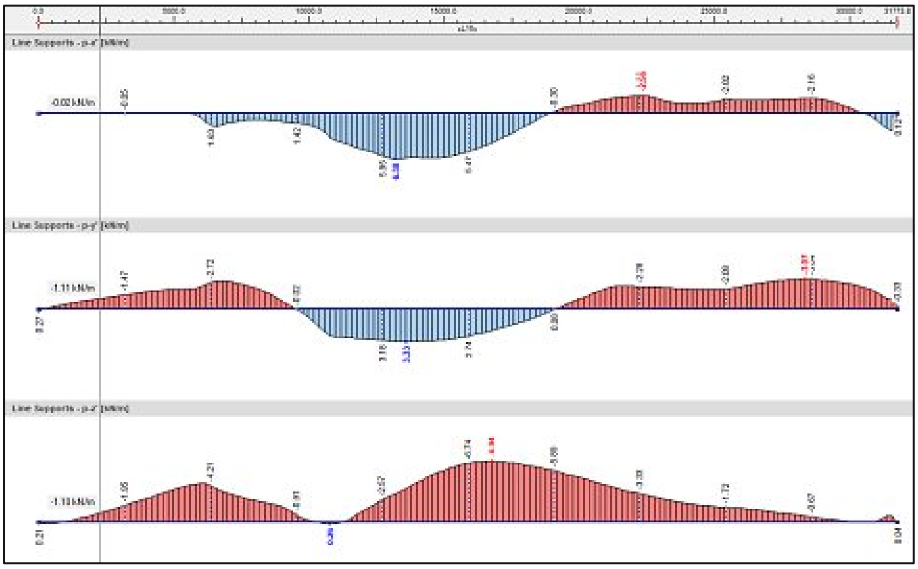


Figure 8: Local x-, y- and z-directional support forces of one membrane at one exemplary member in one wind load case of the project >The Sea Star< separate model MEM (by author)

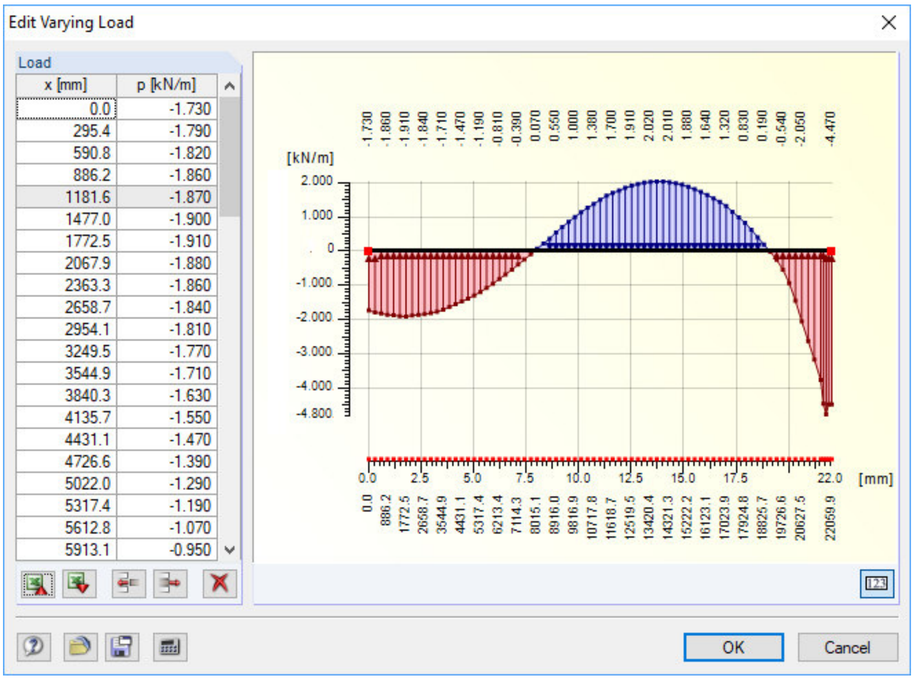


Figure 9: Exemplary applied load in project >The Sea Star< separate model STR – for visualization of the impossibility to simplified apply loads by hand (by author)

2.4.5 Separate Calculation; Membrane Forces Determined and Applied Roughly by Hand

It is even much less accurate when the membrane forces are not even calculated in a separate model, but roughly determined by hand and applied very improperly to the structural model, which is most likely far from any realistic outcome. For many conventional engineers not having had much contact with lightweight structures before this may seem accurate enough. As this understanding clearly underestimates the topic of tensile forces of non-conventional components and due to the unacceptable working process, this should not be discussed more in detail. Worst thing is that this practice is often used in the industry. Some further argumentations in this direction can be found in the following section.

2.4.6 Not Understanding; Underestimating & Doing Things Wrong

From own experience the author does not consider the following aspects to be highly exceptional, which is why they explicitly should be mentioned here and not considered excludable, as unfortunately they are not.

It happens that conventional engineers who never had any or only little contact with membranes before, immensely underestimate an effect or in worst case even do not know about or forget to apply it. The effect that is mainly meant in this context is the additional component of the load that is induced into the structure by a membrane or cushion compared to conventional cladding such as glass panes or panels. This force is simplified called horizontal component (also refer to Section 5.1 Basic Structural Principle). In reality it is an “in-plane-force”, a tensile force, but for simplification it is called horizontal force in the following. When conventional bending-stiff components like glass cladding are used, such a force component usually does not exist. Only forces perpendicular to the surface under wind and vertical under gravity are induced into the structure by conventional claddings. No further force component exists. However, this does apply for membranes – the effect being immense and often very much underestimated or even neglected. The author had conversations with engineers who did exactly that. They argued it is negligible or simply did not even think about it. This mistake should not happen in constructions where very wide-spanning membranes are installed. When calculating small membranes or ETFE cushions for the first time an engineer may simply see this as one of several types of cladding and does not think about the horizontal force component. To illustrate this component, Figure 10 below shows the support forces of an arched frame with a membrane, which is loaded by a standard downward loading. The horizontal component of the membrane force acting on the arches with its 4.63 kN/m is more than double the vertical component with its 2.01 kN/m. It should be clear that neglecting the higher component would be fatal.

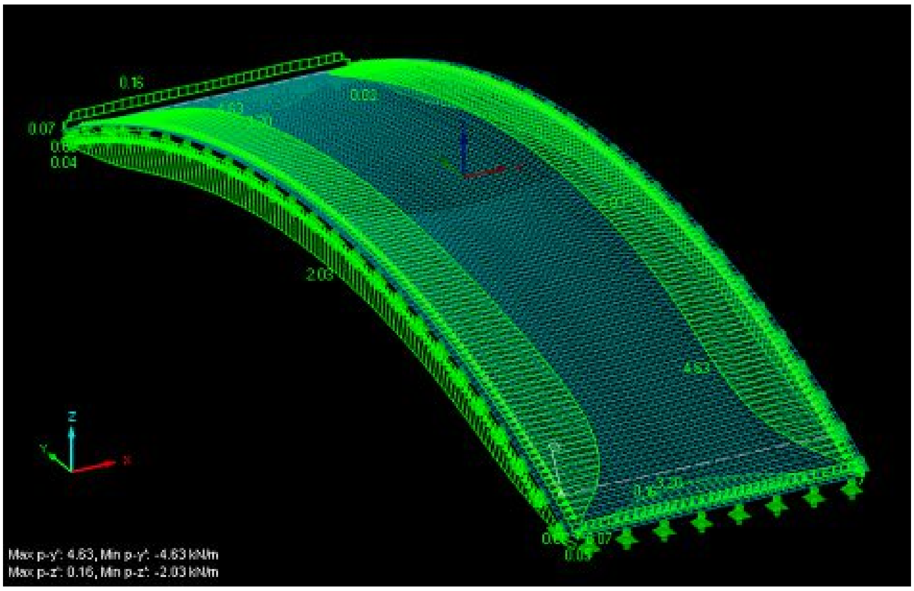


Figure 10: Support forces of an arched membrane – RFEM (by author)

For smaller tensile force components like ETFE cushions, especially structures in which they are installed in a grid such as the Eden Project (refer to Figure 13 and Figure 14), the effect of this horizontal force component is smaller. For the inner members of the substructure it may even be negligible, since the horizontal components of the forces cancel each other out when cushions of the same size and load pull a beam to the opposite direction. If cushion failure is required to be considered, then as in most codes this is to be handled in exceptional load case combinations, often resulting in not being governing for the dimensioning of the members. However, for edge beams this must be considered, as the horizontal force always acts in one direction only. Underestimating or even neglecting without being sure this can be done is of course wrong and can lead to damage and risk to human life.

3 Methodical Approach of the Investigations

As an introduction to the topic of this thesis at first it is described in general terms. Secondly, on the basis of basic systems, the effects of the different calculation methods – hybrid and separate – are presented with regard to the effects on the forces and the dimensioning aspect. Detailed investigations are carried out on the basis of the basic system of a membrane installed in an arched frame. Finally, a practical example will reveal the results of the different approaches with regard to design questions – what is feasible hybrid and what is not possible conventional. The presented project is rated to have a medium to high degree of influence.

3.1 Approach of this Thesis

This work should be practice-oriented and not too theoretical, from the perspective of an engineer in the industry and not a theorist. Software-based tools are the instruments used in this work, as are the tools of engineers in their daily work. No engineer in daily practice deals with integrals or differential equations. The author sees too much of these theoretical works, which some may find fine for universities or research, but in fact are not very useful for engineers in the industry – in the practical world. Too often, the author sees theory-focused engineers and a lack of practical relevance mentality of teaching as one of the main reasons why so many in business are theorists, not professionals. By this statement the author explicitly does not mean the educational institutions he attended. The lack of suitable material available on this important subject is also seen as an evidence for this.

3.2 Working Methods

On the basis of examples, which are calculated the one way and the other, hybrid and separate, it is shown what the differences are for the engineer in the market and what the consequences are in terms of architecture, costs and safety. Especially, when very important issues like competitiveness to win or lose a tender are concerned this may be of decisive relevance for a company.

The importance of accurate load application, especially with regard to the complicated wind load in complex shaped lightweight structures, is discussed in other chapters in more detail. The wind load application in this paper is considered to be well, but not the most precise one. The exact procedure used in the workflow of this paper can be followed in Appendix E.1 in detail.

As this paper aims to investigate the influence of hybrid versus separate calculations isolated, some boundary conditions are not considered since they might also have an influence on the comparisons presented and therefore distort them. Such boundary conditions include, for example, eccentricities of membranes on the substructure due to upstands or other details that cause additional effects. For the realisation of projects, it should certainly always be checked whether all these effects need to be included in the calculation or they are always simply included to be sure.

This work also includes systems that are something like unrealistic practical ones, which are normally not realised this way in practice. For example, a single triangular cushion or a single wide-spanning, bending-stiff frame with a membrane is usually not a realistic project that is really built that way. The aim is to illustrate the very special difference of the separate versus hybrid calculation. Thus, also very simple systems were chosen. A realistic project with its real dimensions, realistic wind loads etc. is shown in the practical project Festival Tents >The Sea Star<.

3.3 Modelling and Preparation

The overall workflow of the examples presented is as follows:

- Modelling of the structural geometry in Rhino
- Import of the centreline model into the structural analysis software RFEM
- Definition of model data like supports, materials, cross-sections, hinges, etc.
- Definition of the various calculation parameters always used for both methods
- Generation and fine-tuning of the lightweight components
- Definition of load cases and load case combinations. Application of the loads (the procedure will be explained later) and the steel dimensioning cases

As from here, this is the identical basic model for both approaches. For the hybrid calculation this is the final model (abbreviation in the following: HY) and the dimensioning can be done hybrid. The separate calculation requires further intermediate steps in which the two separate models are created:

1. Membrane partial model (abbreviation in the following: MEM)
2. Partial model of the substructure (abbreviation in the following: STR)

3.4 Workflow in the Comparative Calculations

The detailed procedure in the presented examples is always as follows:

A. First, the structural hybrid model is built, the loads applied, the form-finding and calculation settings calibrated and everything prepared for the hybrid calculation. The hybrid model HY is then ready for calculation and dimensioning.

B. For the separate calculation, the same model is taken and separated into two:

   1. MEM:
   - a. Removal of the substructure
   - b. Rigid support of the membrane edges
   - c. Calculation and dimensioning
   - d. Export of the support forces to the substructure partial model STR

   2. STR:
   - a. Removal of the membranes and thus the loads
   - b. Import of the support forces from the MEM model, which are always the three member internal forces in local x-, y- and z-direction
   - c. Calculation and dimensioning

C. Comparison of the results of the hybrid calculation with those of the separate. Sometimes the basis of the comparison is one of the following, sometimes both:

   1. Identical cross-sections are used in the models compared

   2. All models are dimensioned according to their specific requirements so that different cross-sections are used in the models compared

This procedure ensures good comparability, as the basis is always the same. The basic model is the same, the dimensions are the same and the loads are identical. And, very important, the load transfer between the separate models is precise, which will be verified later. There are more accurate methods of load application, but the approach used is considered very good for the use in this work. This is approved in practice, but above all due to the fact that the loads applied are identical for the two different calculation methods, which is the most important thing here to ensure comparability.

4 The Influences

This chapter describes the basics, presents and defines the investigations and provides further information.

4.1 Different Kinds of Load-Carrying Behaviour

Regarding the structural aspect, two main types of substructures can be classified to take the tensile forces of the lightweight components. The decision on this type of load-carrying behaviour is very decisive for the achievable slenderness of a structure. A fluent transition between both types or even a mixture is often the case.

1. Load transfer by axial forces – possibility to achieve a slender structure
2. Load transfer by bending – resulting in more massive members

The simplest example to illustrate the two types is the typical hypar structure. For pure axial forces load transfer, it usually consists of six to eight stay cables and two to four struts as pure axial compression components when neglecting secondary bending effects like those resulting out of imperfections. This enables the realisation of a very slender structure.

Figure 11: Typical hypar – Axial forces type – Slender (website www.jjcarter.com)[5]

[5] https://www.jjcarter.com/images/galleryImage/cropped/20160817130828.png – retrieved on 2/ May 2018

The corresponding load transfer by bending is shown in the following example. The membrane tensile forces are taken by bending of the rigid supported columns.

Figure 12: Hypar with four columns under bending (website areatenda.com)[6]

The difference is very clear and should be visualised. The decision for axial-force systems for the substructure result in very slender components. The choice of load transfer by bending requires much more massive structures. In the example in Section 6.2.2 these two types are compared and the required sections visualised in renderings.

4.2 Degree of Influence Depending on the Structural System

The difference between separate and hybrid calculation very much varies depending mainly on the umbrella term of the statical system. This term includes influencing factors such as types of structural components, span, static boundary conditions such as hinged or rigid connections and supports and further.

Little influence is given in many typical cushion projects. Typically is defined here as for the cushion grid in the Eden Project in Cornwall, England (Figure 13 and Figure 14). The domes were realised by a substructure of a two-layer special spare grid spaceframe system with the cushions directly installed on the upper layer components. This upper layer had to be of an adapted structural character as the spaceframe is a system of only axial forces. The upper layer receives the tensile forces of the cushions,

[6] http://areatenda.com/tende-a-vela/ – retrieved on 28 May 2018

which cause bending and torsion in the members. Thus, there must be a system that can transfer these internal forces.

The tensile forces of the cushions only act on the upper layer elements causing bending and torsion. The rest of the structure receives axial forces only, no direct influence of the cushion axial forces on those. Therefore, it was possible to build very slender. Figure 14, a photo taken during installation, visualises the slenderness of the structure.

Figure 13: The Eden Project, Cornwall, England (website www.interactivearchitecture.org)[7]

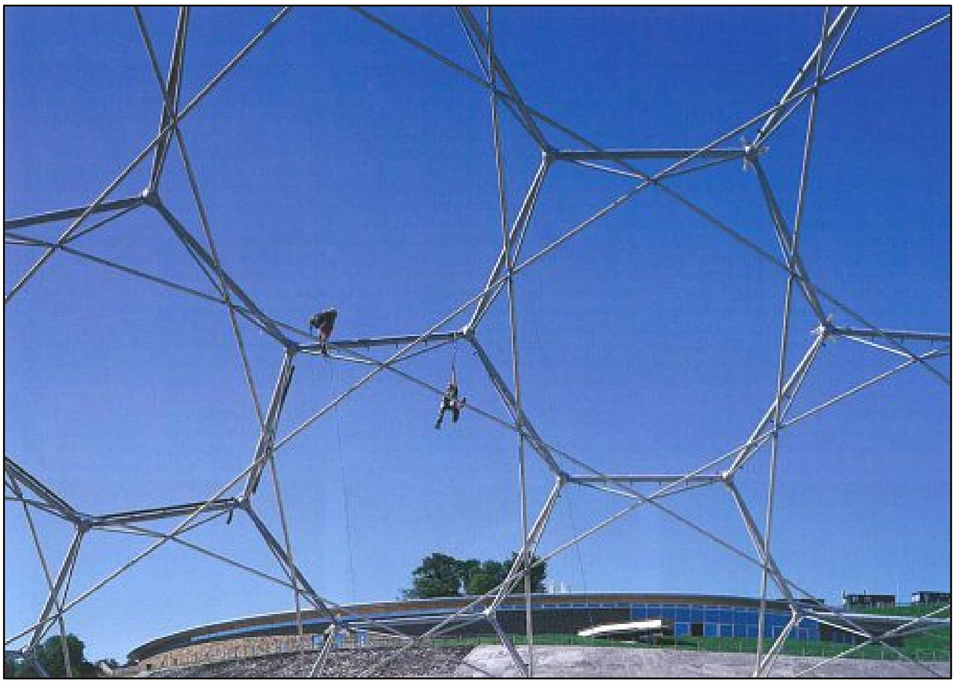


Figure 14: The Eden Project, Cornwall, England – Dimensions and slenderness
(Prospect Architecture Steel – ECCS No. 91-14 – ISBN 92-9147-000-73 – www.steelconstruct.com)

[7] http://www.interactivearchitecture.org/captaincy-of-the-dymaxegrity.html – retrieved on 19 February 2018 – copyright: Jonathan Makepeace/ RIBA Library Photographs Collection

The influence is even lower when the lightweight system is statically uncoupled from the load-carrying substructure. The lightweight components with their secondary frame transfer only vertical (for gravitational loads) respectively perpendicular (for wind) forces to the primary structure. No tensile forces are induced to the primary structure, as is the case with conventional claddings like panels or glass. An example is the Gondwanaland at Leipzig Zoological Garden in Figure 15, also an ETFE cushion project. The inner secondary structure is suspended from the outer primary system. This uncouples the additional tensile forces that lightweight structures cause in comparison to conventional claddings from the primary system.

Figure 15: Gondwanaland, Leipzig Zoological Garden, Germany (website www.structurae.net)[8]

Another possibility to achieve an economic structure by reducing the unfavourable impact of the tensile forces in regard of dimensioning is to induce the forces to the substructure statically as favourable as possible. This was accomplished for the roof of the grandstand of the Sheikh Khalifa Bin Zayed International Stadium in Al Ain in the UAE (Figure 16 and Figure 17). The membranes are installed between arches on their long sides and edge cables on their short sides. The arches are stabilised by cables. Membranes, arches and cables form a kind of secondary structure, but do not completely uncouple the tensile forces from the substructure. All forces are directly induced to the nodes of the spaceframe. This is the best way to achieve a slender and economic spaceframe. Only the arches the membranes are attached to are subjected to bending moments, the rest of the structure only receives axial forces.

[8] https://structurae.net/structures/riesentropenhalle-gondwanaland – retrieved on 19 February 2018

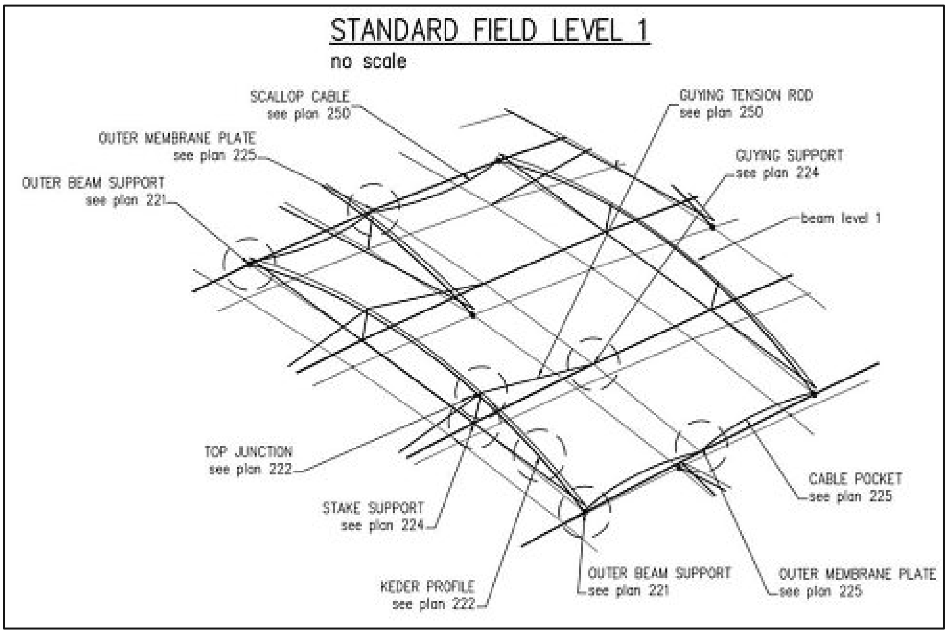


Figure 16: Grandstand Roof, Sheikh Khalifa Bin Zayed International Stadium, Al Ain, U.A.E. – Structural components (drawing by if_group, Reichenau, Germany)

This sophisticated engineering allowed a very light architecture despite a very wide free span of 105 m and a total roof surface of 4,200 m². The result was an economic and slender construction. With only 24.7 kg/m² a very low tonnage was required despite the additionally very unfavourable supporting conditions of the overall design.

Figure 17: Grandstand Roof, Sheikh Khalifa Bin Zayed International Stadium, Al Ain, U.A.E. (website www.structurae.net)[9]

[9] https://structurae.net/structures/sheikh-khalifa-international-stadium – retrieved on 16 May 2018

There are also ETFE cushion projects in which the influence can be very high. For example, when very long cushions are installed between arched members. A hybrid calculation can achieve much more slender components and can do without components that interconnect the arches. In separate calculations, however, such additional elements are very often unavoidable.

Figure 18 shows such an ETFE cushion project supported by long arched frames with required longitudinal connectors. Such connectors are not used in the project of Figure 19. The aim is certainly to omit such additional components on one side and to minimise the cross-section of the arches on the other. This is the typical aspect that makes a big difference between separate and hybrid calculation.

Figure 18: Long arched ETFE cushion roof with interconnecting members and high upstands – Islands at Chester Zoo Building, Chester, England (website: e-architect.co.uk)[10]

For such arched ETFE cushions with structural interconnecting longitudinal members there are three main possible designs:

- Continuous cushions without contact with the connectors, like in Figure 18. This requires high upstands to avoid a collision of the cushions with the longitudinal connectors, leading to additional strain due to the high eccentricity of the cushions. Moreover, this has a negative effect on the optical appearance.
- Continuous cushions with contact to the longitudinal connectors. The lower layer of the cushion rests on the longitudinal connectors.
- Separate cushions between arches interconnecting members

[10] https://www.e-architect.co.uk/england/islands-at-chester-zoo-building – retrieved on 01 June 2018

None of this is the case when building without such longitudinal connectors. As shown in Figure 19, this solution allows a very elegant appearance also due to the geometric possibility of installing the cushions directly on the beams without visually intrusive upstands. Upstands were used in this project, which are only not visible in the following perspective. In other perspectives they are.

Figure 19: Long arched ETFE cushion roof without interconnecting members
Adidas Laces, Herzogenaurach, Germany (website: architecturelist.com)[11]

Another option for achieving an economic and slender architecture is to optimise the sag of cushions, membranes, edge cables and other tension-only structural components. The decision on such design issues is normally taken at the beginning of a project, when at best the communication works well and architect and engineer discuss all aspects. Regarding this project development phase another good advantage of hybrid calculation should be mentioned. When working with a holistic model, different options can be processed quickly and easily such as evaluating the appearance of the different options in shapes, structural systems and others, resulting in different required cross-sections and overall appearance. It is therefore a good instrument in the project development. The separate approach is too inert for such interactive studies, discussions and presentations.

The highest degree of influence is given in systems where the membrane is an essential part of the static system or plays an important role as a stabilising component of the system. For such structures, hybrid calculation achieves a very big difference compared to the separate. This is exemplarily the case in the following project of the Amphitheatre Bilkent University, Ankara, Turkey.

[11] http://www.architecturelist.com/2011/09/23/adidas-workout-%E2%80%93-furniture-as-a-team-by-kinzo/ – retrieved on 01 June 2018 – copyright: Werner Huthmacher, Berlin

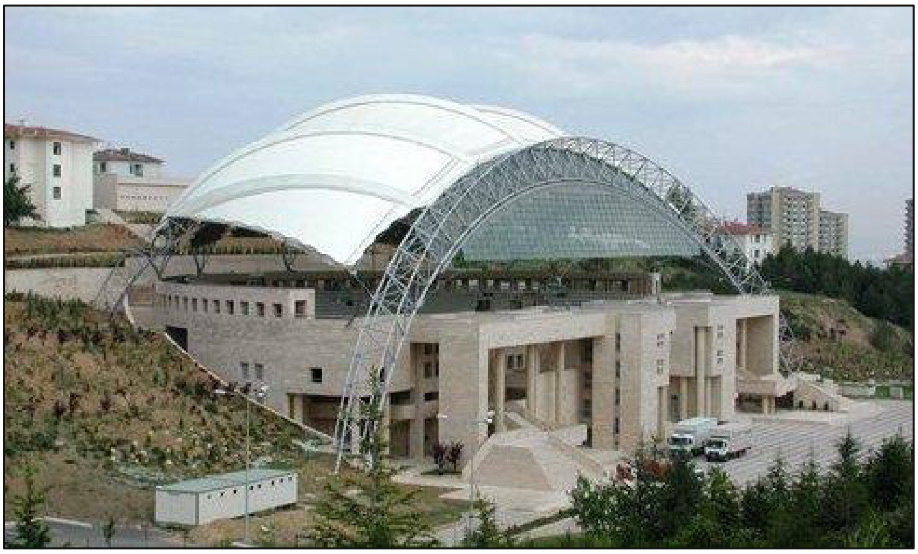


Figure 20: Amphitheatre Bilkent University, Ankara, Turkey (website: sattler-global.com)[12]

Figure 21: Amphitheatre Bilkent University, Ankara, Turkey (photo by MERO GmbH)

The dimensions of this project deliver an indication about the achieved slenderness. The six secondary trussed arches span between 34 and 46 metres connecting at the front to the 118-metre, hinge supported main arch. Without a hybrid calculation this slenderness would not have been possible to achieve. The entire project would not have turned out this slender. In this project the front cable net and especially the membranes are an integral and crucial part of the primary structural system. The

[12] https://www.sattler-global.com/textile-architecture/lightweight-roof-1304.jsp – retrieved on 01 June 2018

membranes are installed between three-chord spaceframe arches, connected to the main arch at their front end, also a three-chord spaceframe truss. All trusses are hinge supported. The elements between the arches in Figure 21 are no elements of any structural sense, but acoustic installations, thus even additional loading. At the front a glazed cable net for rain shelter is installed between the main arch and the building with two tie-down cables.

This structure was presented by Wolfgang Renner and Herbert Klimke, MERO GmbH, Würzburg, Germany, at the IASS Symposium 2000 in Istanbul. The authors state: *"The analysis is done as an overall analysis for the total structure including framework system, membrane and cable net façade."* (Renner & Klimke, 2000). This reveals clearly that a hybrid structural calculation was conducted. A separate calculation would have resulted in a much more massive structure and additional members. A separate calculation for the realised system would not have been possible as the separate structural model of the steelwork would no iterate. Most of the slender profiles as shown in Figure 21 would be highly overstressed. And not only that, the structure as a whole would be globally unstable in a separate calculation.

This structure also serves as an example for the crucial issue of global stability. In case a membrane fails and there is no safety measure for a failure situation, global collapse may happen in worst case. Scenarios of possible failures always need to be considered. Such a safety problem may arise if, as in this case, membranes are used as part of the main structural system. Without their stabilising effect the structure could collapse in worst case. One possibility would be the installation of safety cables, which come to action in the event of a membrane failure and stabilise the structure until defective components are replaced. This is illustrated in the project of the Chemical Research Centre in Venafro, Italy in Section 4.4. The safety cables in Figure 28 are slack as long as the membranes are intact and only come to action in the event of failure.

In the lightweight construction sector, there are also structural systems in which hybrid calculation is something of a must since it makes no real sense to calculate separate. Such systems are for instance cable membranes or cable net structures, where the cable net is the main load receiving or load carrying part of the structure, where conventional components are often even inconspicuous. Examples include funnel-shaped membranes, cable membranes or cable nets. Such a structure is depicted in Figure 22, a funnel-shaped cable net with perforated panels for shading purpose. A steel compression ring with cantilever members is held in place by the top suspension cables and the funnel-shaped cable net. In other words, this is a kind of tensegrity structure. A separate calculation for such a structure does not make a real sense and it should always be modelled and calculated hybrid. This was done by the author in RFEM with its form-finding module RF-FORMFINDING. In the practical realisation the pretensioning was applied by pushing up the central mast by means of a hydraulic jack after the pre-assembly of all components.

Figure 22: Prototype/Mock-up Sunshades Expo 2020 Dubai
(photo by author)

4.3 Examples of Obviously Over-dimensioned Structures

As part of the separate/hybrid comparisons, examples of obviously over-dimensioned structures are presented which may have resulted from a separate calculation. The author does not intend to state that these structures are really over-dimensioned in terms of errors or poor engineering, as there may be other reasons such as architectural intent, customer requirements, availability of cross-sections or any other. Since this work concentrates on the engineering aspect in order to calculate hybrid structures slender and cost-effective, exemplary projects of non-slender appearance should be presented.

Figure 23: Massive steel front frame of a stage roofing (website www.archiexpo.com)[13]

Figure 24: Massive steelwork of a stage roofing (website www.tallyishome.com)[14]

13 http://www.archiexpo.com/prod/fabritec-structures/product-151879-1749620.html – retrieved on 21 May 2018

14 https://www.tallyishome.com/2016/10/21/why-make-tallahassee-your-home-cascades-park/ - retrieved on 21 May 2018

4.4 Examples of Obviously Hybrid Calculated Economic Structures

The following exemplary projects demonstrate the realisation of slender and graceful engineered structures that are assumed respectively known been calculated hybrid and would not have been possible to realise that way in separate calculations.

The first example to be presented in this category is the already mentioned roof construction of the Amphitheatre Bilkent University in Ankara, Turkey on page 28, for which it is not only obvious but also known having been calculated hybrid. Considering the wide spans, the high load, for example the 0.8 kN/m² snow load, requiring PVC-coated polyester type V, and the nevertheless achieved slenderness, other examples such as those of Section 4.3 appear very disproportionate.

The following also visualizes a structure assumed to have been calculated hybrid. This is the ETFE cushion roof of the DWI Leibniz Institute in Aachen, Germany. The developed static system in this example is a very efficient, sophisticated engineered one. This should also be an example for improving the chances for winning tenders when proposing form-efficient solutions or efficient ones in terms of the static system.

Figure 25: ETFE cushion roof, DWI – Leibniz Institute for Interactive Materials, Aachen, Germany (website: airsculpt.com)[15]

[15] https://airsculpt.com/latest-news/etfe-used-atriums/attachment/etfe-canopy-2 – retrieved on 02 June 2018

The arches in this project meet at the apex, which is also the middle of the span, leading to a structural system that stabilises itself without giving the optical appearance of being of reinforcing purpose. The same applies to the almost invisible cables, stabilising the arches and short-cutting horizontal support forces of the arches.

Another example for projects separate calculation does not make sense for, besides the hypar in Figure 11, the funnel-shaped cable net structure in Figure 22 or the hybrid calculated and slender dimensioned Amphitheatre Bilkent University in Figure 21 is presented in the following very light project. Despite the fact that this is not useful to calculate separate, thus not part of the basic topic, it should be presented here. The importance of considering project redundancy and safety should be emphasised, which is particularly important for structures that require hybrid calculation and are often susceptible to stability issues. It is the former membrane roof over the parking facilities of the Office for Waste Management in Munich, Germany. This project collapsed under high snow load. This project is a good example for the grace in architecture achievable by sophisticated engineering. In this project almost pure axial forces act. Only the top rings of the flying columns are subjected to minor bending, no further element is identified to be strained by bending without knowing the statics.

Figure 26: Collapsed former roof of car pool, office for waste management, Munich, Germany (website: DETAIL inspiration: inspiration.detail.de)[16]

[16] https://inspiration.detail.de/office-for-waste-management-in-munich-106880.html - retrieved on 02 June 20188 – copyright: Hans Neudecker

This project demonstrates quite well what could happen in case a crucial element fails. When studying Figure 26 this becomes clear. A chain reaction ending in an overall collapse could be the result for such a structural system. It is a core task of the engineer to investigate such worst-case scenarios. Having found such a possibility involving unjustifiable risks measures need to be taken to avoid fatal consequences. Such measures could be cables that do not receive any load as long as the structure is intact, but come to action in failure scenarios, stabilising the structure until the defects are repaired. An example of such safety cables is the following project, the membrane roof over the Chemical Research Centre in Venafro, Italy. This structure consists of three-chord arches with membranes spanning in-between.

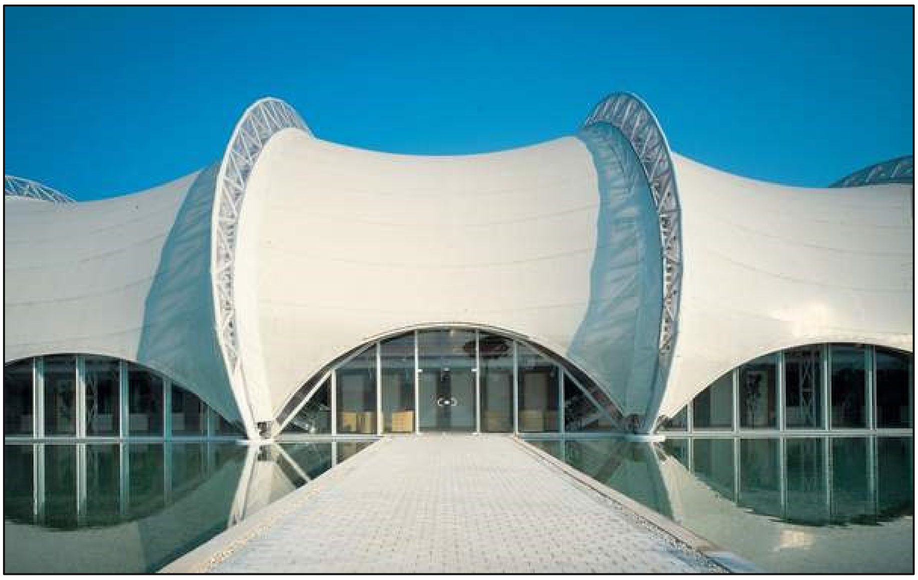


Figure 27: Roof over the Chemical Research Centre, Venafro, Italy – View from outside (website: samynandpartners.com)[17]

As described in Section 4.2, the structure may collapse in the event of a membrane defect. For this scenario, longitudinal arches interconnecting cables are installed as shown in following Figure 28. Particularly due to the fact that this work concentrates on optimisations and the achievement of aerial slenderness, it should be emphasised that all the more such safety considerations must be taken into account. The more a structure is shape-efficient, the higher the risk towards global failure scenarios like snap-through buckling of gridshells. When not aiming to build slender, light, cost-efficient, omitting as many components as possible and reducing the diameters like in the big example >The Sea Star<, such considerations are of course not of such high importance, because then usually lying in the range of high buckling factors.

[17] https://samynandpartners.com/portfolio/mg-ricerche/ – retrieved on 02 June 2018

Figure 28: Roof over the Chemical Research Centre, Venafro, Italy – Internal view with the arches inter-connecting cables (website: samynandpartners.com)[17]

4.5 “On the Safe Side”

A philosophy frequently used in statics is the "on the safe side" directive. This is not randomly mentioned here since this approach is not as simple as it may seem on first sight. Moreover, since this work is very much focused on building structures slender and avoiding over-dimensioning, this philosophy is often one of the main reasons.

Yet the aim of this philosophy is often missed as it may end up being the opposite, "the unsafe side" even where it is not expected. That's why the “safe side” issue should always be handled carefully. The problem is that in practice this philosophy is often applied recklessly without verifying that it is fulfilled. For an engineer, believing to be on the safe side does not help. Not being sure is not an option, so not verifying is not an option. The author would like to encourage readers to do what is done extensively in this paper. Perform comparative calculations and examine differences and effects in detail with recommended automated evaluations. This should also be exercised during the work on a structural system when doing alterations or trying options. The engineer will often be surprised about unexpected effects or ones not thought about and learn from the findings time and time again. When applying the "safe side" approach and subsequently comparing the results, it can be observed in most cases that in complex structures the opposite is the case at certain points. Members are strained less and thereby under-dimensioned.

The reason is that an expression like “on the safe side” can only reliably be said in extremely simple structural systems like a single-span beam. When it comes to a still extremely simple two-span beam it can already end in under-dimensioning and damages. This is illustrated in Figure 29 below, a two-span beam with spring stiffness for supports or connections between two beams. Exemplarily, the middle support as a substitute for a substructure in a simplified or separate calculation. Three moment gradients are displayed with their maximum values for field and support moment.

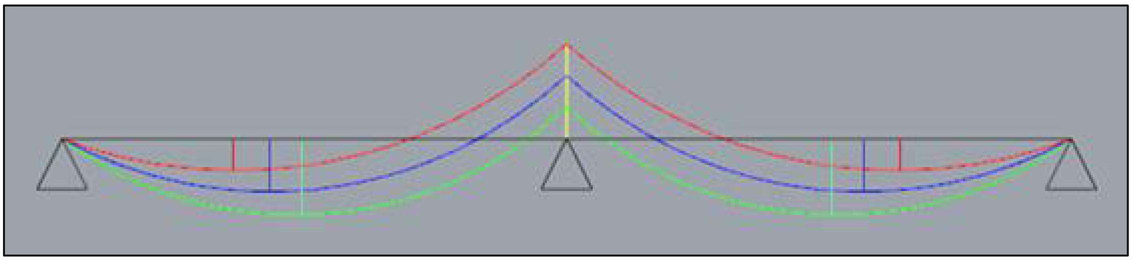


Figure 29: Sketch moment gradients two-span beam with different stiffness used (sketch by author)

Blue line = Moment gradient with correct spring stiffness (or automatically correct when calculating hybrid)

Red line = Moment gradient with too high stiffness
→ support moment too high, field moments too low (unsafe side)

Green line = Moment gradient with too small stiffness
→ support moment too low (unsafe side), field moments too high

This example of an extremely simple structural system already shows that even with such a simple system incorrect values of boundary conditions can lead to incorrect dimensioning. Over-dimensioning for the field moment and under-dimensioning for the support moment or vice versa. In this extremely simple system the aim of the philosophy "on the safe side" is already missed.

The general analysis process should always be, and is even required in codes, to model a structure in the calculation process as close to reality as possible, because for complex structures one cannot simply say “on the safe side”. If model data are not correct, this is usually on the safe side for one situation or component, but on the unsafe side for others. In complex systems, there is hardly a chance for a complete "safe side calculation" when using incorrect data of whatever nature. And the risk of overlooking negative effects is high when following this philosophy.

According to the author´s experience, there is perhaps only one real possibility for the so-called "safe side". This lies in an increase of the safety factor on the material side or the limitation of member utilisations in realistic calculations. And even this needs to be checked. Not checking oneself and own decisions is the biggest fault an engineer can do.

4.6 Theory Third Order (Th. III. O.)

At this point another critical issue of separate calculation should be pointed out. According to engineering diligence and even as required by many codes, structures of high deflection like lightweight structures should respectively must be calculated following Theory Third Order (Th. III. O.[18]).

Briefly described, Th. III. O. is a more complex, time consuming and adequate calculation method than First and Second Order. Expressed simplified, a calculation according to Th. III. O. finds, when iterating, an equilibrium of the final form of a structure together with its final forces. The shape is updated after each iteration step by setting up a new stiffness matrix. First and Second Order Theory neglect the change of shape of a structure with respect to the stiffness matrix. The Theory Second Order includes effects like additional bending moments in columns caused by deflections (e.g. P-delta effect). But the shape remains the initial one in the solver.

To calculate structures of high deflection separate by not modelling and calculating them holistically as it is easily possible in hybrid software today, can certainly be judged as an engineer's negligence or even a violation against codes and state-of-the-art. The problem of this matter becomes all the clearer when reading Chapter 4.7 below. For the author, calculating structures of high deflection separate can never be categorised as compliant with Th. III. O., regardless if those settings are used in a separate calculation, which someone might argue here. The entire issue of high deflection and its consequences cannot be adequately addressed in a separate calculation methodology.

4.7 Accuracy of Models and Meeting State-of-the-Art

Most standards contain requirements for the models to fulfil. The structural models have to be sufficiently accurate and should correspond to the state-of-the-art. Exemplarily the Eurocode states in Section 5.5.1 Structural modelling:

[18] Th. III. O. = Abbreviation for Theory Third Order

- *(1): “Calculations shall be carried out using appropriate structural models involving relevant variables.”*
- *(2): “The structural models selected should be those appropriate for predicting structural behaviour with an acceptable level of accuracy. The structural models should also be appropriate to the limit states considered.”*
- *(3): “Structural models shall be based on established engineering theory and practise.”* (Eurocode 1990:2002)

Such formulations are very likely to become the basis for interpretations or even a question of opinion. If the reader thinks about the content of these sentences, there is no need to describe that an engineer may run the risk of being prosecuted, since in cases of damage such formulations in codes can easily be interpreted to the detriment. The separate calculation in the context of the sentences above certainly gives the reader some idea of what the problem is to think about regarding the separate approach. Simply the thought of whether separate calculation meets such demands of a code. And this is what the reader should do when working on a project and deciding about calculating separate or hybrid.

5 The Investigations

This chapter introduces with the basic principle, deepens with basic examples and a concluding practical project. Boundary conditions are presented to make the examples comprehensible for best comparability and traceability.

5.1 Basic Structural Principle

The positive effect of hybrid statics is mainly based on a simple static principle. When a tensile forces system like a membrane, a cushion, a cable or the like is supported fix, then its sag remains unchanged under load when neglecting elongations. But when elements such as arches supporting membranes deform under load, the sag increases, reducing the membrane forces. In the following the in-plane force component in the membrane, respectively the force perpendicular to the load (green arrows below) is called horizontal force for a simplified basic principle description.

Under the load q the supporting structure, which is represented by the supports in the following sketch, deflects inwards. The sag of the membrane increases and thus the forces in the membrane and the horizontal force H decrease, which then is the load that the membrane induces into the structure.

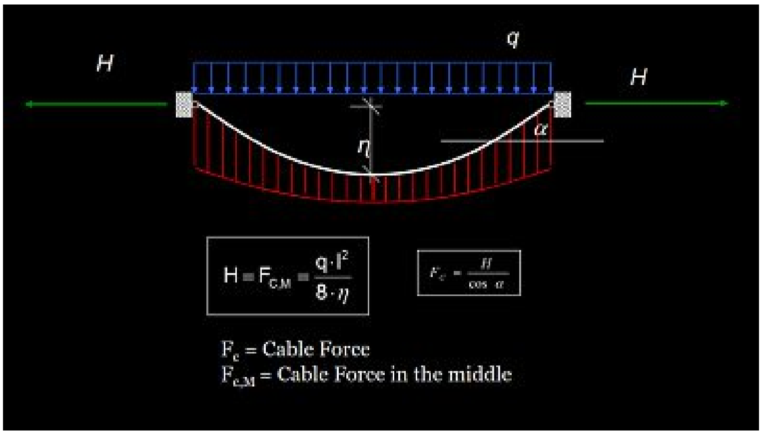


Figure 30: Relation between deflection and forces (extract from course material TU Vienna)

Since this work should be practice-oriented, give input easy to understand and remain engraved in memory, the simplest and easiest to remember sentence should be mentioned here. This describes the relation between sag and horizontal force H:

>> Double the sag, half the force <<

The context should be visualised further by the following example of a membrane installed in an arched frame. The hybrid model including the deflection results is presented in Figure 31. The frame deflects, especially the arches horizontally inwards, the membrane sag increases and consequently the membrane forces and the utilisation decrease. The same applies to the supporting structure, especially for the long arches. The membrane forces decrease and thus the utilisation and the required cross-section of the frame. A reduction of the cross-sections then increases the deflection further. In a separate calculation, the membrane edges would normally be supported fix. No deflection of the membrane and increase of its sag would be there when neglecting the elongations. Consequently, the forces in the membrane and the support forces later applied to the structure in the substitute model would be too high as well as the dimensioning. This is the main effect on which this work is focused. The interaction of the components of different kinds of structural behaviour, which is covered by hybrid but not by separate calculation.

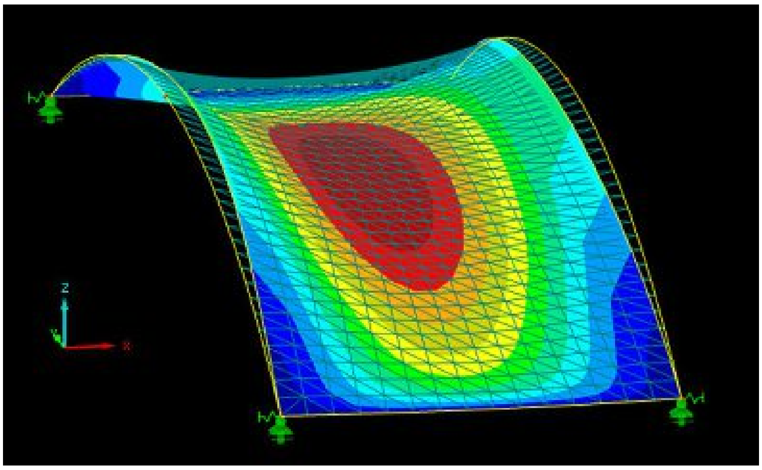


Figure 31: Deflected model of an arched hybrid membrane/steel frame structure under live load (by author)

In case for the membrane partial model the support conditions are intended to be modelled and the membrane not supported fix, which a frame cannot provide, then deforming supports are required as a substitute for the frame. This would be achievable with supports including spring stiffness. The spring stiffness would have to be non-continuous, almost rigid at the corners, high in the middle of the short edge beams and low in the middle of the arches in in-membrane direction (horizontal direction for the simplified sketch in Figure 30). This would be the supporting spring support in plane of the membrane. Perpendicular it would be similarly complicated. Furthermore, the springs would have to be non-linear. One thing unrealistic to model in the separate approach of above frame would be the short edge support spring stiffness. These short edges deflect outwards under downwards loading, caused by the rigidly connected arches which deflect inwards. The spring stiffness of the short edges would thus depend not only on their own cross-section, but also on the static behaviour of the adjacent arches and those cross-sections. This would require a “negative spring stiffness” for this short edge under snow load. By "negative spring stiffness" is meant that the supports would deflect in the opposite direction of the load it is strained by.

This method is not practical and realistic since it is very complicated to model, requiring the modifications of the spring stiffness each time the dimensioning of the substructure changes. Furthermore, the spring stiffness depends on other hybrid responses of the whole structure and further. It is much easier, faster and accurate to calculate hybrid. In practice, however, separate calculations are often still carried out. Not only by engineering offices or engineers who rarely deal with lightweight components. The author experienced this himself in his professional life. The membrane partial model is rigidly supported, then the model of the supporting structure is loaded with the support forces of the membrane and the dimensioning is carried out. This is often the case in practice today. Even worse if non-linearity is neglected by applying unfactored membrane forces in load cases and then factorising them in the load case combinations. This non-linearity problem is also discussed in this paper, in Diagram 12 and Diagram 13 and the descriptions of the respective sections. The procedure of the non-linearity investigations is described in the example of Section 5.2.1.

5.2 Fundamental Investigations on Basic Systems

In the following basic structural systems, the difference between hybrid and separate calculation is visualised. An insight and a basic feeling for the influence of the different approaches on the outcome should be conveyed.

The following basic systems are examined and compared according to the procedure described in Chapter 3 Methodical Approach.

5.2.1 Membrane in an Arched Frame

The following system of an arched frame with an installed membrane is investigated separate and hybrid. This example is examined and evaluated in detail. Different models are built to investigate the influence depending on the span. Several detailed evaluations of the comparative calculations are presented in Section 6.2.1.

Figure 32 below shows the dimensions of one of the several models investigated. All models have a width of 5 m. The maximum sag of the membrane in warp direction (x' in the figure) and the percentage of the arch rise are always identical. The span is increased for the different models in 1 m increments.

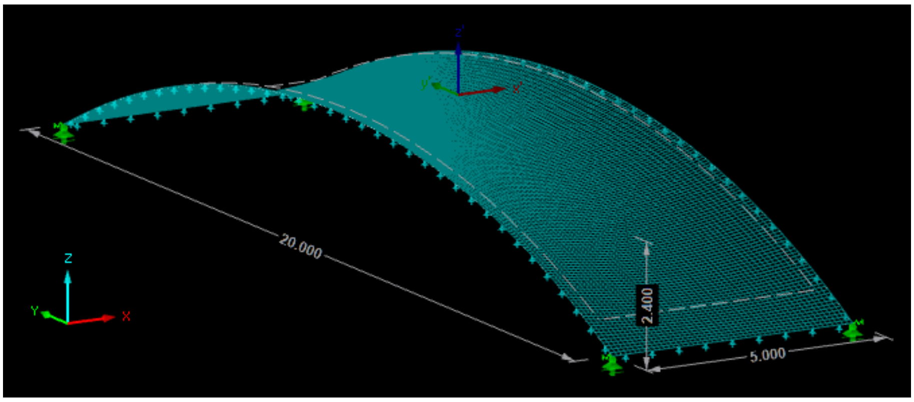


Figure 32: MiAF – RFEM model – Geometry (by author)

Note: In the figure above and models of the following arched frame, very small rectangular elements were used in the FE settings. It is clear to the author that for reasons of element distortion of rectangles in 3D curved surfaces etc. it is normally recommended to use triangles for membranes. Rectangles were used here due to the computational speed of the large number of models and calculations and also for more uniform colour plots for documentation and others. The author checked the plausibility and reliability of the results, which were very good. Triangles are used for all cushion calculations and stronger curved areas of >The Sea Star<.

System data and parameters:

- Membrane installed in an arched frame
- Shape of the arches: constant curvature = sector of a circle
- Span of arch: 5,000 mm to 30,000 mm (where feasible) in steps of 1,000 mm
- Width = span of the membrane in warp direction: 5,000 mm
- Arch rise: always 12%
- Max. membrane sag in x-direction: always 10% = 500 mm
- Membrane prestress in x-direction: always 1 kN/m
- Membrane prestress in y-direction: calibrated to achieve the desired sag
- Membrane chosen: PVC-PES type III
- Membrane material properties used in the calculations: according to Figure 33
- Membrane thickness: 0.78 mm

- Details like supports, spring stiffness, upstands, membrane offset and else neglected (to isolate the separate/hybrid effect)
- Chosen surface type in RFEM:
  - Geometry: B-spline surface
  - Stiffness: membrane orthotropic
- Steel members:
  - 219.1 mm outer diameter for all models and members
  - Wall thickness always exactly dimensioned according to structural requirements
  - One exception to the two items above: comparison by outer diameter dimensioning (here same wall thickness)
  - All elements rigidly connected to each other, complete bending-stiff frame
- Support conditions:
  - Fix in z (vertical)
  - Fix in y (horizontal in arch direction)
  - Free in x (e.g. for bolted supports with eye bars allowing movement; friction neglected). For smooth colour plots of member deflections all supports defined "free in x" with an extremely low spring stiffness.
  - All supports free around all axes (moment hinges)
  - No spring stiffnesses used
- Load cases:
  - Self-weights: automatically included according to cross-sections
  - Snow load: 1.0 kN/m² (same for all models, Figure 35)
  - Wind suction (Figure 36): barrel-vault wind according to Eurocode: basic wind load: 1.0 kN/m²

    Wind zones (according EN 1991-1-4; Figure 34)
    - Zone A: c_{pA} = -1.2
    - Zone B: c_{pB} = -0.9 (chosen)
    - Zone C: c_{pB} = -0.4

    Additional for A-C: internal pressure: +0.2
- Load case combinations for steel dimensioning (HY):
  - 1.35 DLs + 1.50 SL (governing and chosen for initial dimensioning)
  - 1.00 DLs + 1.50 WS
- Load case combinations for membrane stress investigations (MEM):
  - 1.00 DL + 1.00 SL
  - 1.00 DL + 1.00 WS
- Load cases and combinations for load transfer between separate models (STR):

- 1.35 DLs + 1.00 (1.35 DLmem + 1.50 SL)
- 1.00 DLs + 1.00 (1.00 DLmem + 1.50 WL)

In brackets: load case combinations in MEM and load case in STR for load transfer from MEM to STR; outside the brackets LCC in STR. Equivalent HY and STR calculations are carried out using this procedure.

- Investigation of the non-linearity of load effects by using pure load cases in MEM, transferring the resulting membrane forces to the respective load cases in STR and only then combining according to Eurocode with their combination factors. This should visualise the difference of combining already correct in MEM and incorrect only in STR, not meeting the nonlinearity issue.
  - Load cases in the non-linearity incorrect calculations:
    - DLs (Self-weight structure): no influence for the MEM model
    - DLmem (Self-weight membrane)
    - P (Prestress membrane)
    - SL (Snow Load)
    - WL (Wind Load)

    In order to avoid that prestress forces are included several times in the STR load case combinations, they are eliminated in the MEM load cases except the prestress load case by using the same prestress ratio to achieve the intended shape of the membrane, but a minimum value leading to max. 0.001 kN/m support forces, which is negligible.

  - Load case combinations in the non-linearity incorrect STR calculation:
    - 1.35 DLs + 1.35 DLmem + 1.00 P + 1.50 SL
    - 1.00 DLs + 1.00 DLmem + 1.00 P + 1.50 WL

  All loads in the incorrect procedure are applied unfactored in the load cases of the STR model and then factored in the load case combination. This is usually acceptable for conventional structures and claddings. In lightweight structures this is not correct due to an existing non-linear relation between the loads and the load effects.

- Steel grade: S 355
- Design: steel stress design elastic, no plastification; equivalent stress design according to von Mises

The outer diameters and wall thickness used in the dimensioning of the following are always according to the structural requirement to achieve a stress utilisation of exactly

1.000 (refined to 1.0000 where required for accuracy of result graphs) under elastic dimensioning conditions. Those outer diameters and wall thicknesses are mostly not common industry stock sections. The reason for this decision was to achieve accurate calculation results for better comparability and to avoid distortion of the results by the coincidence of cross-section availability on the market. In reality, when realising projects, the average value of variations should correspond to the studies as the results presented are really precisely calculated requirements. Moreover, no support spring stiffness is used since any distortion of the results should be avoided and only the effects studied should influence the results. In addition, the membrane used in the calculation is always the same in order to avoid distortion of the steel dimensioning results caused by the influence of different membrane properties.

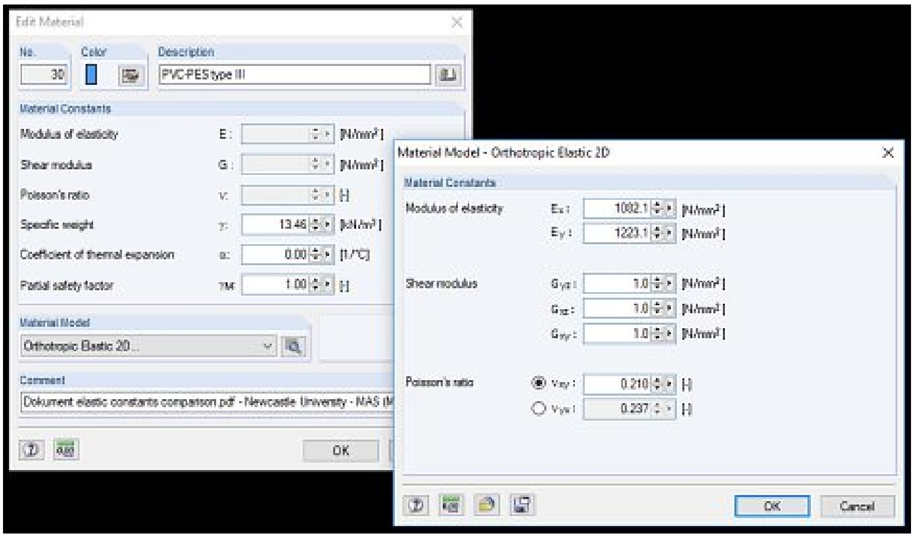


Figure 33: MiAF – Membrane material properties used in RFEM (by author)

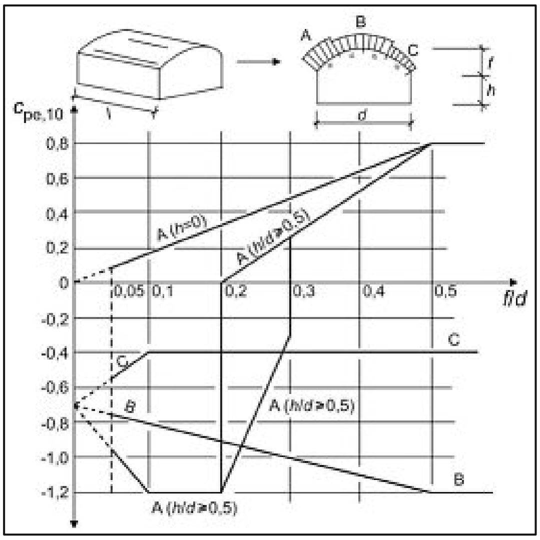


Figure 34: MiAF – External pressure coefficient $c_{pe,10}$ for vaulted roofs (EN 1991-1-4 – Figure 7.11)

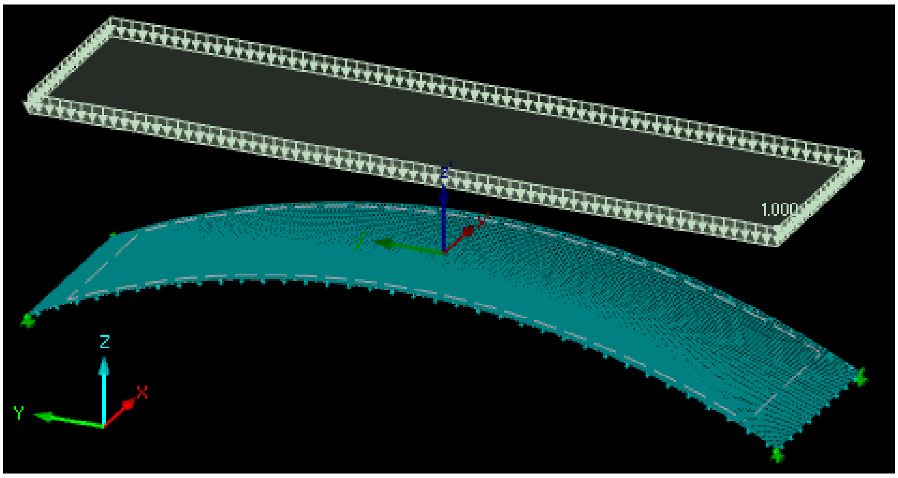


Figure 35: MiAF – RFEM – Snow load (by author)

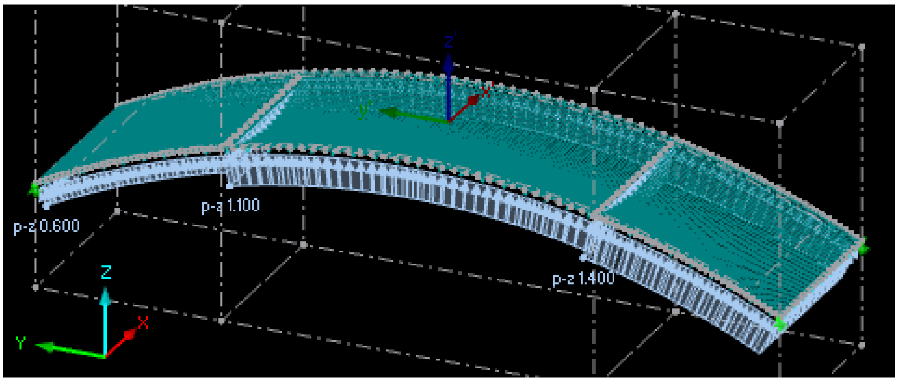


Figure 36: RFEM – Wind suction (by author)

A main step in the procedure of the separate approach is to transfer the membrane support forces of the MEM model (membrane partial model) to the STR model (substructure partial model). The procedure is exemplarily shown in the following illustrations and descriptions.

For the local support forces in MEM and the transfer of these as local member forces to STR, the supports are defined as local and rotated according to the surface of the membrane respectively the inclination at the end of the arches.

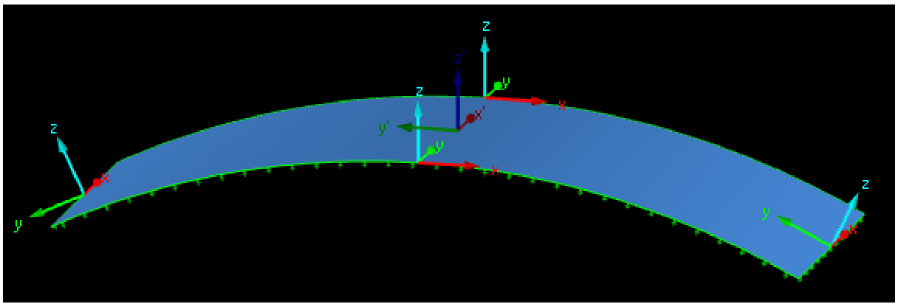


Figure 37: Local line support orientation in MEM (by author)

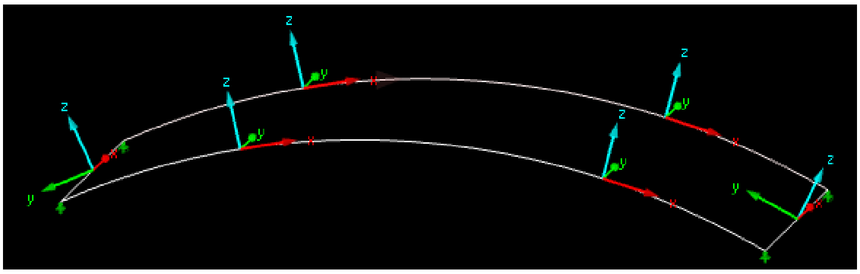


Figure 38: Local member orientation in STR (by author)

These equivalent rotations of the line supports in MEM and the members in STR allow the forces to be transferred correctly between the two partial models. This is exemplarily shown in the following two figures for the model of 15 m span and the local z support forces of the load case combination 1.35 DL + 1.5 SL.

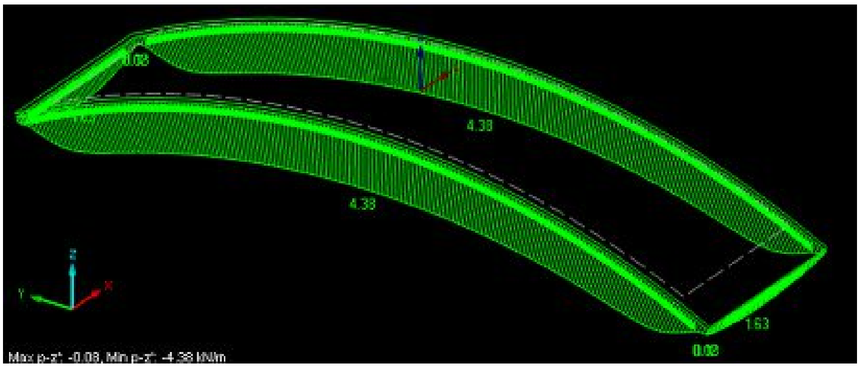


Figure 39: MEM model – Support reactions in local z in LCC 1.35 DLmem + 1.5 SL (by author)

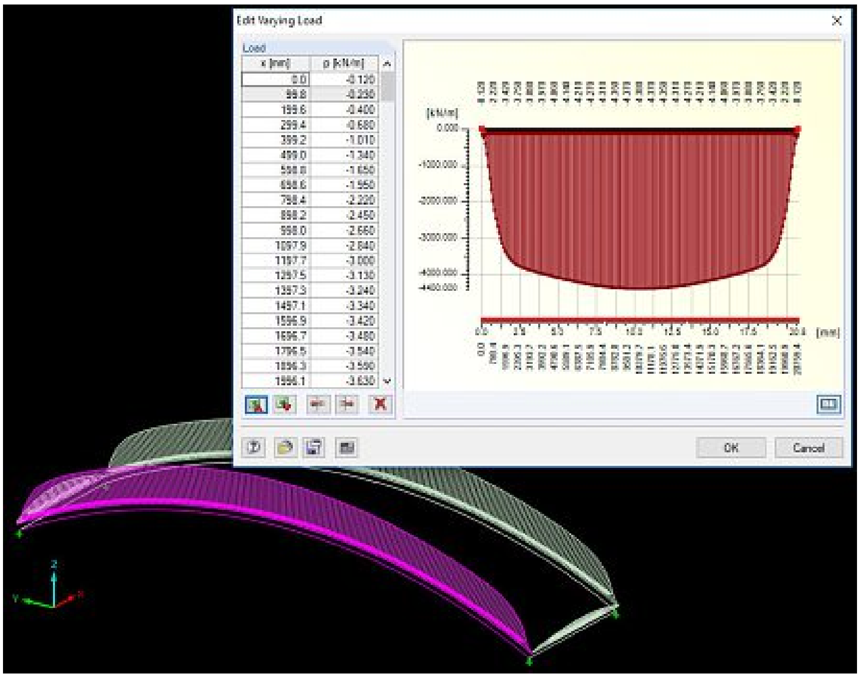


Figure 40: Tabular import of the support forces of model MEM to STR as varying member line loads (by author)

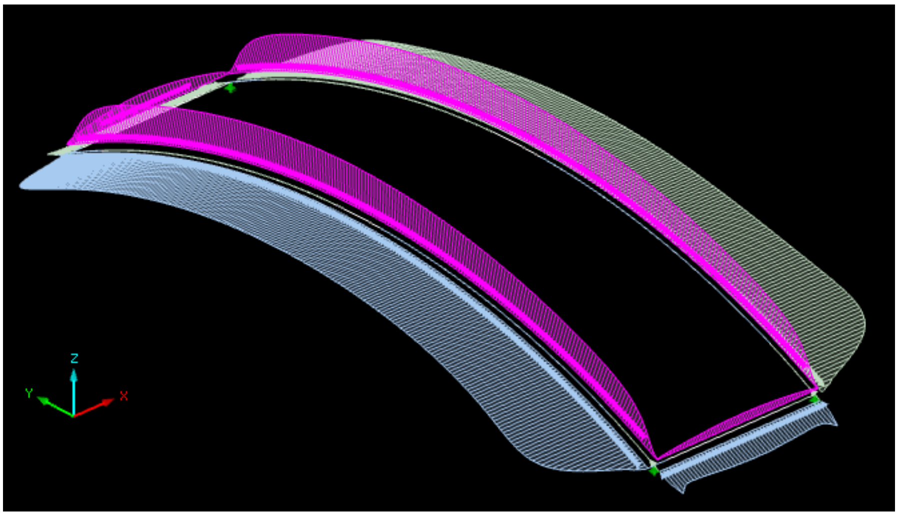


Figure 41: STR model – Applied member forces in local x, y and z (selected in magenta) direction – Load case 1.35 DLmem + 1.5 SL (by author)

The accuracy of the procedure can exemplarily be seen in Diagram 7, in which the utilisation caused by the membrane prestress is depicted. It can be said that the results in the hybrid (HY – without) and the separate (MEM) calculations are 100% identical.

In the investigations three main perspectives were selected to achieve a good evaluation and comparability of the effects to be presented. In all comparisons the lowest to dimension model, the hybrid with form-finding supports, is dimensioned to achieve a stress utilization of 100.0%. In each model all elements have an outer diameter of 219.1 mm. The dimensioning of the members is carried out via the wall thickness. Then the separate model and sometimes the hybrid model without form-finding supports are compared under the following aspects:

1. Overstress perspective: all models calculated with the same cross-sections as required in the hybrid model with form-finding supports. The degree of overstress visualises the difference.
2. Wall thickness up-dimensioning: keeping the outer diameter of 219.1 mm. The increase of tonnage is the perspective of comparison. It becomes quite clear with this procedure that compared to hybrid, by far not that wide-spanning structures are feasible using separate calculation.
3. Outer diameter up-dimensioning: keeping the wall thickness: the increase in outer diameter is the perspective of the comparison and also shows how much more massive and therefore optically spoiling members need to be separate.

The models are all dimensioned for the mostly governing load case combination including snow. For small spans the wind load case combination would be governing. A further up-dimensioning is not carried out for wind in order to keep the view on the influences and the comparisons. Diagram 8 compares the utilisation of the members and the influence of the wind strain in the two approaches.

5.2.2 Hypar

For the system of a hypar, a separate calculation does not really make sense. Nevertheless, also for this very basic system the difference between separate and hybrid calculation should be visualised as this provides a good indication.

Both hypar types described in Section 4.1 are investigated, the hypar type of exclusively axial forces like in Figure 11, hereafter called hypar type A, and the column bending type of Figure 12, hypar type B. The dimensions and all boundary conditions of the compared models are identical apart from the missing bracing cables and the fix supports in the column bending type.

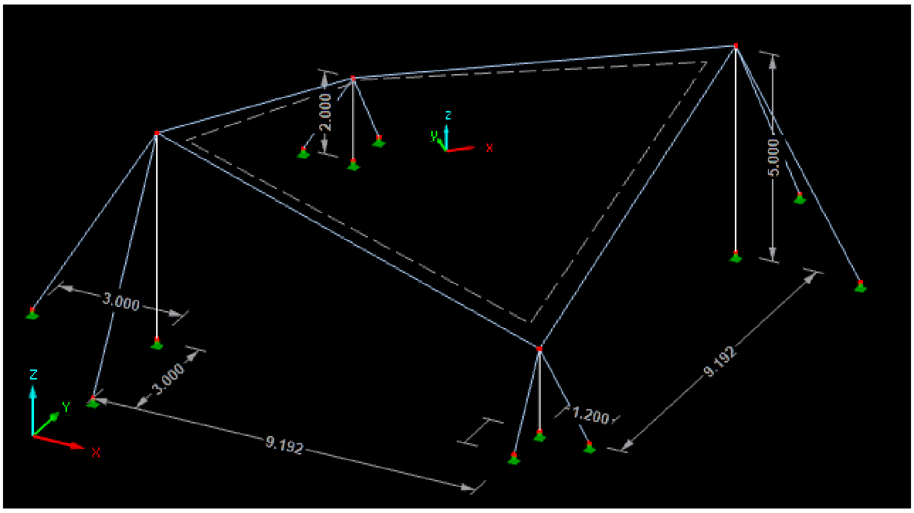


Figure 42: Hypar type A – RFEM structural model centreline mode (by author)

System data and parameters:

- Hypar with four struts and eight cables
- Dimensions according to Figure 42
- Membrane chosen: PVC-PES type II (E_x: 942,857 kN/m²; E_y: 950,000 kN/m²)
- Membrane thickness: 0.56 mm
- Form-finding parameters:
  - Membrane warp direction x: highpoint to highpoint
  - Membrane prestress 1.5 kN/m for warp and weft
  - Sag of membrane edge cables 5%
  - Form-finding for struts and cables deactivated for good comparability

- Details neglected
- Chosen surface type in RFEM:
  - Geometry: quadrangle surface
  - Stiffness: membrane orthotropic
- Cross-sections of components:
  - Struts: industry standard diameters (long: 139.7 mm; short: 88.9 mm)
  - Wall thickness adjusted to achieve stress utilization of 100.0% for the hybrid model without form-finding supports
  - Membrane edge cables d_s = 14.1 mm
  - Bracing cables d_s = 20.5 mm
- Support conditions:
  - Hypar with four struts and eight cables: all supports hinged
  - Hypar column bending type: all supports rigid for all six internal forces
- Load cases:
  - Self-weights: automatically included according to cross-sections
  - Snow load: 1.0 kN/m²
  - Wind suction: overall 1.0 kN/m² (Wind zones neglected for simple comparison. Other load distributions were checked, resulting in comparable differences)
  - Bow imperfection struts: L/200 for cold-formed CHS according to Eurocode
- Load case combinations for steel dimensioning (HY):
  - 1.35 DLs + 1.50 SL
  - 1.00 DLs + 1.50 WS
- Load case combinations for membrane stress investigations (MEM):
  - 1.00 DL + 1.00 SL
  - 1.00 DL + 1.00 WS
- Load cases and combinations for load transfer between separate models (STR):
  - 1.35 DLs + 1.00 (1.35 DLmem + 1.50 SL)
  - 1.00 DLs + 1.00 (1.00 DLmem + 1.50 WL)

  In brackets: load case combinations in MEM and load case in STR for load transfer from MEM to STR; outside the brackets LCC in STR. Equivalent HY and STR calculations are carried out using this procedure.

- Procedure of work similar to the descriptions in 5.2.1
- Steel grade: S 355
- Design: steel stress design elastic, no plastification; equivalent stress design according to von Mises

5.2.3 Flat Triangular Cushion (Edges in Plane)

In this example another aspect of hybrid versus separate/simplified calculation should be presented. This aspect is located in the cushion calculations. One of the main differences of the hybrid approach is to include the gas volume of a cushion in the calculations. Here, only the cushion is considered as it is focused on another special effect. When mixing with the membrane/substructure interaction, it would not be clear what exactly the influence is of which effect. So, for this example the cushion is calculated in a fix supported triangle for comparable calculation of both methods.

The dimensions, loads and further data are those of a real project the author realised in India. He was not allowed to mention the project name here.

Abbreviations in the following: IP = Internal Pressure; LL = Live Load; WP = Wind Pressure; WS = Wind Suction; TL = Top Layer; BL = Bottom Layer

System data and parameters:

- ETFE cushion
- E-modulus ETFE (different ones are used in the market): 900 N/mm²
- Equilateral triangular frame; 6,000 mm edge lengths
- Cushion sag: 12% (upper and lower layer)
- Membrane thickness: 200 µm
- Nominal internal pressure: 250 Pa
- Increased internal pressure (often SL, sensor-controlled, here LL): 640 Pa
- Live Load: 0.64 kN/m²
- Wind pressure: 0.61 kN/m²
- Wind suction: 0.95 kN/m²

In the hybrid calculation, the gas volume is also modelled together with all the further data listed which is valid for both approaches.

In the separate/simplified calculation, which is often practiced in the market, no gas volume is included and the external loads are applied directly to the relevant layers according to theoretical considerations.

For snow or live loads in the hybrid model, the relevant internal pressure is to be applied to the gas volume as these are long-term loads and the internal pressure remains unchanged. For wind loads which are of a short-term character, a closed gas volume is defined and the gas laws apply. This is important in order to calculate the cushions correctly under wind load. The cushion air supply system usually does not allow a relevant change of the gas volume in the very short-term event of a wind gust.

In case of separate cushion calculation without the gas laws, a major problem is the load that has to be applied to the layers of the simplified model. There are essentially the following two different loading approaches:

Option 1:

- LL: TL: 0.25 kN/m² (IP); BL: 0.89 kN/m² (LL + IP)
- WP: TL: 0.25 kN/m² (IP); BL: 0.86 kN/m² (WP + IP)
- WS: TL: 1.20 kN/m² (WS + IP); BL: 0.25 kN/m² (IP)

Option 2:

- LL: TL: 0; BL: 0.64 kN/m² (LL)
- WP: TL: 0; BL: 0.61 kN/m² (WP)
- WS: TL: 0.95 kN/m² (WS); BL: 0

Explanations on the theoretical background of the loading approaches can be found in Chapter 6.2.1 Results and Discussion, as this is regarded as results respectively discussion of findings and not as a description of the example and the procedure.

5.2.4 Membranes Between Three Arches

The following structure is presented as a basic example of structural systems with medium influence of the different approaches. It consists of two membranes installed between two boundary and one central arch. The central arch is free-spanning between the supporting columns and the boundary arches are anchored back to the ground at three locations each.

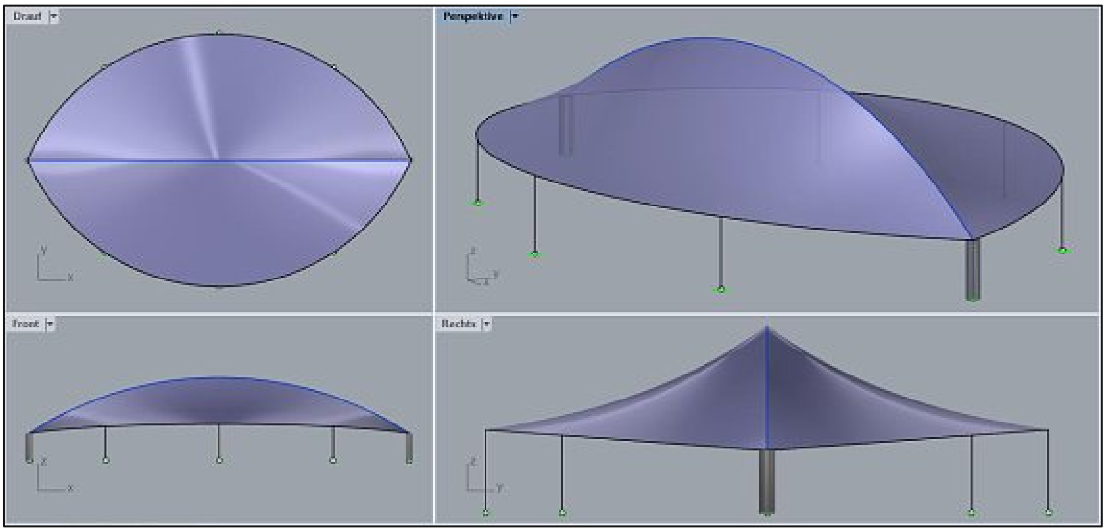


Figure 43: Membranes between three arches – RFEM form found model exported to Rhino (by author)

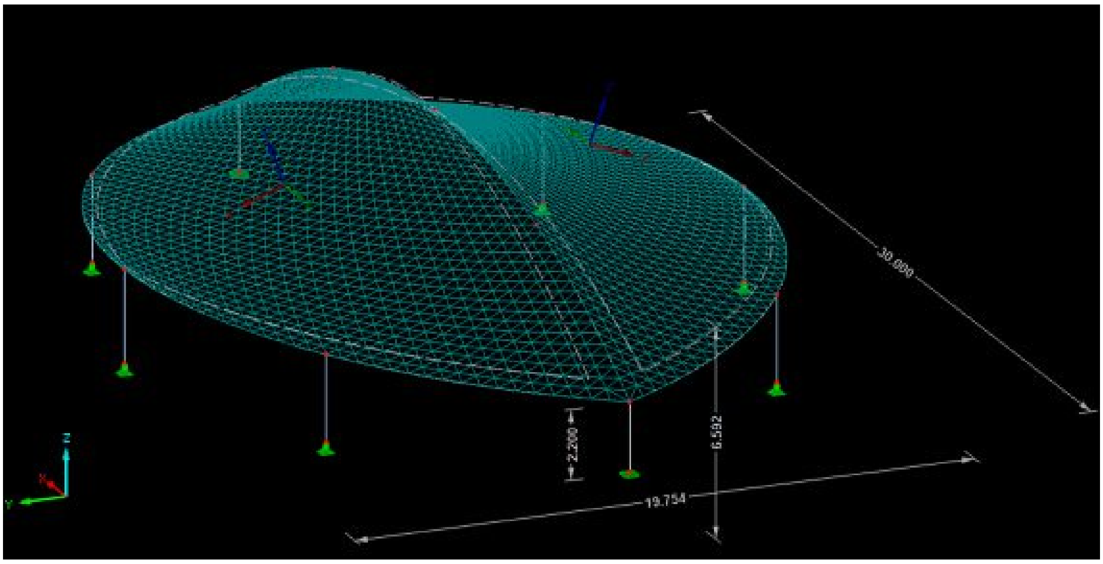


Figure 44: Membranes between three arches – RFEM structural model (by author)

System data and parameters:

- Two membranes installed between two boundary and one central arch; supported by two columns; boundary arches tied back to the ground at three locations each
- Dimensions according to Figure 44
- Membrane: PVC-PES type III (E_x: 1,082,100 kN/m²; E_y: 1,223,077 kN/m²)
- Membrane thickness: 0.78 mm
- Form-finding parameters:
  - Membrane warp direction x: middle of arch to middle of arch
  - Membrane prestress: n_x = 1.3 kN/m; n_y = 2.8 kN/m (ratio calibrated to achieve desired shape)
- Details neglected
- Chosen surface type in RFEM:
  - Geometry: quadrangle surface
  - Stiffness: membrane orthotropic
- Cross-sections of components:
  - Columns and arches according to dimensioning results in chapter 6.2.4
  - Cables d_s = 24.1 mm
- Support conditions:
  - Column supports: fix
  - Cable supports: hinged (irrelevant due to cable character)
  - No spring stiffnesses used

- Load cases:
  - Self-weights: automatically included according to cross-sections
  - Snow load: 0.5 kN/m²
  - Wind load: two load cases applied: in +/- y-direction with overall pressure respectively suction for the relevant membrane
    - Wind pressure: 0.6 kN/m²
    - Wind suction: 1.0 kN/m²
  - Imperfections for cold-formed CHS according to Eurocode:
    - Bow imperfection for all beams: L/200
    - Sway imperfection for the columns: L/200
- Load case combinations for steel dimensioning (HY):
  - 1.35 DLs + 1.50 SL
  - 1.00 DLs + 1.50 WL+y
  - 1.00 DLs + 1.50 WL-y
- Load case combinations for membrane stress investigations (MEM):
  - 1.00 DL + 1.00 SL
  - 1.00 DL + 1.00 WL+y
  - 1.00 DL + 1.00 WL-y
- Load cases and combinations for load transfer between separate models (STR):
  - 1.35 DLs + 1.00 (1.35 DLmem + 1.50 SL)
  - 1.00 DLs + 1.00 (1.00 DLmem + 1.50 WL+y)
  - 1.00 DLs + 1.00 (1.00 DLmem + 1.50 WL-y)

  In brackets: load case combinations in MEM and load case in STR for load transfer from MEM to STR; outside the brackets LCC in STR. Equivalent HY and STR calculations are carried out using this procedure.

- Steel grade: S 355
- Design: steel stress design elastic, no plastification; equivalent stress design according to von Mises

5.3 Practical Project – Festival Tents >The Sea Star<

On "Festival Tents >The Sea Star<" the influence on a practical project should be visualised. On the one hand it should be shown what is possible by hybrid calculation, e.g. the omission of members not necessary in hybrid but in separate calculation, the possibility of more slender members, more graceful overall structures and the beauty of the achievable slenderness. On the other hand the main focus should be on the impact on tonnage and thus costs, which are the basis for a company applying for a project in the market and therefore decisive for winning or losing a tender. Of course, the advantages for the customer should also be considered. Cost savings, optical appearance and safety are just a few of them. The author worked on this project in a concept phase. The separate calculation was the approach. The desired substructure geometry, forces, etc. were provided with the task of dimensioning the structure accordingly for first budgetary pricing. The initial design idea was the following.

Figure 45: Rendering of >The Sea Star< (source: Gerry D'Anza, ixRay Ltd.)

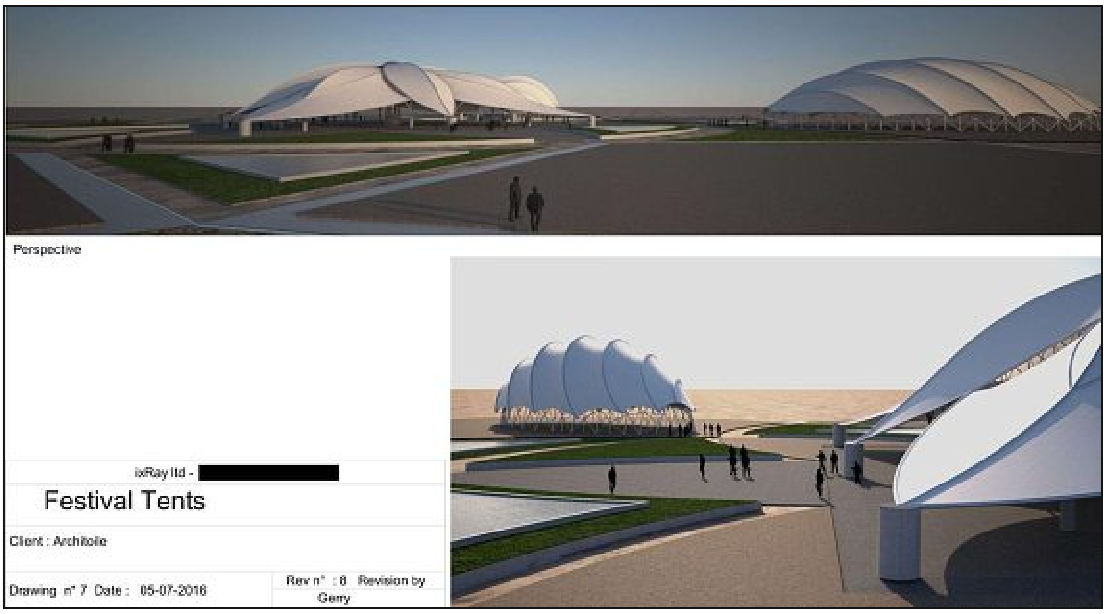


Figure 46: Rendering of >The Sea Star< (source: Gerry D'Anza, ixRay Ltd.)

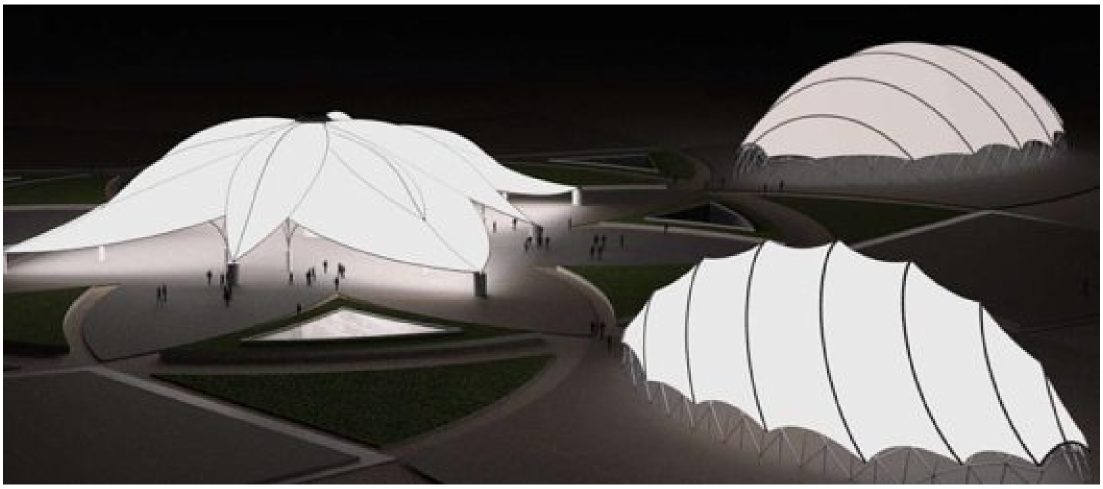


Figure 47: Rendering of >The Sea Star< (source: Gerry D'Anza, ixRay Ltd.)

For this example of a practical project, again a large number of different cross-sections were selected to work with, especially many different wall thicknesses. This is usually not done this way in practice. Here it has been done to investigate in detail the possibility of reducing cross-sections in the hybrid calculation. In reality, only a few different profiles or wall thicknesses are usually used. This somehow by chance leads to either more or less difference in total steel mass. The presented is a detailed computational difference. It was decided to use a large number of cross-sections here to avoid a falsification of the results caused by the coincidence of available sections.

In the course of the project several options were examined and finally the membrane layout (prior to form-finding) was chosen as follows.

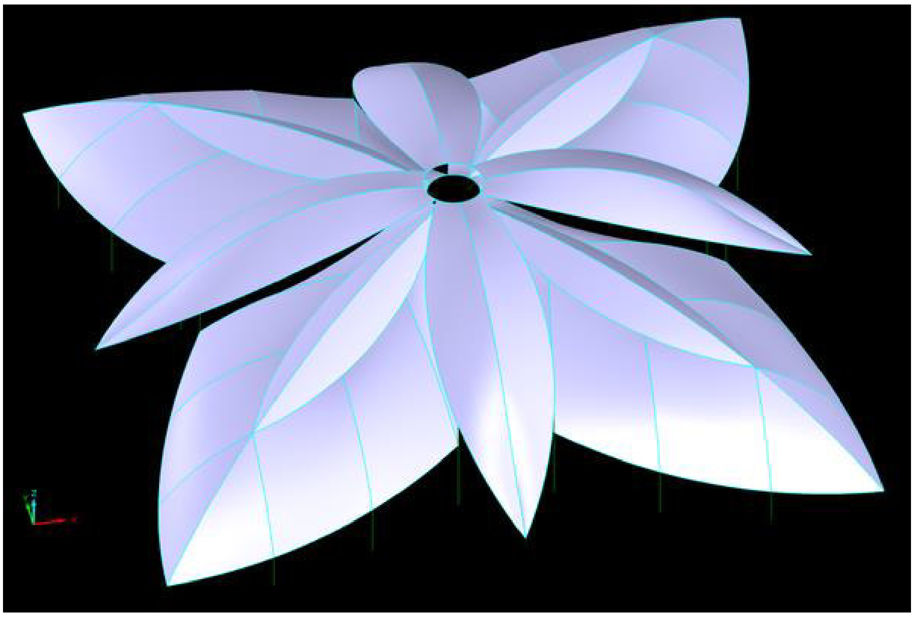


Figure 48: >The Sea Star< RFEM-model in solid display mode (prior to form-finding) – Membranes & centreline mode of the beams (by author)

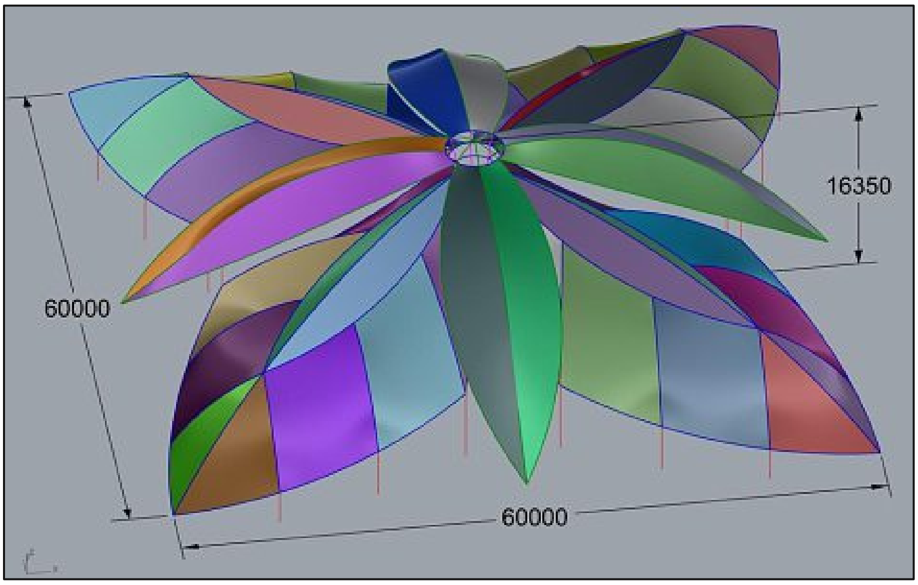


Figure 49: >The Sea Star< Rhino-Model – Membranes in different colours & dimensions (not final RFEM form-found shape) (by author)

The main objective of the author when deciding on the initial geometry of the substructure was to reduce the number of elements as much as possible. And in a next step to further minimise cross-sections and costs. Then, depending on the client's intent to choose one of the two often pursued opposing goals of clients or architects – best price or best optical appearance:

- Best price: reduction of wall thickness, additional elements to reduce structural span and improve the global structural behaviour in order to reduce tonnage and optimise costs
- Best optical appearance: minimisation of the outer diameter thus higher wall thickness, tonnage and costs, further reduction of the number of elements

Typically, these two opposing customer goals decide on the final outcome. A cost reduction increases the outer diameter of the elements and reduces the wall thickness to optimise the tonnage. An optical optimisation leads to the opposite, smaller outer diameter and higher wall thickness which increases costs. Furthermore, exemplarily additional members are incorporated to reduce structural free spans to achieve further optimisations. Normally a compromise between the two goals is the actual result.

In the project phase different options of the structure were examined at that time. Two of them should be presented in the following illustrations. In the author´s opinion both are not acceptable with regard to both aspects, optics due to the abundance of components and also costs. When taking a look at the two options, it is clearly identified that many members, which were additionally included, are either set back or curved to avoid a collision with the membranes. More on this in the following.

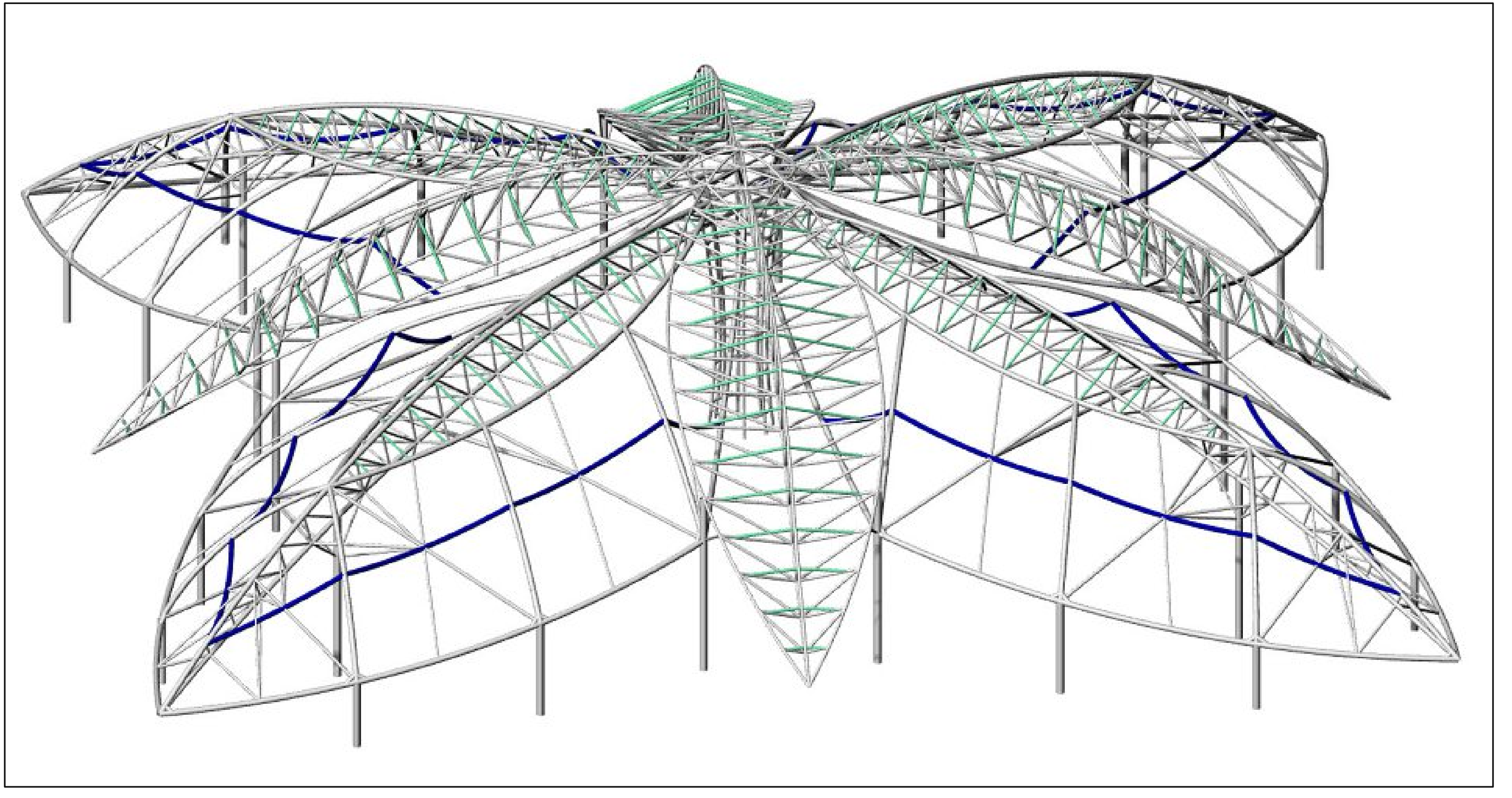


Figure 50: >The Sea Star< Rhino model – Members as tubes – Structural option A (by author)

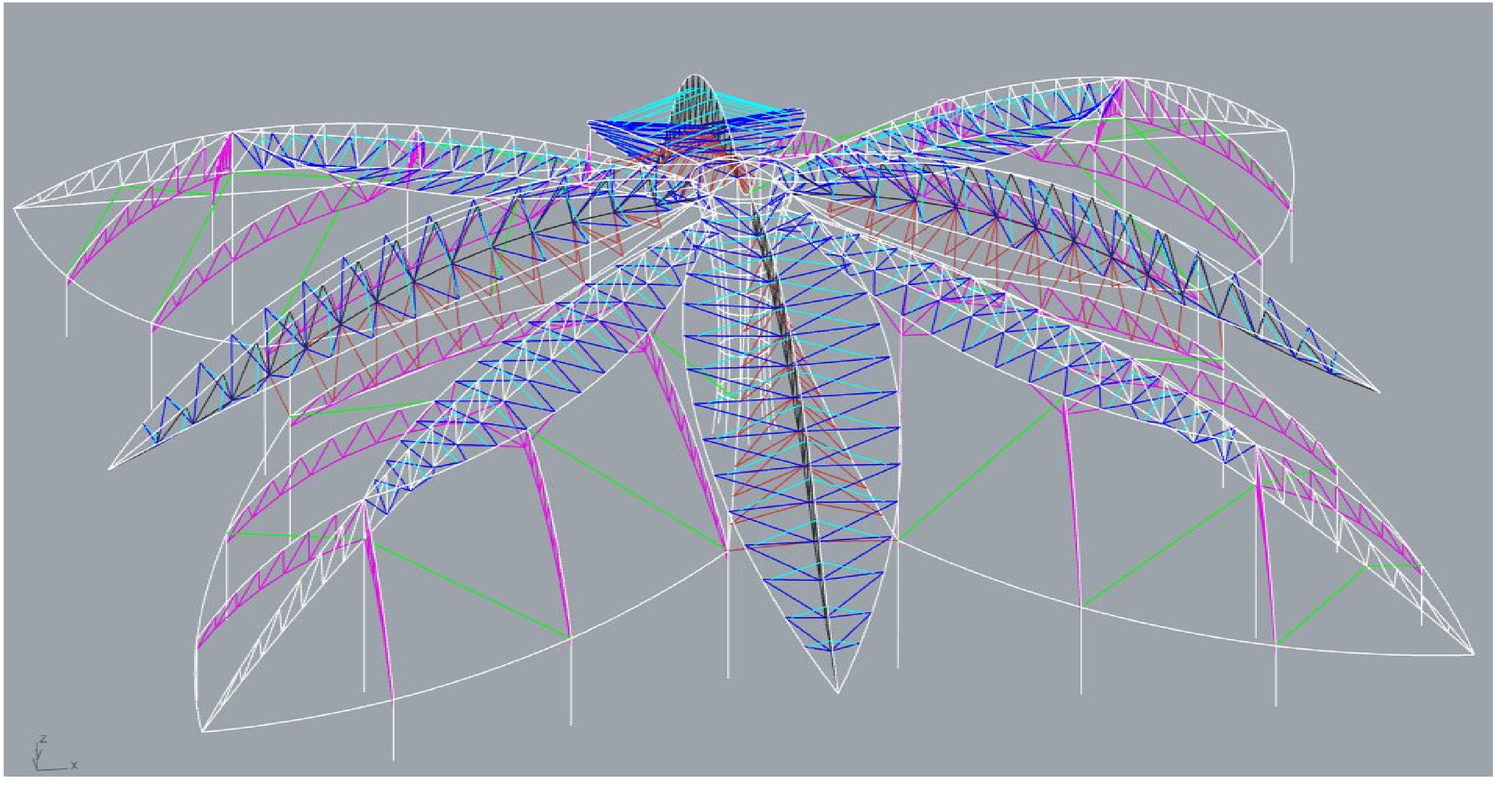


Figure 51: >The Sea Star< Rhino model – Centreline model – Structural option B (by author)

In the following a weighing-up of options and questions respectively answers to thoughts which led to the decision about the static model to start with:

- In both options: far too many members – optically and in regards of costs
  → should be reduced wherever feasible/appropriate
- Exemplarily blue and green coloured elements in Option A, similar ones in Option B: These were added to stabilise the elements to which membranes are attached. They are set back or curved to avoid collisions with the membranes, which is a typical problem. This set back alone is expensive anyway.
  → should be omitted wherever possible/appropriate
- Many composite assemblies aiming for very high global stability and stiffness, e.g. the structures that form a kind of "complex 3D spaceframe trusses"
  → reduction of those "plenty-member" 3D spaceframe assemblies to a minimum wherever possible/appropriate
- Elimination of also 2D trussed girders as far as possible/appropriate; single beams instead
  → decision to start with only four 2D trussed girders for the big leaves
- Stabilising members in the fields of the membranes
  → identified as certainly possible to omit in the hybrid calculation without ending in too massive cross-sections; were omitted from the beginning
- Short stiffening tubes in option A at the intersection of edge beams, arches and columns
  → omission of those expensive details certainly possible
  → reduction of production costs and architectural improvement
- Plenty of complicated connections in regards of geometry, engineering hours for detailing, welding joint preparation, overall production costs, etc.
  → reduction to a minimum where feasible/appropriate

After such discussions and considerations how to achieve the desired result, the geometry of the following Figure 52 was chosen as the starting geometry.

This geometry was remodelled in Rhino to obtain a clean and precise geometry, also in terms of perfect symmetry. The workflow was again as already described in Section 3. An important additional step in the work for >The Sea Star< was the implementation of more precise wind loads than the rough conventional approaches according to codes. CFD wind load determination results were available and these were incorporated. The results of the CFD wind load determination for one wind direction are shown in Figure 53 and further information in the appendix.

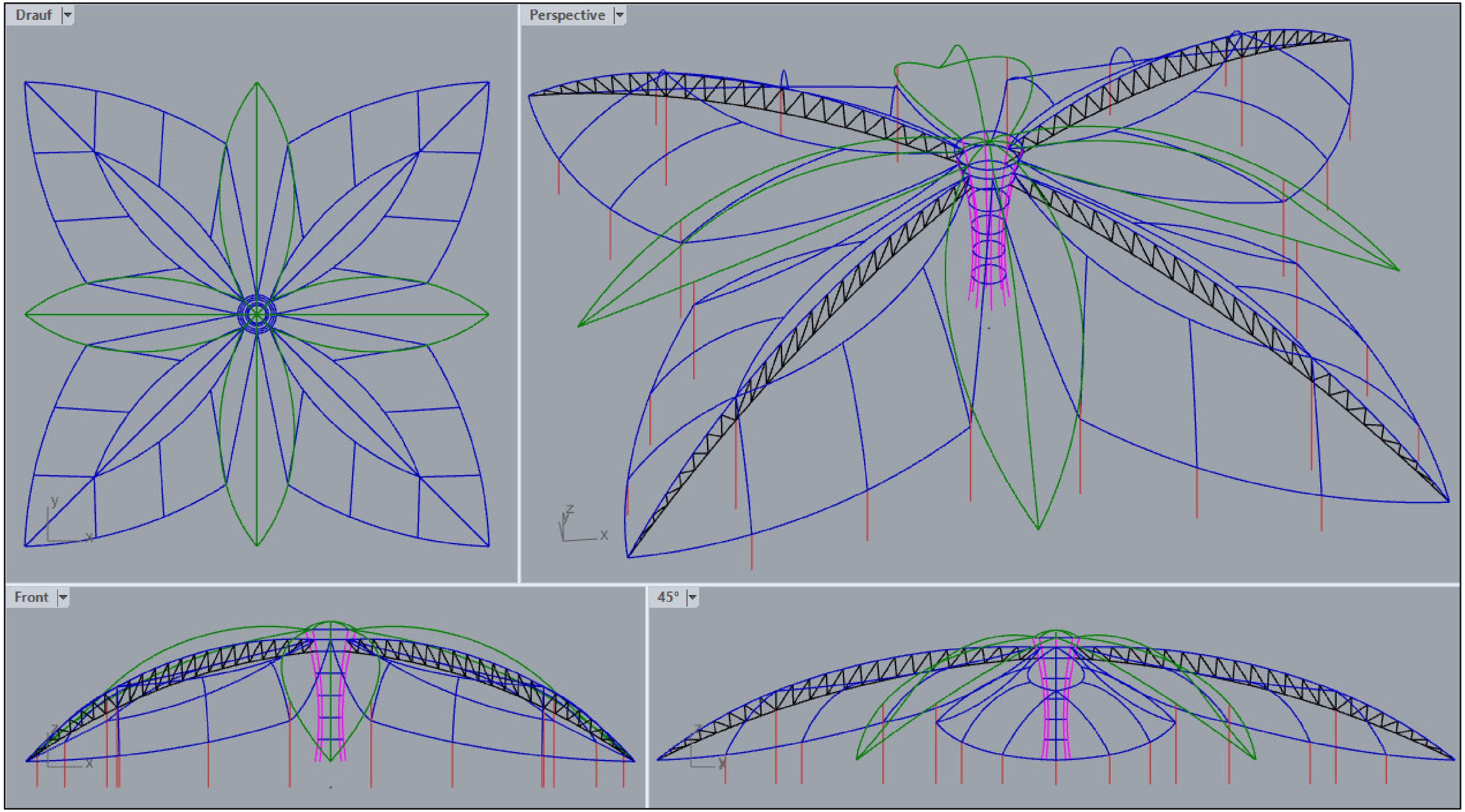


Figure 52: >The Sea Star< Rhino model of intended starting model for calculations (by author)

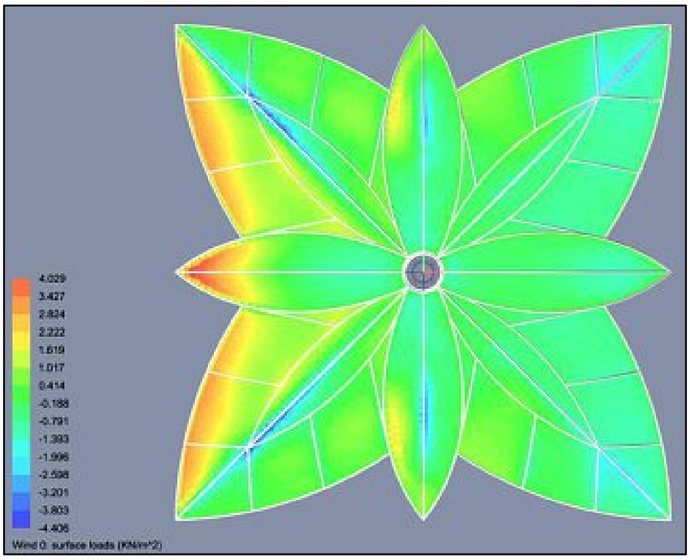


Figure 53: >The Sea Star< CFD wind load determination – Wind direction 90° (+x)
(source: Gerry D'Anza, ixRay Ltd.)

One of the final wind loads applied according to the above CFD calculation results can be viewed in following Figure 54. For more information on the procedure for implementing these loads and on the entire workflow, refer to Appendix E.1.

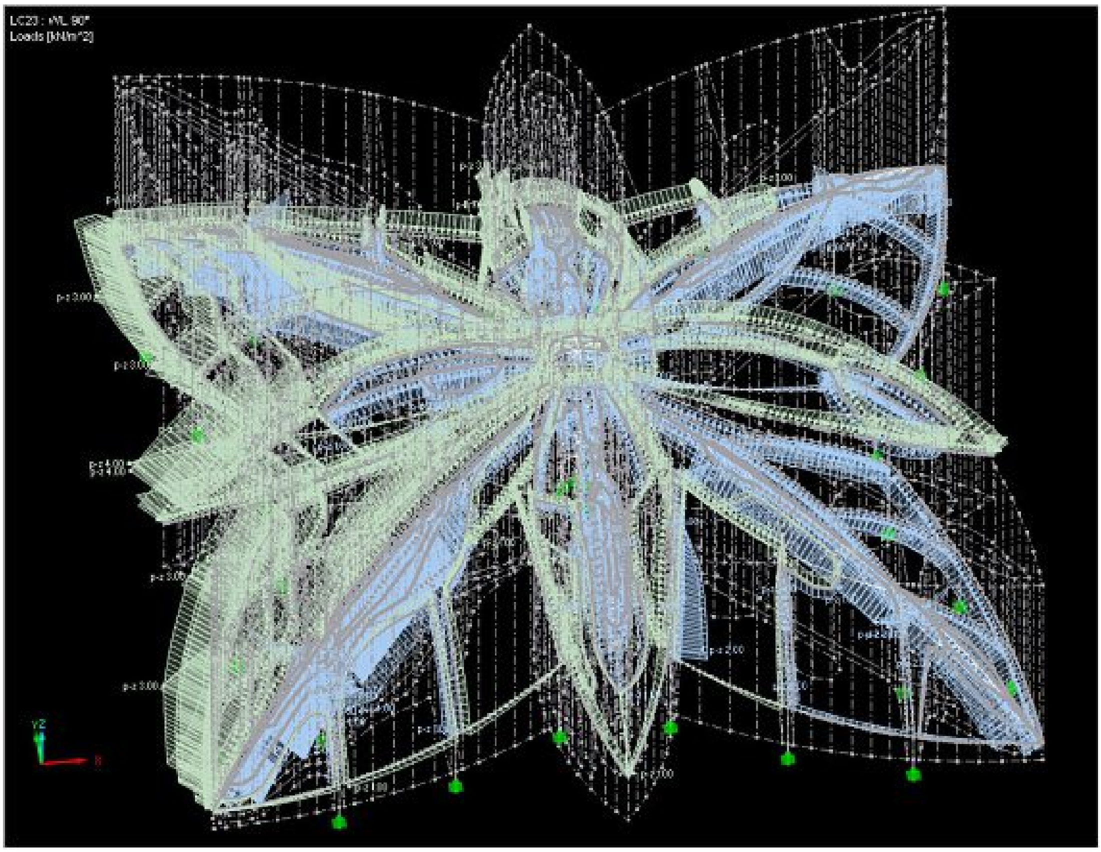


Figure 54: >The Sea Star< Finally applied wind load in RFEM acc. CFD – Wind direction 90° (= +x)
(by author)

Since >The Sea Star< is a practical project, all further loads and load case combinations for dimensioning should be provided as well. The tables can be found in Appendix E.1. Table 12 lists the load cases of the hybrid HY and the separate MEM model, Table 13 the load case combination scheme for the hybrid dimensioning. Due to the non-linearity, the factorisations in the separate approach must already be done in the membrane partial model MEM and not only by the combination factors in the STR model. For the separate calculation the "combined factored load cases" for the MEM partial model are given in Table 14 and the load case combinations for the separate dimensioning of the structure in the STR model in Table 15. An examination of the non-linearity of load effects in lightweight structures was carried out in the example of a membrane in an arched frame (MiAF) and the results can be found in Diagram 12 and Diagram 13, respectively the corresponding chapters.

System data and parameters:

- Festival Tents >The Sea Star<
- Geometry according to Figure 52; overall dimensions according to Figure 49
- Individual membrane sags developed according to optical appearance and structural considerations (n_x/n_y forces)
- Membrane chosen: PVC-PES type III; thickness: 0.78 mm
- Details like support details, spring stiffness, upstands, membrane offset and else neglected (to isolate the separate/hybrid effect)
- Chosen surface type in RFEM:
    - Geometry: B-spline surfaces
    - Stiffness: membrane orthotropic
- Membrane material properties used in the calculations: according to Figure 55
- Steel members:
    - Decision on the outer diameter of the various parts of the structure according to structural requirement in iterative work steps
    - Wall thickness of the various outer diameter components according to structural requirement
    - All members rigidly connected, except those explicitly specified
    - Steel grade: S 460 (to achieve a more gracile structure)
- Support conditions:
    - All fix in x, y and z
    - The four girder column supports rigid around all axes (no moment hinges)
    - All other supports free around all axes (moment hinges around all axes)

  - No spring stiffnesses used
- Load cases: according to Table 12
- Load case combinations for steel dimensioning: according to Table 13 for hybrid HY and Table 15 for separate STR calculation.
- Design: steel stress design elastic, no plastification; equivalent stress design according to von Mises

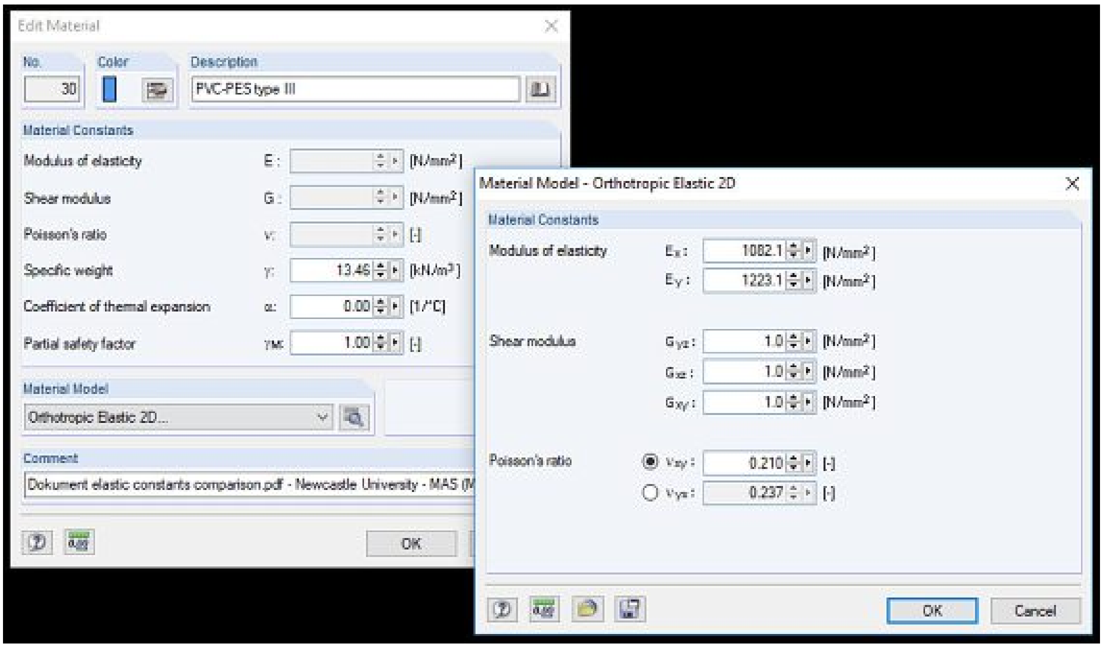


Figure 55: >The Sea Star< – Membrane material properties used in RFEM (by author)

6 Results and Discussions on Findings

In the following, the results of the investigations are presented, discussed and theories and explanations given. However, the author prefers the attitude not to interpret results too much and to draw conclusions. Instead he rather considers it the better way to present results without influencing the thoughts and impressions too much. The figures and graphs presented speak for themselves. An interpretation is to a special degree a matter of opinion and a subjective classification. Engineers should always gain own impressions and draw own conclusions. Own experiences and conclusions resulting from own investigations and calculations are the best way and not to follow the opinion of others. Nevertheless, it is somehow impossible to refrain entirely from conclusions and ratings in such a paper. In the following, conclusions of the author should always be considered as such, subjective assessments as some amongst many. Others certainly interpret things differently and on most issues there is simply no ultimate truth.

The descriptions of the investigations and procedures are presented in Section 5, conclusions and perspectives in Section 7.

6.1 General Items

The decision about the calculation method does not only affect forces, required cross-sections, costs and thus competitiveness, but also design and aesthetics. In addition, it is a decision considering safety as well. Hybrid calculations allow the realisation of more attracting and impressively slender architectures even requiring less elements than separate calculations. This is very significant in the presented practical project "Festival Tents >The Sea Star<" in Section 5.3, as well as in the basic examples.

The selection of the used static system is a first decisive item for the slenderness of a construction. The decision on the choice should be made jointly between architect and engineer during the project development phase and in the further course of a project. Unfortunately, it is often the case that architects only consult an engineer when having already finally decided on solutions. The engineer then has to struggle with a design, not allowed to adjust anything, not having the chance to add any positive influence in a design stage. A much better solution could be achieved if architects and engineers worked together very closely, investigating and exploring different options. Engineers should be involved in the development process to prevent technically impossible intents from being chosen, which then lead to visually questionable manifestations. Also, not only consulting "star engineering offices" which often only develop projects but do not execute, should be involved in a project development as these do not require optimised solutions due to lack of competition in their field. Thus, according to the author's experience, the result of "star engineering offices" is often unnecessarily over-dimensioned in terms of the overall structure, cross-sections, tonnage, costs, but also optical appearance. The author realised projects, very impressive and beautiful, but would have been possible to achieve even more beautiful, cost-efficient, impressive and explicitly mentioned also safe, if proposals of the executing company had not been rejected, often even without any argument why.

As an example, especially in lightweight construction, when an architect intends to achieve a very slender structure, but the design includes components subjected to bending, the engineer must advise and discuss the axial-forces-only possibilities to achieve a more slender architecture. This final decision on the type of structural behaviour: axial-forces-only on one side or load transfer by bending on the other, is a very decisive decision mostly taken very early in the course of a project.

6.2 Basic Structural Systems

6.2.1 Membrane in an Arched Frame (MiAF)

In this example, various comparative evaluations are presented, which are intended to facilitate various insightful and informative perspectives.

Initially, the hybrid models are used to determine which of the loading types has which effect on the given shape. There are the three most important basic types of loads:

- Local related to true area (e.g. wind pressure)
- Global related to true area (e.g. self-weight of cladding)
- Global related to projected area (e.g. snow load)

The results are depicted in Diagram 1. The load for all types is 1.0 kN/m². It was found that the load type >global related to true area< causes the highest utilisation for the given form. Other forms are more favourable for other loading types since the best form of a structure is also highly load-dependent. As an example, the most effective form under snow load for a vaulted structure is not a section of a circle but that of a parabola. This can exemplarily be seen in the gradient of the stress utilisation in Figure 57. A slight change in shape towards a parabola would be more effective here. The deformation gradient is also a very good indication. This is one aspect of engineering, the determination of the best form in shape efficiency investigations.

The best form can be found, for example, in iterative form change investigations in parametric programs such as Rhino together with Grasshopper. Most structures are loaded in scenarios that are too complex that theoretical approaches could easily solve the problem, or the structures themselves are very complex like structures including funnels. As stated above, a parabola is the best form for a uniform snow load, but there are further, completely different loads with unbalanced characteristics such as snow drifts or wind. A change in loading results in a different best shape-efficient form.

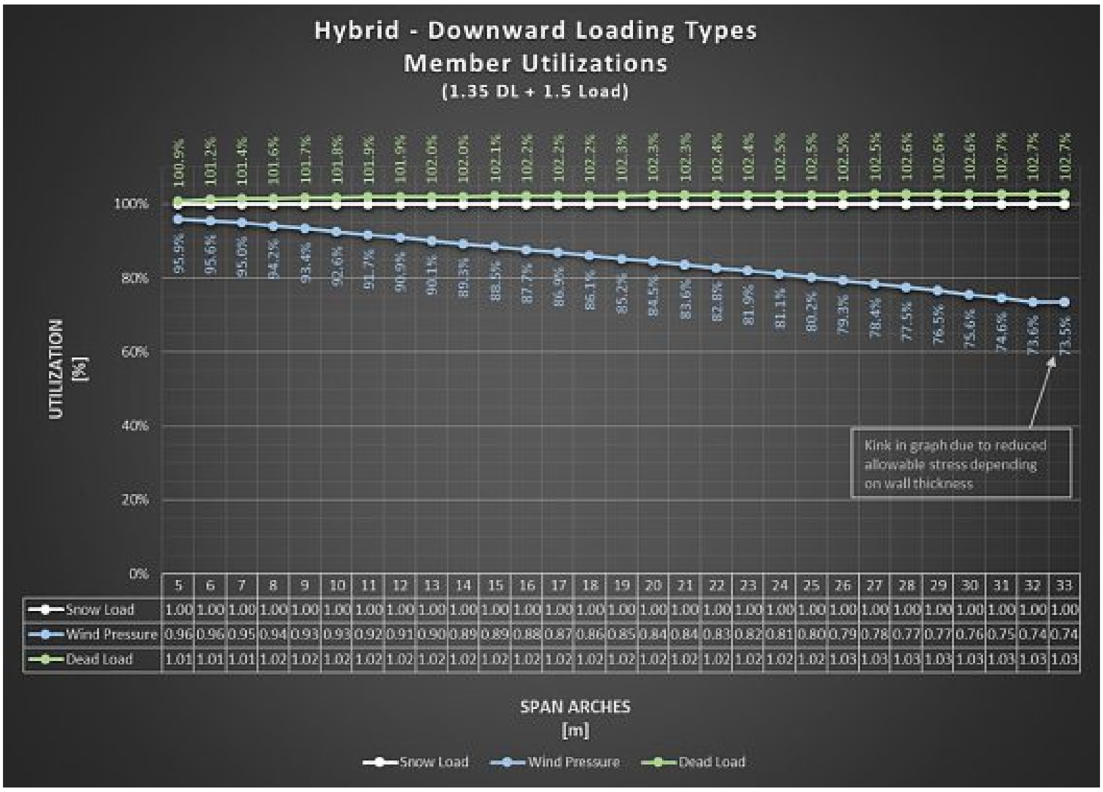
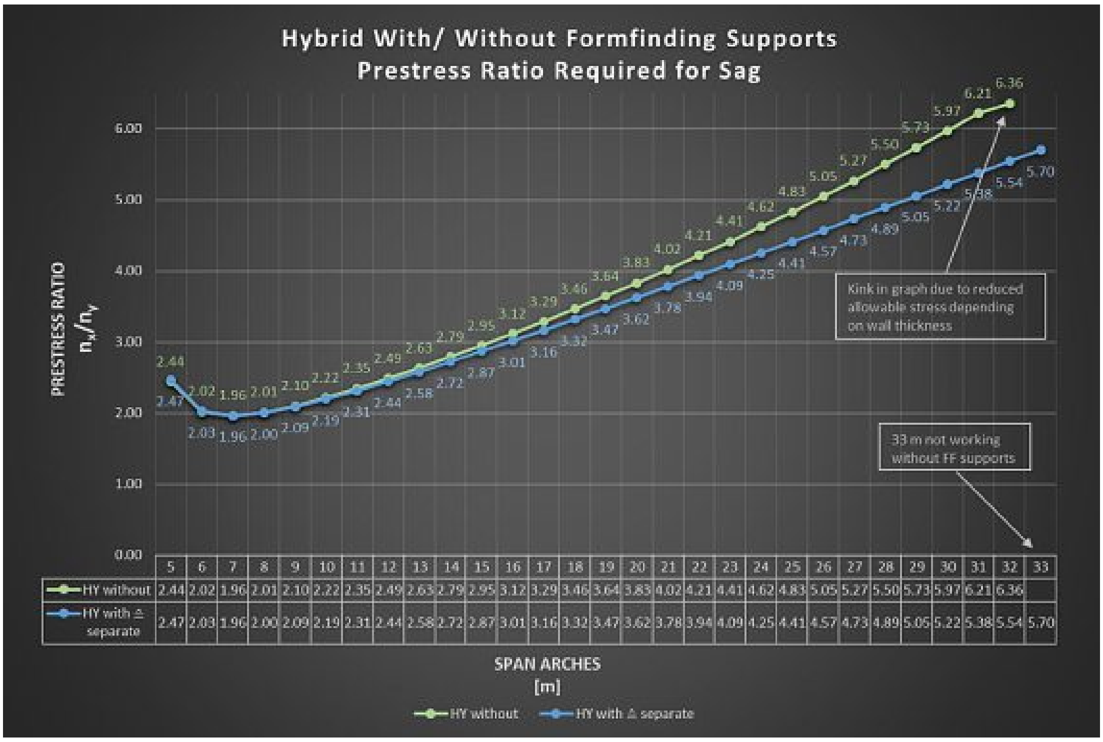


Diagram 1: MiAF – Investigation of governing downforce load direction/type (by author)

Diagram 1 shows a significantly deviating curve for the load direction >local related to true area< (blue curve) which stands for a pressure load, here wind pressure. The interesting thing is that the sum of loads, expressed simplified, is the same as that of >global related to true area< (e.g. self-weights), but the impact on the structure is much more favourable. By “the same in respect of the sum of the loads” is meant here, equal in relation to force times area. Only the direction of action vectors differs. One time it is perpendicular to the surface, the other time it is in gravitational direction. The reason of the different effect of the actions is clear. This is because a vaulted structure with the form of a section of a circle is loaded most favourably with this kind of loading. A simple comparison is a sphere under water which is the best shape for the water pressure to withstand. If such loads act on a parabolic arch with best shape to resist snow, then the graphs would invert. The results would be more favourable for the snow load, worse for the wind pressure.

The first results of the comparative investigations, shown in Diagram 2, illustrate the difference in the required prestress ratio to achieve the desired sag, here 10%.



	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
HY without	2.44	2.02	1.96	2.01	2.10	2.22	2.35	2.49	2.63	2.79	2.95	3.12	3.29	3.46	3.64	3.83	4.02	4.21	4.41	4.62	4.83	5.05	5.27	5.50	5.73	5.97	6.21	6.36	
HY with ≙ separate	2.47	2.03	1.96	2.00	2.09	2.19	2.31	2.44	2.58	2.72	2.87	3.01	3.16	3.32	3.47	3.62	3.78	3.94	4.09	4.25	4.41	4.57	4.73	4.89	5.05	5.22	5.38	5.54	5.70

Diagram 2: MiAF – Prestress ratio required for membrane sag (by author)

This aspect is also directly related to the prestresses that establish in the installed membrane or that are not as intended due to incorrect procedures. Without form-finding supports the prestress ratio needs to be higher than without form-finding supports. Or in the separate calculation – since the arches deflect inwards in the form-finding calculation – the span of the membranes is reduced, etc. All this leads to the effect of required higher prestress ratio settings in the form-finding calculation.

Maybe most impressively the following Diagram 3 and Diagram 4 illustrate the difference between hybrid and separate calculation.

Diagram 3 visualises the stress utilisation of the separate calculated models compared to the hybrid. The blue horizontal bar is the 100.0% utilisation of the components in hybrid statics. The separate statics according to Th. II. O. shows overstress up to 434.3%. In the separate statics according to Th. III. O. the iterations even abort with an error message of instability from a span of 28 m on. Therefore, not only an overload is given but also the possibility for a global stability issue is pointed out.

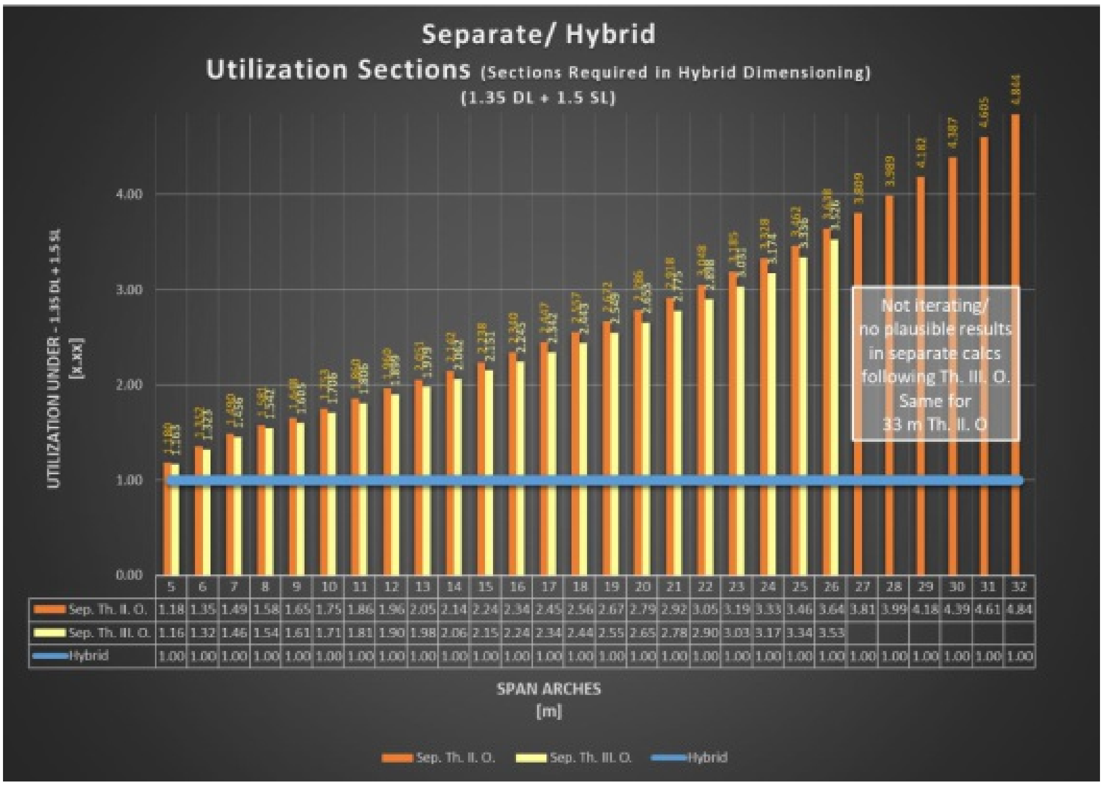


Diagram 3: MiAF – Separate/hybrid – Stress utilisation of sections (by author)

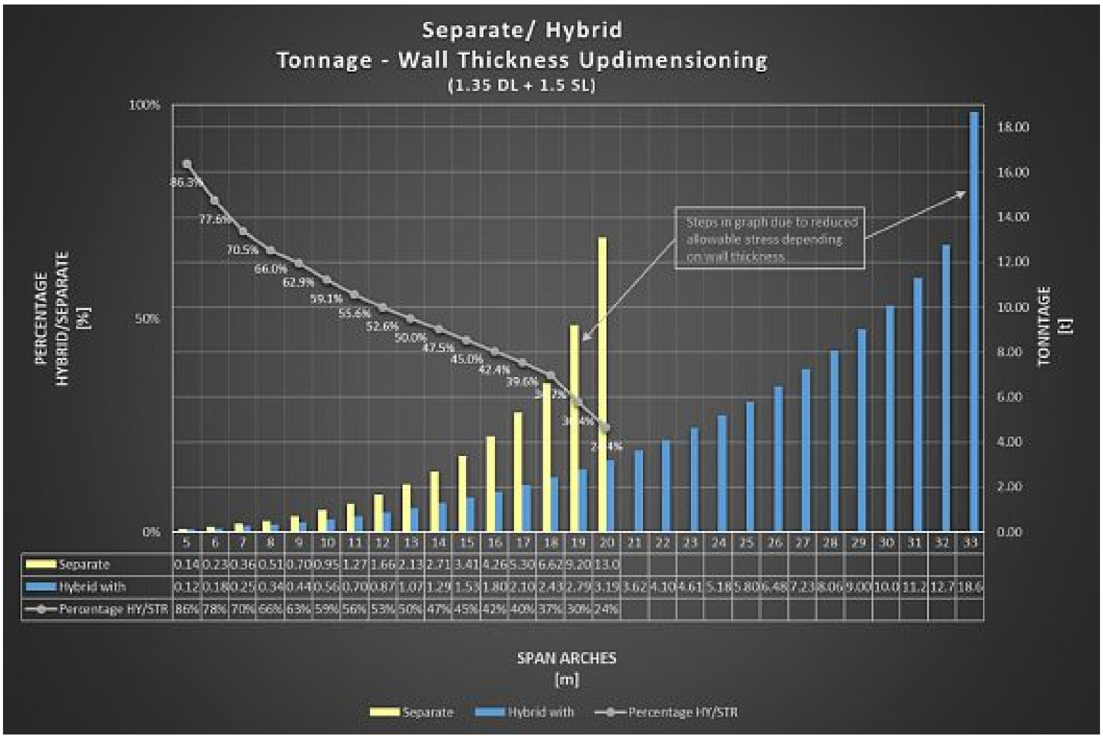


Diagram 4: MiAF – Separate/hybrid – Required tonnage and feasible spans (by author)

Diagram 4 clearly shows how enormously the tonnage can increase when calculating separate instead of hybrid. Maintaining the outer diameter and dimensioning over the wall thickness results in the steel tonnage presented. The ratios are immense when the span increases. For the presented example a span of 30 m is possible in the hybrid calculation whereas the separate approach allows a maximum of 20 m. This even with already overstressed members (103.2% in Th. II. O. and 101.5% in Th. III. O. program settings). For the 20 m span, which is the maximum feasible separate, and this even with already existing overstress, only 23.6% of the steel mass is required hybrid. Or conversely, 4.24 times the steel mass is required separate compared to hybrid.

The tonnage comparison of the required cross-sections according to hybrid Th. II. O. and hybrid Th. III. O. is shown in Diagram 5 below. The 20 m model was omitted here since it does not meet the basic procedure of this work to always remain within the elastic range in the dimensioning.

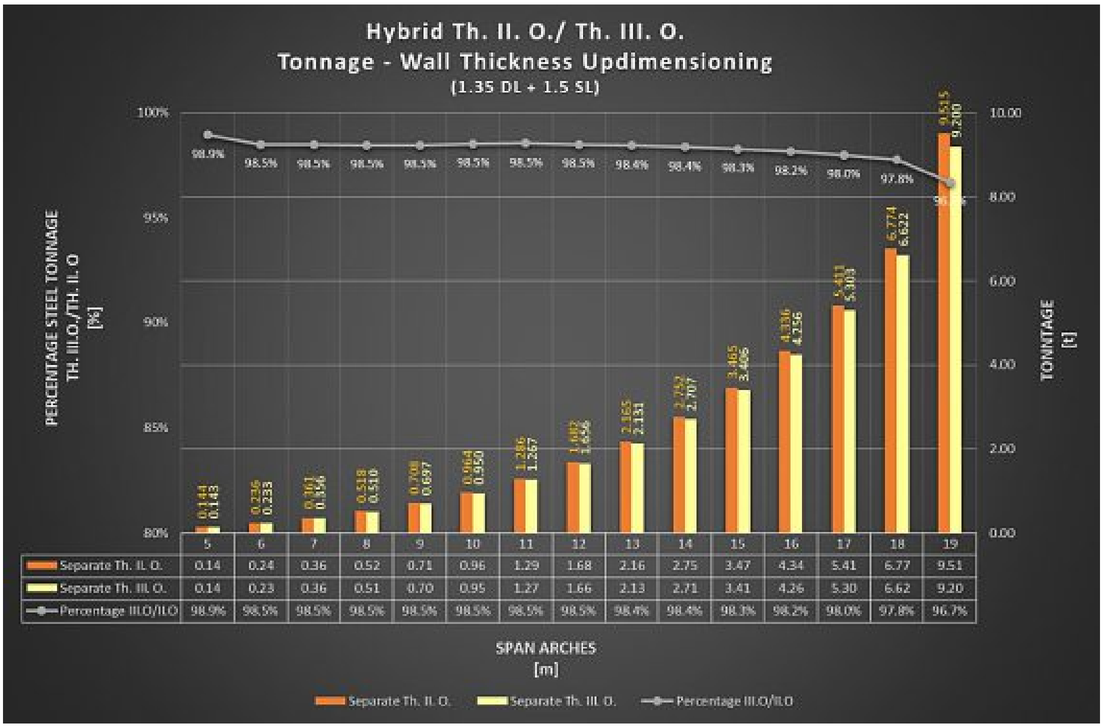


Diagram 5: MiAF – Hybrid – Comparison tonnage Th. II. O./Th. III. O. (by author)

The Th. II. O. and Th. III. O. setting calculations of the separate model STR should not be rated here, as the decision on this includes several aspects, not only accuracy, which may be argued being higher in Th. III. O. Very important also is whether the deflections in the separate calculation make sense to work with or not. The results are only presented here without classifying one of them as better or worse.

The following Diagram 6 shows the influence of another special point. In the hybrid calculation two different approaches exist how to deal with the geometry of the substructure in the form-finding process in conjunction with the technical implementation in reality. Including the structure in the form-finding process would mean in the real world a pre-deformed structure corresponding to the form-finding results. These pre-deformations should be those necessary to achieve the original geometry after the deformations that occur during membrane installation and pre-tensioning. Otherwise the calculation would not meet the conditions of realisation. To imagine, an empty load case is to be assumed in which only the prestress is included then. Results of this load case are for instance stresses in membranes and internal forces in components, but no deflections, thus the original geometry. This is practically only possible if the structure is pre-deformed and the deflections back to the original geometry lead to these stresses and internal forces. When building the structure, here the frame, according to the initial geometry without precambering, then form-finding supports are required to be correct in regard of the calculation. This issue is described in more detail in paragraph 7. One main thing when mixing up things here is the prestress which the membrane receives after being installed. When including the structure in the form-finding (not using form-finding supports), the prestress of the installed membrane is mostly remarkably lower than the calculations indicate. In practice this may result in wrinkles. Many codes or guidelines recommend a maximum warp/weft prestress ratio to avoid wrinkles. Keeping this ratio in the calculations does not help when making the above described mistake and the prestress ratios in the physical project exceed the calculated ones.

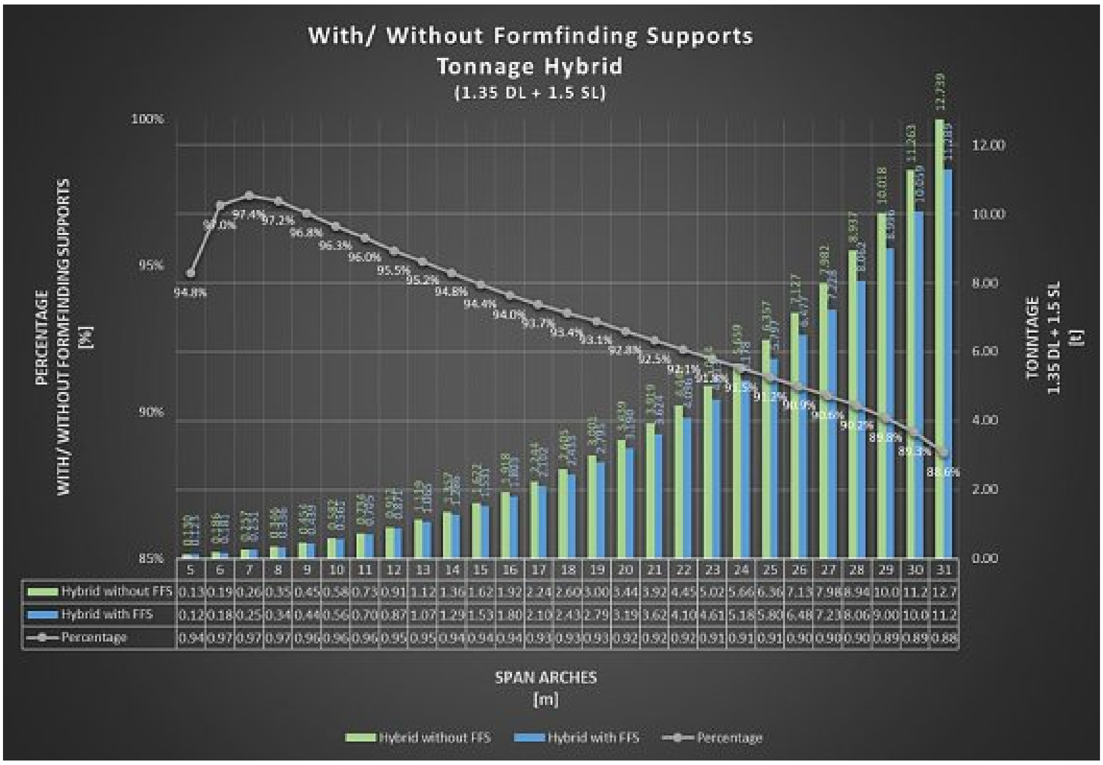


Diagram 6: MiAF – Hybrid with/without form-finding supports – Required tonnage (by author)

Diagram 6 depicts the tonnage required when using form-finding supports or not. Normally it should not be the case that there is a deviating prestress in the membrane other than planned. Nevertheless, this situation is often the case and thus the deviations are given. This effect should only be visualised here, not rated, especially not the handling in practice. Furthermore, the engineer can decide to neglect this effect, to follow this procedure and operate in the described range. Therefore, it is not rated as an error here, however, this effect should be presented. In the example the ratio of tonnage ranges from 97.4% for low spans up to 88.6% for wide spans.

Diagram 7 below shows the difference in the influence of the prestress on the dimensioning. The graphs indicate the member stress utilisation caused by the membrane prestress. For reasons of comparability the same cross-sections were used for all three methods, those of the least cross-sections requiring calculation, the hybrid with form-finding supports dimensioning. If the cross-sections were different for all methods, this would falsify the comparison, because the stress utilisation of a special effect is self-explanatory lower if the cross-sections are stronger. Therefore, the same cross-sections were used for all three methods.

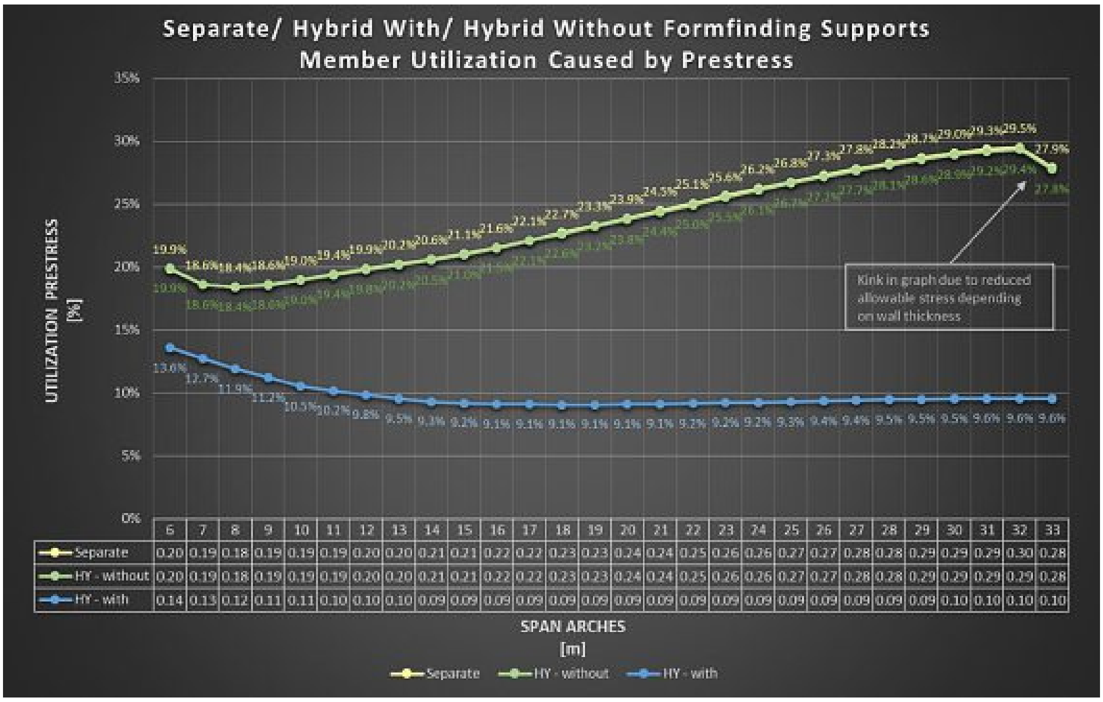


Diagram 7: MiAF – Separate/hybrid – Utilisation sections under prestress (by author)

As it can be seen in Diagram 7, stress utilisation resulting from the prestress is by far the lowest in the hybrid statics with form-finding supports. The main reason is again the issue mentioned before. In the calculation with form-finding supports, the prestress in the form-finding calculation is the one according to the software settings like it is for the other methods as well. However, in the calculations with form-finding supports the resulting prestresses after physical installation and the settled deflections are then lower. Thus, the stress utilisation caused by the prestress is lower. Another effect influencing the results are the higher resulting deflections in this procedure.

The yellow and green graphs in Diagram 7 also verify the very good matching results of the exercised working method. The separate and hybrid calculations with form-finding supports show that the results are so to say absolutely identical. In case of a deviation, this is max. 0.1%.

The comparison process was geared to the dimensioning of the cross-sections according to the mostly governing load case of snow. All models were dimensioned for the load case combination snow (1.35 DL + 1.5 SL). The following graph shows the utilisation of the such dimensioned structures in the wind suction load case combination (1.0 DL + 1.5 WS). Here, the same cross-sections were used in the different methods as well.

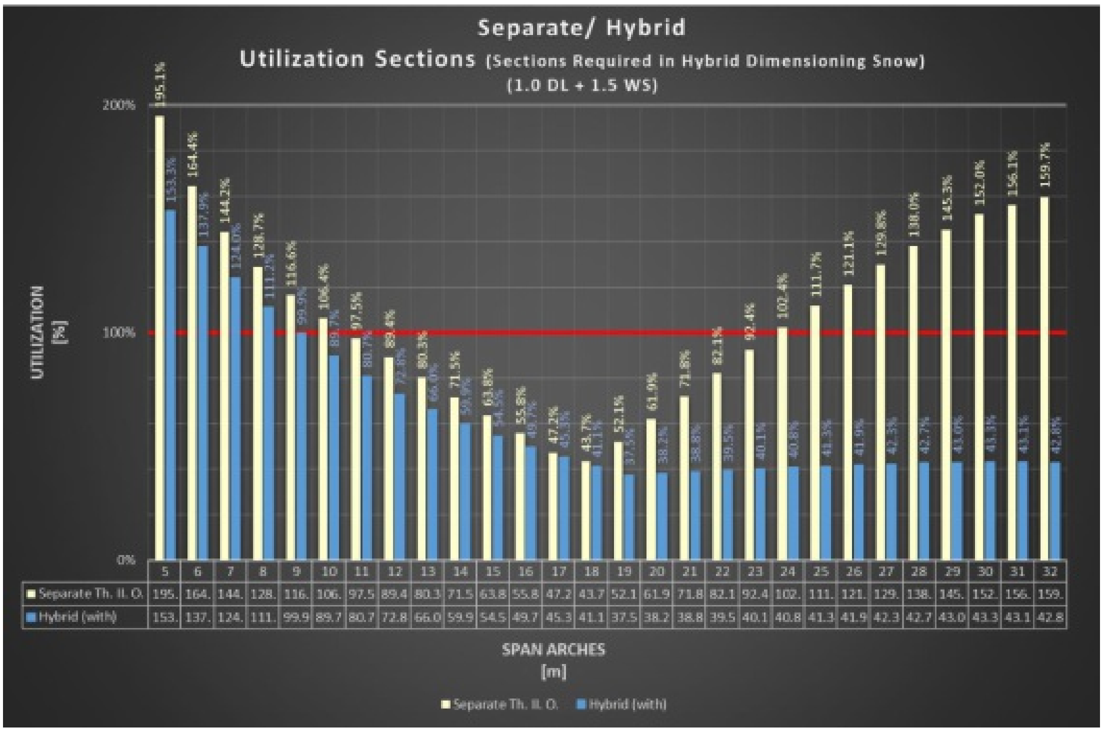


Diagram 8: MiAF – Separate/hybrid – Stress utilization wind (by author)

As the diagram illustrates, up-dimensioning would be required for the ≤ 10 m span models in the separate calculation and for the ≤ 8 m span models in the hybrid calculation. The members required to dimension up would be the short members here, not the arches, as the following utilisation plot depicts exemplarily, which makes sense since the wind suction being carried by the membrane in y-direction.

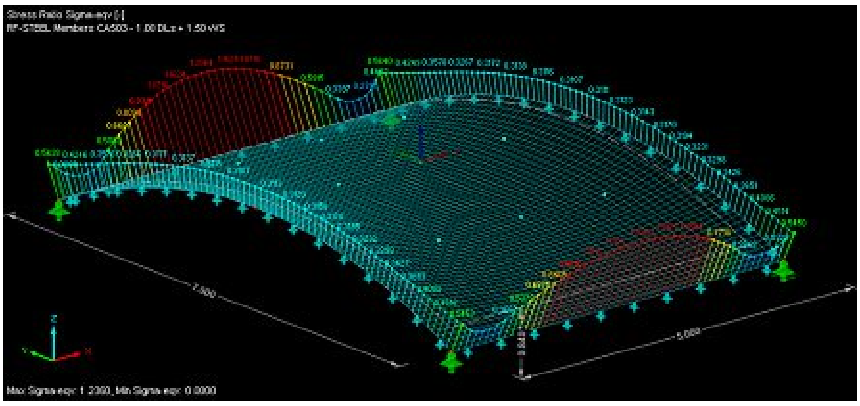


Figure 56: MiAF – Overstressed members in RFEM – wind suction – hybrid model HY (by author)

It should be mentioned that for the spans ≤ 7 m the upwards/y-directional sag of the membrane for wind suction is low and would likely be increased in a real project.

Diagram 8 also shows that in hybrid calculation no wider spanning models would require up-dimensioning with a maximum wind suction utilisation of 43.3%. So, if the wind suction would be the governing load, an immense down-dimensioning would be possible hybrid. Different for the separate calculation. Already for spans ≥ 24 m up-dimensioning for all sections would be necessary due to a utilisation of 102.4% for the 24 m span model and up to 159.7% for the 32 m span model. The utilisation ratio for wind suction separate to hybrid is up to 372%.

Figure 57 depicts the maximum stress utilisation profile within the frame of the 32 m spanning separate calculation model STR, which is 159.7%. The corresponding one in the hybrid model HY in Figure 58 is only 42.88%.

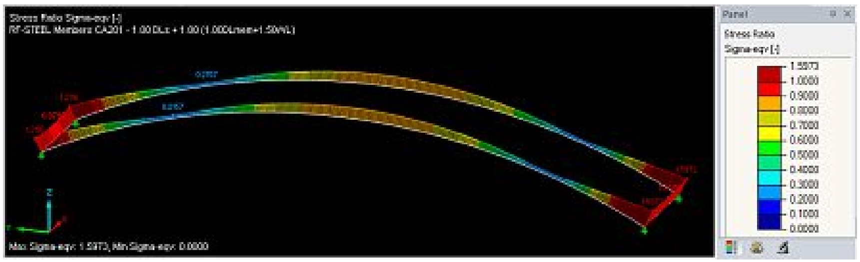


Figure 57: MiAF – Utilisation members – Wind suction – Separate model STR – 32 m (by author)

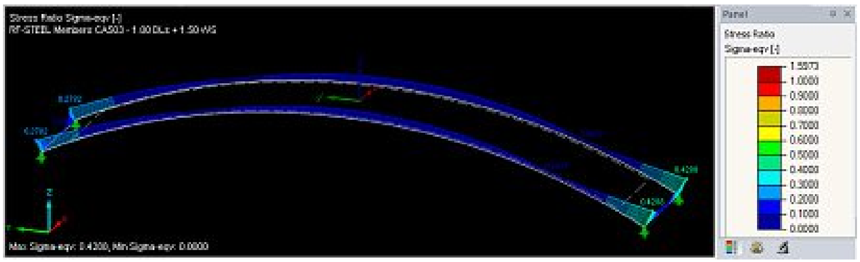


Figure 58: MiAF – Utilisation members – Wind suction – Hybrid model HY – 32 m (by author)

The other comparative procedure in this thesis is dimensioning the cross-sections by their outer diameter, keeping the wall thickness the same for the different methods. This should visualise one of the optical, architectural effects, the more massive cross-sections required.

The outer diameter in the hybrid design is always 219.1 mm, which is represented by the horizontal blue bar in Figure 9 below. The up-dimensioning of the separate models result in an outer diameter of more than 260 mm already for the 7 m span model, more than 280 mm for the 10 m span and up to almost 350 mm for the widest spanning investigated model. This illustrates very clearly that the dimensioning by separate calculation is not only a question of cost, but also of great importance with regard to optically more massive and less appealing structures. Already in the past, this optical aspect has become more and more important in the market and will certainly gain even more importance in the future. Today it is often not the costs that is of highest priority for the client when deciding about the company for a project realisation. Optical appearance and slenderness are often the number one priorities for many clients and even more often for architects.

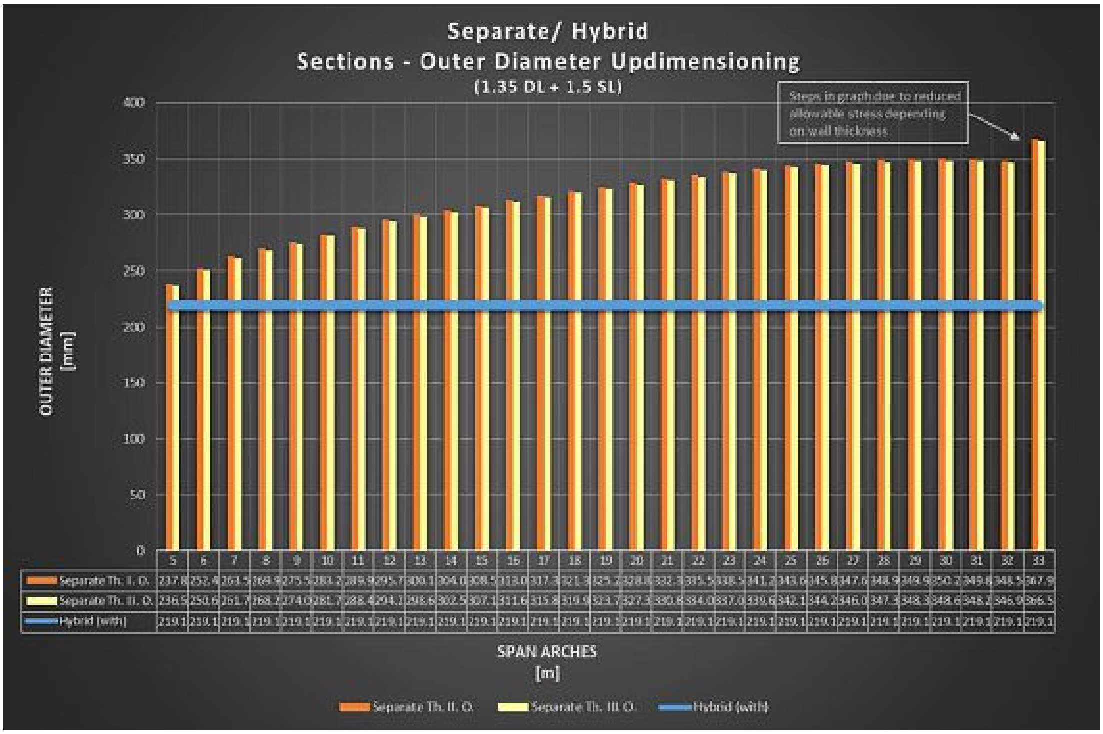


Diagram 9: MiAF – Separate/hybrid – Required profile diameters (by author)

The next comparison in this example shall focus on the membrane stresses. The following diagrams always show only the membrane forces in the direction taking the respective load as they are the relevant ones. The first following graph compares the membrane forces in y-direction for the wind suction load case combination 1.0 DL + 1.0 WS. The second one shows the membrane forces in x-direction for the snow load case combination 1.0 DL + 1.0 SL.

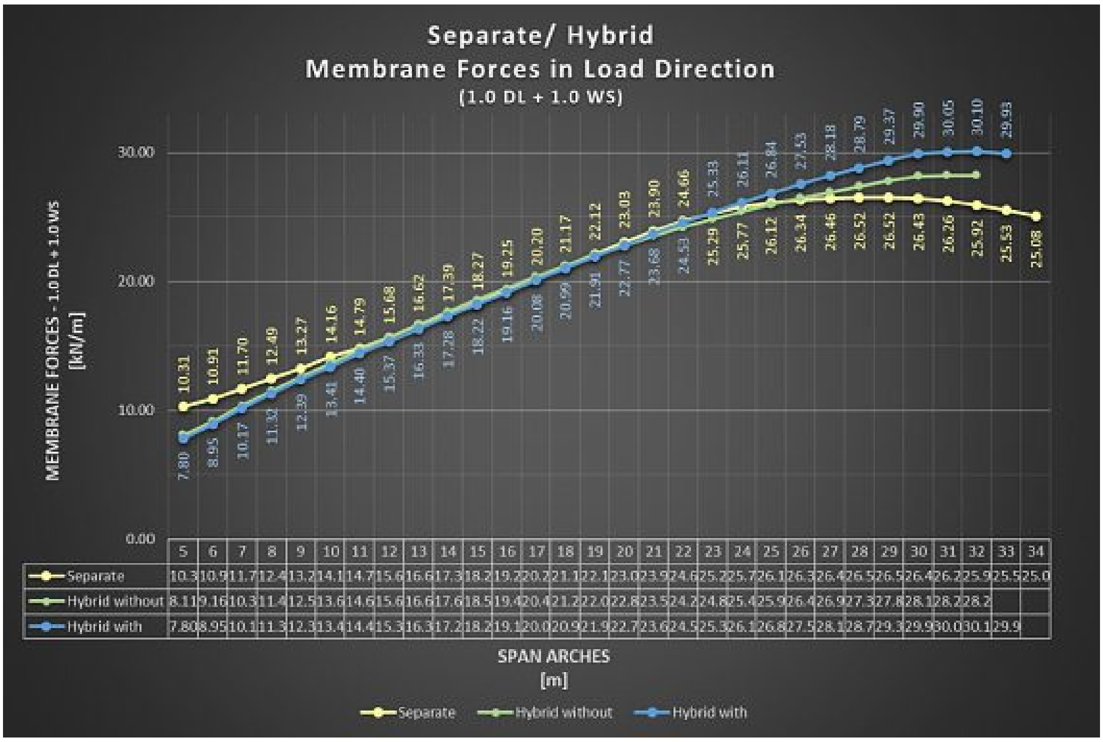


Diagram 10: MiAF – Membrane forces in y-direction – Wind (by author)

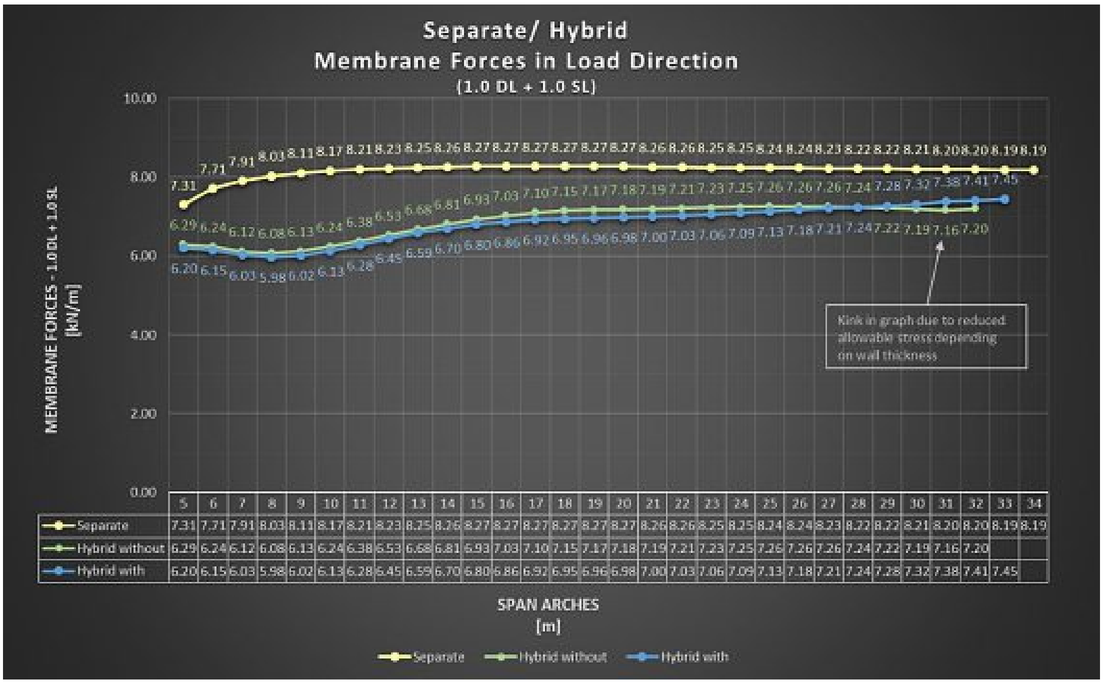


Diagram 11: MiAF – Membrane forces in x-direction – Snow (by author)

According to engineering guesses, it seems clear that the deviation in membrane forces is higher under snow load as this loading result to an inwards deflection of the arches to a higher extent, which is a main reason for the decrease in membrane forces. Nevertheless, also for wind suction remarkable deviations exist although only relatively small deflections of the short members may be expected. Under snow load the membrane forces with and without form-finding supports remain quite similar. Only for wide spans a remarkable deviation arises. The main reason for this can be found in the effect that high arch deflections lead to a decrease of membrane forces at arch midspan, ending in a kind of stress concentration at the outer membrane edges. Another reason is the lower sag at these locations, which may be an item for adjustments.

Some comparative results regarding the non-linearity of load effects in lightweight structures are shown in the following two diagrams. The correct procedure, in case this can be said for a separate calculation, is to combine the loads already in the membrane partial model MEM and transfer the forces to the structural model STR. The stress utilisations of this method reflect the orange graph in Diagram 12. The results of the wrong procedure ignoring the non-linearity of load effects, are represented by the yellow line. A clear non-linearity can be identified.

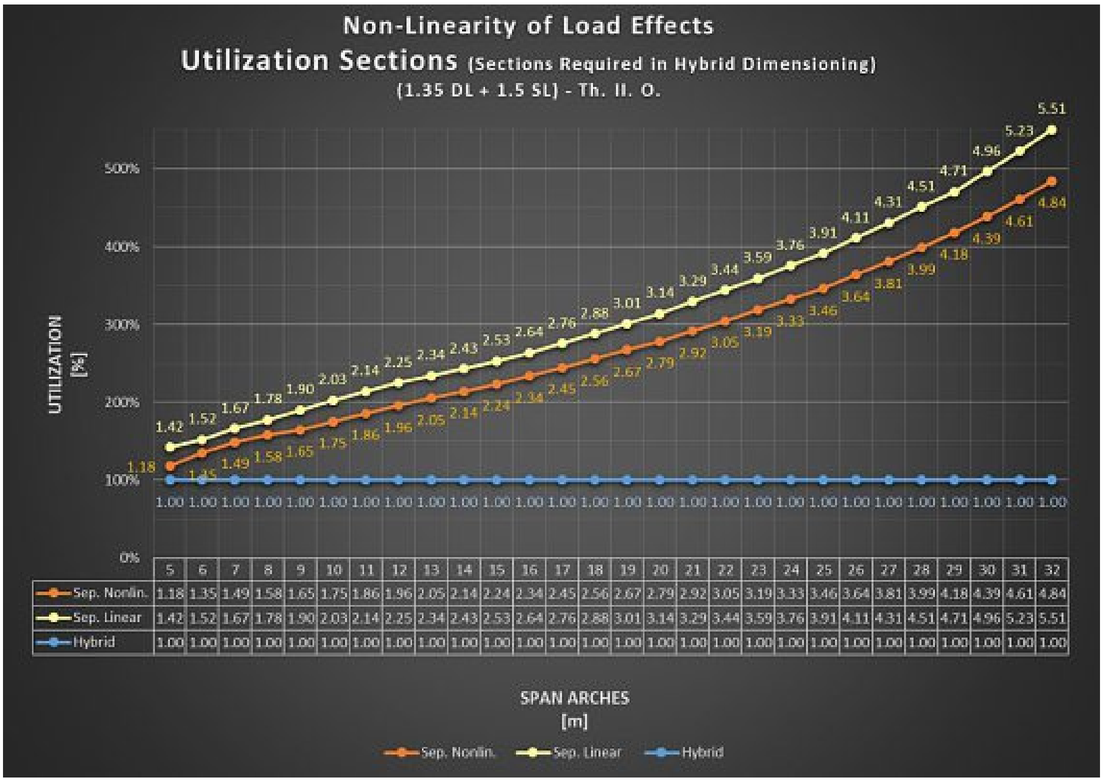
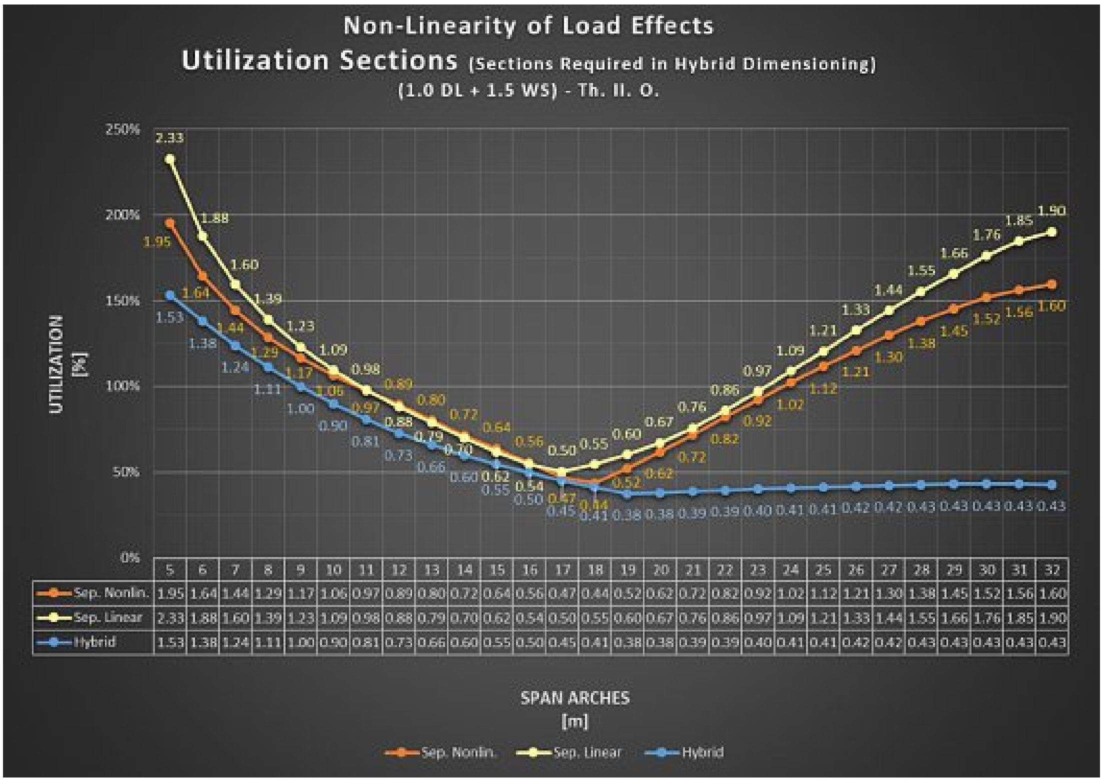


Diagram 12: MiAF – Non-linearity of load effects – LCC 1.35 DL + 1.5 SL (by author)

The same applies for wind suction in the following Diagram 13. To once again emphasise the immense deviations between separate and hybrid calculation, the results of the hybrid models are also included in both diagrams.



	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Sep. Nonlin.	1.95	1.64	1.44	1.29	1.17	1.06	0.97	0.89	0.80	0.72	0.64	0.56	0.47	0.44	0.52	0.62	0.72	0.82	0.92	1.02	1.12	1.21	1.30	1.38	1.45	1.52	1.56	1.60
Sep. Linear	2.33	1.88	1.60	1.39	1.23	1.09	0.98	0.88	0.79	0.70	0.62	0.54	0.50	0.55	0.60	0.67	0.76	0.86	0.97	1.09	1.21	1.33	1.44	1.55	1.66	1.76	1.85	1.90
Hybrid	1.53	1.38	1.24	1.11	1.00	0.90	0.81	0.73	0.66	0.60	0.55	0.50	0.45	0.41	0.38	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.42	0.43	0.43	0.43	0.43	0.43

Diagram 13: MiAF – Non-linearity of load effects – LCC 1.0 DL + 1.5 WS (by author)

Some membrane stress plots are intended to visualise typical differences and give an idea about how the conspicuous change and mapping of stresses within the membrane is located in the different approaches. Several colour plots are given in Appendix A. Exemplarily, the distinctly deviating deformations of Figure 76 is a very typical result of separate calculation of membranes or cushions of this type. On the first page in the appendix the results of the membrane forces in warp direction under 1.0 DL + 1.0 SL are shown. It can be identified very clearly that the membrane forces decrease starting with the stiffest, the separate calculation with fix supports, over the hybrid without form-finding supports, ending with the hybrid with form-finding supports. The key factor is the freedom of the arches to deflect, which results in lower membrane forces mainly at arch midspan. This is one major effect that should always be kept in mind.

For best comparability, the colour scale was chosen to be always identical for all and not from zero to the maximum in each, which would spoil the optical effect. All three colour plots are displayed on one page to allow a direct comparison. On the second page diagrams depict the exact membrane forces in x'-direction (warp) for the above forces in a section at x-midspan (x = 2,500 mm). Furthermore, the local z'-deflections are given, which differ immensely. Membrane deflections and forces are in direct relation to each other.

The following table summarises the most significant values. The listed max. membrane forces n_x are located at the arches, the ones in brackets at membrane midspan, according to the two sections in Figure 59. The value u_z' reflects the local membrane deflections perpendicular to the surface, u_y' the member deflection of the arches in local member y-direction. Colour plots of the listed results can be found in in Appendix A in the referred figures in the comment column of the table.

Table 1: MiAF – Membrane forces n_x and local deflections u_z' – 1.0 DL + 1.0 SL – 20 m span models (by author)

	Separate MEM	Hybrid without	Hybrid with	Comment
n_x max. [kN/m]	8.27 (7.99)	7.26 (6.99)	7.45 (6.99)	Figure 67, Figure 68, Figure 69
n_x mid arches [kN/m]	6.76	2.54	2.29	Figure 70, Figure 71, Figure 72
u_z' membrane [mm]	-148.9	-593.2	-731.6	Figure 76, Figure 77, Figure 78
u_y' arches [mm]	0	246.1	326.7	Figure 73, Figure 74, Figure 75

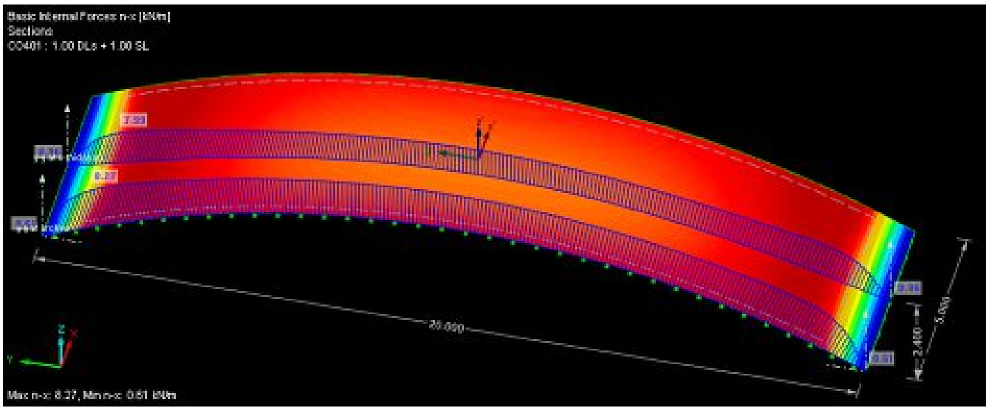


Figure 59: MiAF – Membrane forces n_x at arches respectively membrane midspan – 1.0 DL + 1.0 SL – 20 m span model – Separate model MEM

Finally, perhaps the most impressive difference of hybrid versus separate calculation of the presented example. With the boundary conditions and criteria used, the max. feasible span in the hybrid calculation is 33 m, but only 19 m in separate calculation.

6.2.2 Hypar

For a hypar, not using formfinding supports is the correct way to go if the calculation process and installation are coordinated and carried out accordingly. But also for a hypar, in case the dimensions of components and membrane are manufactured and installed according to undeformed model data and no prestress of cables and membranes or at least the exact dimensions are calibrated after membrane installation, then the resulting outcome is as listed following the model with formfinding supports.

In the following tables some key results of the calculated models are presented. Where two values are listed the first refers to the long struts or cables, the second to the short ones. The membrane forces and deflections relate to the non-factored combinations 1.0 DL + 1.0 SL respectively 1.0 DL + 1.0 WS.

Table 2: Hypar Type A – With four struts and eight cables – Key results (by author)

	Separate	Hybrid without	Hybrid with	Comment
Utilization struts [%]	263.6 111.7	100.0 100.0	48.6 64.2	Figure 79; Figure 80; Figure 81
Max. forces bracing cables [kN]	262.1 236.4	194.5 192.8	174.4 167.8	Figure 82; Figure 83; Figure 84
Max. forces struts [kN]	-534.3 -312.8	-408.9 -253.4	-370.6 -217.9	Figure 82; Figure 83; Figure 84
Max. forces membrane edge cables [kN]	117.0	90.5	80.14	Figure 85; Figure 86; Figure 87
Membrane prestress result (LC DL) n_x / n_y [kN/m]	1.57 / 1.50	1.56 / 1.50	0.58 / 0.52	–
Membrane forces SL n_x max. [kN/m]	12.57	11.70	11.52	Figure 88; Figure 89; Figure 90
Membrane forces WS n_y max. [kN/m]	11.89	11.46	11.09	Figure 91; Figure 92; Figure 93
Local membrane deflection SL u_z' [mm]	-469.9	-667.9	-839.1	–
Local membrane deflection WS u_z' [mm]	458.6	558.5	710.1	–

Table 3: Hypar Type B – Column bending type – Key results (by author)

	Separate	Hybrid without	Hybrid with	Comment
Utilization columns [%]	118.7 112.7	100.0 100.0	93.1 92.0	Figure 94; Figure 95; Figure 96
Max. bending moment [kNm]	924.2 347.3	777.6 308.1	723.5 283.3	Figure 97; Figure 98; Figure 99
Max. forces membrane edge cables [kN]	117.0	99.2	92.0	Figure 100; Figure 101; Figure 102
Membrane prestress result (LC DL) n_x / n_y [kN/m]	1.57 / 1.50	1.56 / 1.49	0.84 / 0.82	–
Membrane forces SL n_x max. [kN/m]	12.57	11.91	11.71	Figure 103; Figure 104; Figure 105
Membrane forces WS n_y max. [kN/m]	11.89	11.64	11.41	Figure 106; Figure 107; Figure 108
Local membrane deflection SL u_z' [mm]	-469.9	-590.5	-689.9	–
Local membrane deflection WS u_z' [mm]	458.6	509.9	593.5	–

The main difference between hypar type A and B is certainly the required cross-section of the columns. The chosen required sections of the columns are according to Table 4.

Table 4: Hypar Type A and Type B – Comparison required sections

	Hypar Type A Struts and Cables	Hypar Type B Column Bending	Percentage Type A / Type B
Diameter long struts/columns [mm]	139.7	457	30.57%
Diameter short struts/columns [mm]	88.9	273	32.56%
I_y long struts/columns [cm^4]	666	12026	1.31%
I_y short struts/columns [cm^4]	99	50691	0.82%

The choice of the type of structural behaviour has a decisive impact on the optical appearance of a lightweight structure and its components. This becomes very clear when comparing the following optical appearance of the two dimensioned types.

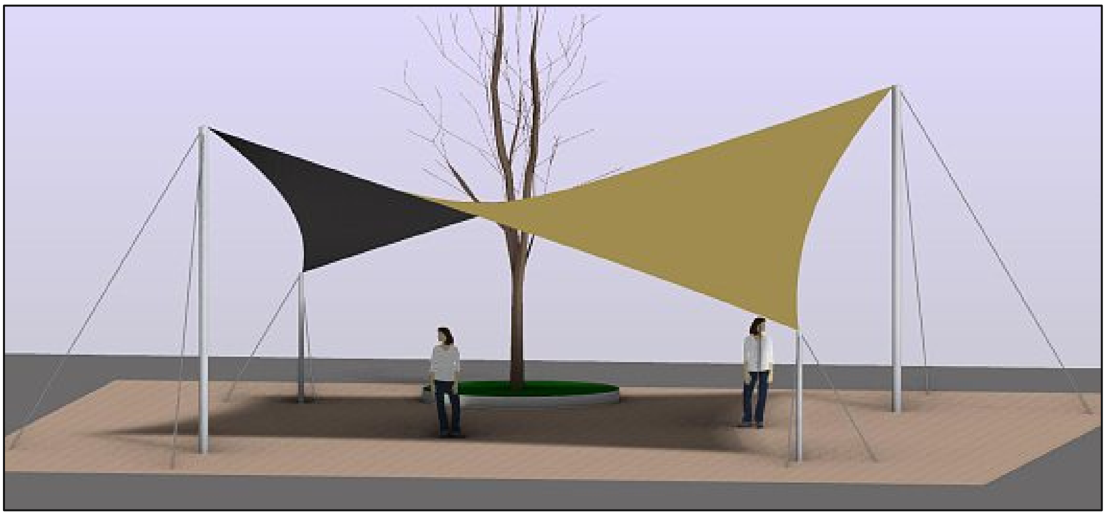


Figure 60: Hypar Type A – Dimension of members

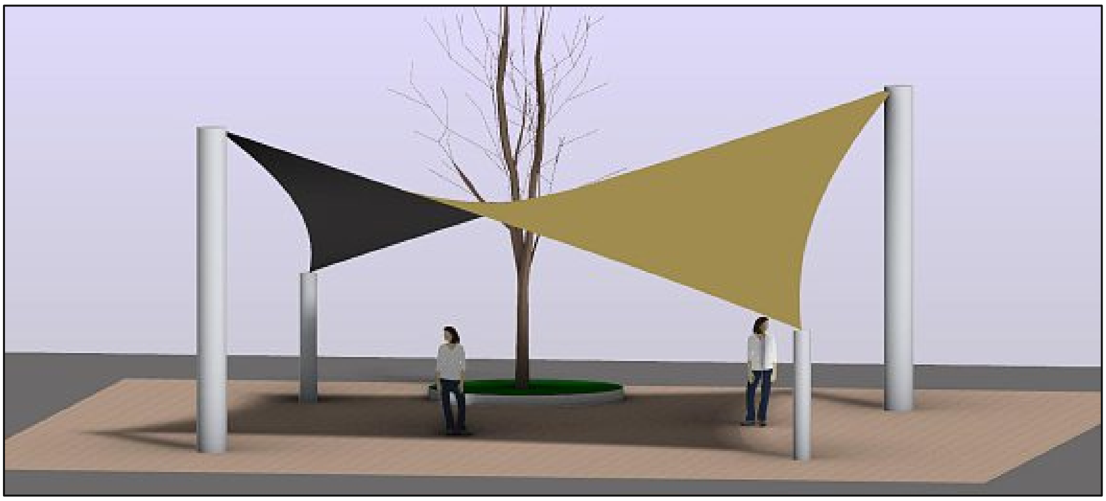


Figure 61: Hypar Type B – Dimension of members

Diverse results of the comparative calculations are presented in Appendix B. On the one hand, comparisons are presented between the opposing calculation methods with regard to member utilizations, internal forces of components and membranes. On the other hand, the two hypar types are compared, Type A in Appendix B.1 and Type B in Appendix B.2.

6.2.3 Flat Triangular Cushion (Edges in Plane)

The following table lists the maximum membrane stresses of the calculated models. The first value always refers to the respective stresses of the top layer, the second to the lower. Illustrating comparative colour plots are arranged in Appendix C.

Table 5: Flat Triangular Cushion – Relevant Stresses (by author)

	Separate loading option 1	Separate loading option 2	Hybrid with gas laws	Comment
LL [N/mm²]	3.21	–	–	–
	10.71	7.87	7.86	Figure 109; Figure 112; Figure 115
WP [N/mm²]	3.21	–	–	–
	10.37	7.52	7.47	Figure 110; Figure 113; Figure 116
WS [N/mm²]	14.12	11.41	11.11	Figure 111; Figure 114; Figure 117
	3.20	–	–	–

A pneumatic cushion is a prestressed system, such as for example a bolted connection is. The general load-carrying behaviour of a prestressed system is as follows. When an external load acts against the load that caused the pretension, the stress decreases until it becomes zero. Until this point is reached nothing is recognisable than the decrease of pretension. Only when the external load reaches the same value as the action causing the prestress, further effects are there. If an external load acts in the same direction as the effect causing the pretension, the stress only increases when the effect causing the pretension is exceeded. Before this point is reached, the stress does not change.

For the example of a pneumatic cushion, this means that a long-term external load is carried 100% by the layer against which prestress causing action it is directed. For wind pressure this is the outer layer and the prestress causing action is the internal pressure. This is the case as long as the load remains lower than the prestress causing action, the internal pressure. When this point is exceeded, 100% of the additional external load is carried by the layer in which the action is directed, the lower layer.

In other words, for a pneumatic cushion the behaviour is that an external constant load (not a short-term load) on the top layer causes the stresses in the top layer to decrease until the load reaches the amount of internal pressure. Up to this point, the prestressed top layer carries the entire load by the reduction of its prestress. For the bottom layer the stresses do not change until this point is reached. If the external load exceeds the internal pressure, the prestress in the top layer is zero and the cushion collapses under long-term load conditions. In the case of short-term loads such as wind gusts, the behaviour is more complex and differs from the one described above. The behaviour under short-term loads will be described later.

In the industry, when calculating cushions separate or simplified, applying loads to pure membranes in finite element software, not modelling a holistic cushion including gas volume and substructure, some of the following mistakes are often made, mostly leading to over-dimensioning or in the case of the second following point are just simply wrong.:

- The internal pressure for some or all downward load scenarios is added to the external load for the lower layer. This approach does not reflect the reality as it does not cover the character of a pneumatic cushion being a prestressed system.
- The lower layer under live load or snow load is always calculated on the basis of the internal pressure. This is only realistic if the load remains lower than the internal pressure or if the load is limited to a small partial area. Otherwise, the cushion collapses in reality.
- A general mistake often made is not following the non-linear character of load effects in such structures by manually applying unfactored loads to the cushion in separate or simplified calculations and then transferring the resulting forces to the model of the substructure, factorising them in the load case combinations. This is not correct due to a violation of the non-linearity behaviour, which mostly leads to over-dimensioning.

The described procedure, calculating ETFE cushions separate or simplified without the gas laws, seems to be a good approach when following loading option 2, as the results of Table 5 and Appendix C may indicate. But this should be handled very carefully as the example shown is something like an ideal one. If for instance the following points are given, which is mostly the case, the procedure is no longer applicable:

- Short-term loads. The load-carrying behaviour described is only valid for constant internal pressure, which is not the case for short-term loads like wind

- Non-flat cushions with regard to the perimeters
- Different sags of the load-carrying membranes
- Different thicknesses of the load-carrying layers
- Multi-chamber cushions in which several layers carry the load
- External loads not acting in the same direction as the internal pressure, which is more or less always the case for live loads or snow loads
- Short-term loads because this procedure does not include the gas laws

Already based just on two of these items it is indicated that the simplified procedure is never really applicable. In theory it could be, neglecting the accuracy, but only for long-term loads acting in the same direction as the internal pressure. But this scenario does not apply for projects in the construction branch. Snow or live loads do not act in the same direction as the internal pressure for a complete cushion and wind load is not long-term. Simplified methods like the described ones are only roughly valid for constant internal pressure, which is not the case for short-term loads like wind. A wind gust causes a change of the internal pressure. In the above ideal example, it principally can be said that for a short-term load both layers carry 50% of the external load until it reaches double the internal pressure, the upper layer by a decrease of the membrane pre-stresses, the lower by an increase. From this point, only the layer that acts in the same direction as the load carries all additional loads, since the other layer is already released.

More on this topic should not be part of this thesis as it is sufficient for a complete work, but at least it should be mentioned as it is also a separate/hybrid issue. And it is even in double respect one of this kind. Firstly, because of the actual topic of this thesis, the separate or hybrid interacting calculation of lightweight components and their conventional supporting structures. And secondly, because of the additionally in this example presented separate or hybrid calculation of the cushion itself, the simplified calculation of membranes of the cushion or the holistic modelling and calculation including its correct behaviour as a system consisting of membranes and gas. The inclusion of the gas laws is crucial for the correct calculation of cushions.

6.2.4 Membranes between Three Arches

The following tables summarise the key results of the calculated models.

For this example, again a hybrid model with form-finding line supports was calculated. In most cases this reflects the correct procedure since most projects are executed using non-deformed components. When the membranes are installed, they cause the prestresses and deflections of components according to this calculation method.

In this example, the separate model is dimensioned to achieve a utilisation of 100.0% and not the separate one as in other examples in this paper as conversely the separate model is far from iterating due to the much stronger cross-sections required. The listed membrane forces and deflections relate to the maximum of the combinations 1.0 DL + 1.0 SL or 1.0 DL + 1.0 WL+y/-y.

The following Table 6 compares the results of the three calculation methods using the same cross-sections for all models. The dimensioning philosophy during the work was decided as follows: all arches have a wall thickness of 12 mm, because otherwise for these slender and wide-spanning arches the self-weight would have too much influence and disturb the comparisons. The wall thickness of the columns is 20 mm. The dimensioning of the separate structure was realised by the outer diameter. In the following table where three values are listed, these refer to 1) central arch; 2) perimeter arches, 3) columns

Table 6: Membranes between three arches – Key results using same sections (SecSame) (by author)

	Separate	Hybrid without	Hybrid with	Comment
Utilization [%]	100.0 100.0 100.0	40.3 50.3 110.0	40.11 51.0 109.7	Figure 118 Figure 119 Figure 120
Max. Bending moment M_{yd} [kNm]	-111.8 -231.9 -878.1	-148.0 -99.4 -969.9	-147.2 -100.9 -966.6	Figure 121 Figure 122 Figure 123
Bending moment M_{zd} [kNm]	433.5 94.8 478.0	82.4 77.9 181.0	83.7 79.5 182.4	Figure 124 Figure 125 Figure 126
Tensile forces cables outer arches middle/outer N_d [kN]	44.5 74.6	72.3 81.4	72.6 81.1	–
Max. membrane forces n_x [kN/m]	10.65	10.34	10.40	Figure 127; Figure 128; Figure 129
Max. membrane forces n_y [kN/m]	28.25	25.25	25.29	Figure 130; Figure 131; Figure 132

The following table presents the results of the comparisons, based on all models with their outer diameters dimensioned so that all have a stress utilization of 100.0%.

Table 7: Membranes between three arches – All models with dimensioned sections (SecDim) (by author)

	Separate	Hybrid without	Hybrid with	Comment
Required outer diameters [mm]	386.7 299.2 431.6	188.4 192.3 536.5	189.1 191.1 536.2	–
Max. Bending moment M_{yd} **(max. absolute)** [kNm]	-111.8 -231.9 -878.1	+79.5 +78.6 -1,407.8	+80.3 +77.1 -1,406.3	Figure 133 Figure 134 Figure 135
Bending moment M_{zd} [kNm]	433.5 94.8 478.0	48.1 85.2 113.7	50.2 90.5 114.4	Figure 139 Figure 140 Figure 141
Tensile forces outer arch middle/outer cables N_d **[kN]**	44.5 74.6	82.6 83.4	83.5 82.7	–
Max. membrane forces n_x [kN/m]	10.65	11.43	11.56	Figure 142; Figure 143; Figure 144
Max. membrane forces n_y [kN/m]	28.25	24.94	24.98	Figure 145; Figure 146; Figure 147

When optimising a component such as the central arch as in this example it is more important than with other structures to focus on global stability. A component that, like the central arch in this example, is optimised under a loading and system scenario like this, is likely to be at its limit in terms of stability. This was the case in the calculations here. For reasons of comparability, this perspective was neglected in the dimensioning here, since the philosophy was chosen to be stress utilisation for all.

The results of this example also show that the difference between the calculation with and without form-finding supports is very small. On the one hand, one of the main reasons is the form of the components, which is very good in relation to the loads they are subjected to, so that the shape efficiency is already very good. Secondly, the geometry of the structure, the component dimensions and the possibility of deflection under load are very favourable, so that the constraints are low.

6.3 Practical Project – Festival Tents >The Sea Star<

This chapter presents summaries of the results and discussions on findings gathered from the practical project >The Sea Star<. Several comparative colour plots about the workflow can be found in Appendix E.1 and the results in E.2. All of this would be too much for the main thesis chapters.

First of all, the final shape of the membranes is shown in Figure 62. This final shape often depends on opposing objectives. The membranes are not always shaped according to their best static load-carrying behaviour, but often even more according to architectural aspects. This may lead to higher costs if the deterioration of the load-carrying capacity of the structure leads to the need for more expensive membranes and substructures. The following form was achieved by focusing attention strongly on the visual appearance, while at the same time avoiding the need to choose stronger and more expensive membranes. This is one of the main tasks of an engineer in the industry. At least it is for engineers in the executing sector, while it is often the opposite of what architects or consulting engineering offices are aiming for. This is at least the feeling of the author, gained in several years of experience in the industry.

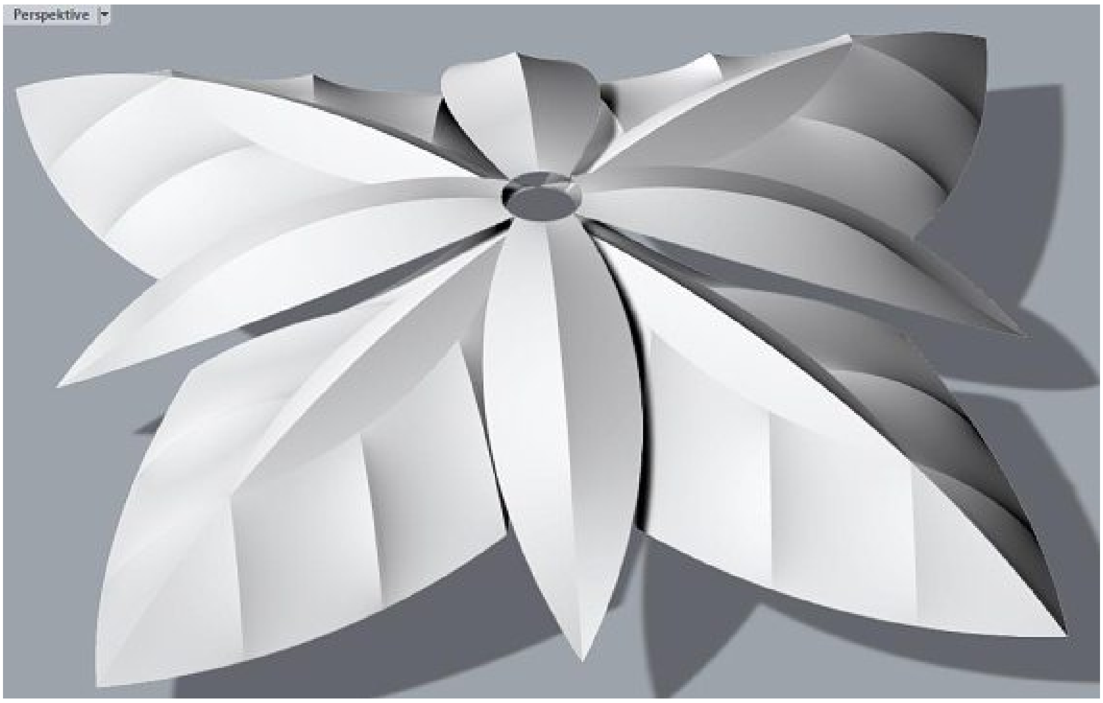


Figure 62: >The Sea Star< Membranes after final form-finding – Exported to Rhino (by author)

The following differences resulted from the contrasting approaches of hybrid and separate calculation. Multiple further information, especially in form of colour plots of the results, can be found in Appendix E.2.

The following tables summarise some of the key differentiated results of the hybrid and separate calculations. All of the following information on the substructure refer to components to which membranes are attached. Internal forces of the members are maximum design forces of the result combination "worst of design". Table 8 summarises the key differences in dimensioning, tonnage and required outer diameter of the components in the course of the calculations in the first iterative cycle of such a project workflow.

Table 8: >The Sea Star< Separate/Hybrid – Tonnage and dimensions (by author)

	Separate	Hybrid	Separate/ Hybrid	Comment
Overall tonnage steel [t]	198.6	139.5	142.4%	–
Max. diameter required [mm]	406.4	323.9	125.5%	outer members small leaves

Table 9 below presents some of the crucial results of internal forces and deflections. Such results are an important indicator for understanding the core problem and the reasons for differences and the outcome.

Table 9: >The Sea Star< Separate/Hybrid – Member internal forces and deflections (by author)

	Separate	Hybrid	Separate/ Hybrid	Comment
Max. M_{yd} [kNm]	816.9	616.8	132.4%	Location: small leaves Figure 201, Figure 202
Max. M_{zd} [kNm]	861.3	370.7	232.3%	Location: small leaves Figure 203, Figure 204
Max. deflection trusses u_y' wind LCs [mm]	478.2	147.0	325.3%	Figure 209, Figure 210
Max. M_{zd} trusses top chords [kNm]	204.6	20.6	993.2%	Figure 207, Figure 208
Max. M_{zd} small leaves [kNm]	440.8	244.2	180.5%	Figure 205, Figure 206

Table 10 and Table 11 compare the results in terms of membrane forces. The maximum deviations are quite small. A main reason is seen in a high shape efficiency of the components and the overall system. The components of the small leaves are a good example. The curvature of the central arch gives a high stability against its strains, which are directed downwards. The outer arches show the same, an efficient form against the load, which for them is an outward curvature for mainly inward directed forces. The same applies to the elements of the big leaves. This high form efficiency leads to a rather small difference between the hybrid calculation and the fix supported calculation in the membrane partial model MEM. If the shape efficiency is lower, much larger deviations arise. Such a characteristic, a high form efficiency is often desired. But often the opposite is sought, a higher flexibility and less stiffness.

Table 10: >The Sea Star< Separate/Hybrid – Max. membrane forces – Big leaves (by author)

	Separate	Hybrid	Separate/ Hybrid	Comment
DL+LL – n_x [kN/m]	5.52	4.61	119.7%	Figure 224; Figure 225
DL+LL – n_y [kN/m]	8.77	8.39	104.5%	Figure 225; Figure 226
DL+WL0° – n_x [kN/m]	18.12	17.17	105.5%	Figure 227; Figure 228
DL+WL0° – n_y [kN/m]	30.20	29.30	103.1%	Figure 229; Figure 230
DL+WL45° – n_x [kN/m]	28.30	27.61	102.5%	Figure 231; Figure 232
DL+WL45° – n_y [kN/m]	33.01	32.64	101.1%	Figure 233; Figure 234

Table 11: >The Sea Star< Separate/Hybrid – Max. membrane forces – Small leaves (by author)

	Separate	Hybrid	Separate/ Hybrid	Comment
DL+LL – n_x [kN/m]	7.47	4.65	160.6%	Figure 235; Figure 236
DL+WL0° – n_x [kN/m]	18.64	16.28	114.5%	Figure 237; Figure 238
DL+WL0° – n_y [kN/m]	8.73	10.78	81.0%	Figure 239; Figure 240
DL+WL45° – n_x [kN/m]	16.84	12.84	131.2%	Figure 241; Figure 242
DL+WL45° – n_y [kN/m]	12.73	16.67	76.4%	Figure 243; Figure 244

In addition to the comparative results listed, more detailed figures can be found in Appendix E.2. On subsequent pages, the utilisations of all components in the separate and the hybrid calculation are shown, as well as further exemplary results like internal forces or deflections. The differences represented in the colour plots are significant and give a better feeling than just a few tabular values.

Regarding >The Sea Star<, some final comments from the author about the status of the performed calculations and in respect of a real project work. The intended structural geometry consisting of significantly less elements, as it was aimed for in this paper, already worked quite well in the first calculation cycle. Nevertheless, the author would not stop working on the project here when really building this structure. Of course, he would continue to design with working on the hybrid model. However, since too much time has already been devoted to such a work it should be stopped at this point, as the author intends to continue immediately after this work on other points mentioned. These are for example CFD calculations, shape and structure optimisations by parametric design, only to mention some. For sure more than one engineering cycle should be spent on the engineering for such a project to develop a final solution than for a structural comparison as envisaged for a thesis like this.

What the author would do in the next steps is exemplary:

- Intensification through further investigations, also based on the conclusions and findings, leading to a good understanding of the holistic structural behaviour of the overall structure as well as in detail, trying out options and investigating possibilities. In the eyes of the author, this is always an important step in the work of a structural engineer. Understanding a structure. Not only dimensioning one option and that is it, but understanding a structure and its load-carrying behaviour in the best possible way and thus creating the best basis for finding better possibilities and solutions. Good examples for the importance of this are e.g. projects like City Walk Dubai or Jewel Changi Airport. For both projects the author was the execution structural engineer. Without the findings gained from the investigations and also by simply trying out options leading to a profound understanding of the load-carrying behaviour of these structures, the results would have been different and the final outcomes would not have been possible. Also very much concerning costs but explicitly also safety. Significantly higher costs or less visual attraction of an architecture can be the result, if the engineer does not spend sufficient time or even takes the time to get to learn a structure and to understand it in detail.
- As a next step for >The Sea Star<, the author sees a main goal in reducing the outer diameter of the members. First results show that there is high potential.

- As the results show, several optimisations should be the next step in the hybrid calculations. As an example, the chords of the trussed girders are too large in their outer dimensions, since an optimisation of these in the hybrid calculation was no longer possible due to the already minimal wall thickness of most of them.
- Several further possible optimisations and favourable adjustments the current investigations had brought up and should be one of the next steps to be taken
- Presentation developed options and possible architectural appearances to the client to find out what the intentions are and what the final solution should be.
- In case slenderness should be the main objective for the client and not costs, the author would continue with:
  - Investigation of the minimum possible outer diameter for all members
  - Investigation of measures as inconspicuous as possible to reduce outer diameters even further, which often also leads to cost reductions
- Improvement of the global structural load-carrying behaviour by adding or removing members, modification of cross-sections and thus stiffness, modification of structural data such as fixed or hinged connections and the like, modification of member angles to improve the structural behaviour and its further optimisation, only to name some. One of these improvements was integrated early in the calculation process by integrating bracing elements at two locations of the four main trusses in the bottom chord to stabilise them, as these trusses were identified to having the tendency of showing global stability issues in the character of lateral torsional buckling. Those bracing components are most likely possible to change to even much less conspicuous cables. Furthermore, these could be possible to avoid in hybrid statics.
- Rigid connected columns instead of pendulum columns. First test calculations seemed to be promising.
- Omission of even the four left 2D trusses. Initial decision to keep them can obviously be revised. Single beams instead.
- Change of support conditions, investigation of the effects whether being favourable or not.
- Many other things that only arise in the course of structural investigations in the project work, which only arise when understanding the structural behaviour of a construction in its entirety and in detail.

The following is an example of a possible measure to reduce the outer dimensions by inconspicuous measures. At the yellow highlighted location bracing cables would allow to reduce the diameter of the outer arches of the small leaves considerably.

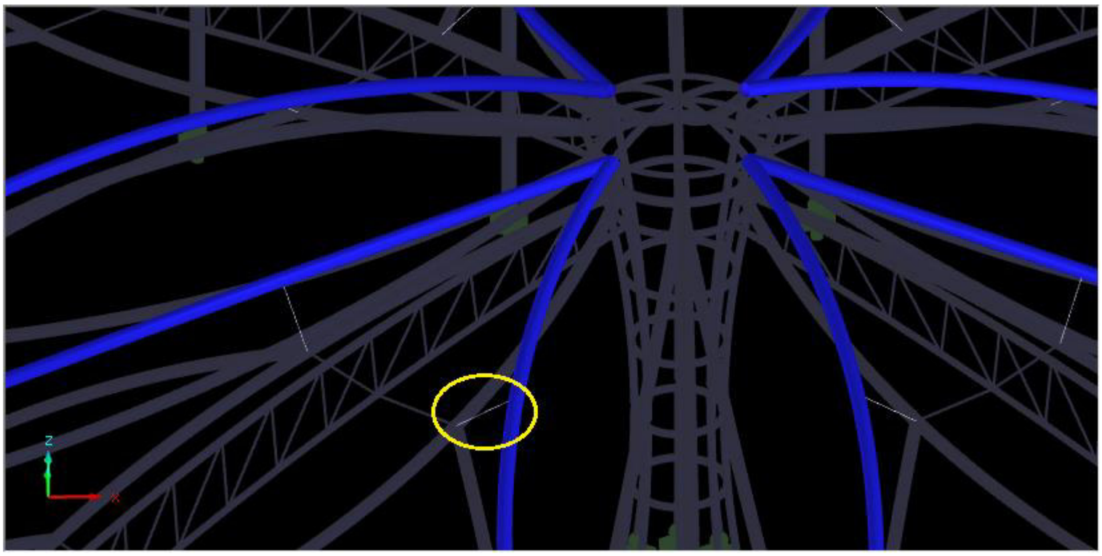


Figure 63: >The Sea Star< Additional cables for reduction of cross-sections (by author)

To achieve a more slender structure, cables with a diameter of only 20 mm would be required. The following figure shows a 50% respectively 78% utilisation of these components compared to 100% before. Adjustments of these bracings would improve this further.

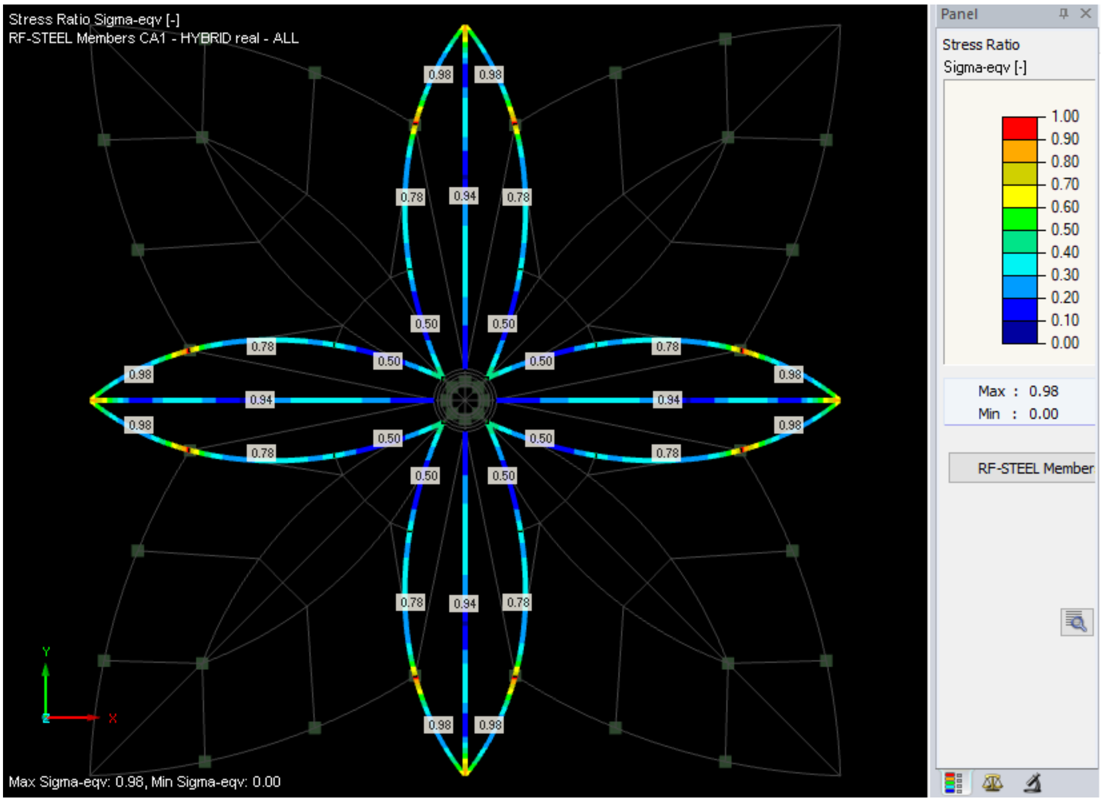


Figure 64: >The Sea Star< Additional cables for reduction of sections – Stress utilization (by author)

6.4 Diverse Further Findings and Thoughts

At this point and based on market experiences it is a concern of the author to express his incomprehension and even criticism of an often-experienced attitude. The attitude meant is renouncing the execution of wind tunnel studies because of the conviction to save money. This is a real misconception at least for structures that exceed a certain degree in size, complexity and total costs due to the fact that the costs of a wind tunnel study would reduce the construction costs much more than the expenses for such a study. This is often underestimated or even not considered. Even with standardised forms such as domes, the wind loads resulting from a wind tunnel study are in general significantly lower than those determined by code. Furthermore, if an engineer cannot rely on a given wind load, needs to take measures to ensure safe dimensioning to avoid risking deficiencies or even harm to human life. Due to the complex shapes which lightweight structures typically exhibit, a wind load determination without a wind tunnel study or CFD calculation is not even worth calling an approximation. The author had discussions on this subject with the worldwide highly renowned wind engineering office of Wacker Ingenieure, Germany, which is highly experienced in all types of structures. Mr. Wacker Senior and Mr. Wacker Junior told the author, that due to the immense complexity of wind engineering with all the diverse influences and effects like vortices, multi-facetted interactions and else, assessed wind loading cannot be much more than a guess and must rather be called dubious, even for a much less complicated structure than it was discussed about. If not even absolute professionals in wind engineering can give good estimates of the wind load without suitable methods like wind tunnel tests or CFD, how then should a structural engineer be able to do this? The result should be clear then, too high loadings and over-dimensioning in the best case. In the worst case under-dimensioning and defects or even worse.

One aspect that is often mistaken in the design of lightweight structures is located in form-finding settings and calculations. In the software the structure is calculated together with the membranes in the form-finding process. This means that the components of the structure are also included in the form-finding, which leads to internal forces and stresses. In principle, this procedure can be the correct one. But it is often treated in a mistaken way. The reason is that this is only correct when the structure is installed precambered or when a deflected shape is the basis for the production of the membranes and not the original geometry. The membranes are often produced according to the boundary conditions of the original geometry without deflections. The substructure is also manufactured according to the undeflected geometry. If this is the case in the practical implementation, the calculation of the model including the elements in the form-finding is not correct. It is often negligible, but it is not correct. In reality, the membranes deform the structure during installation due to their prestresses. Their internal forces deform the structure, thereby the prestresses in the membranes (in most cases) decrease as well as internal forces, stresses and required cross-sections of the substructure. As an example the model of Section 5.2.4, Membranes Between Three Arches, can be seen. The difference is very small between using or not using form-finding supports in the calculations. But very often the differences are not insignificant.

In the hybrid statics the following four procedures are the options in this respect:

1) Execution of a non-precambered physical substructure and manufacturing of membranes according to the original geometry together with accepting deviating (in most cases lower) prestresses in the membranes than those specified as prestress settings in the form-finding process:
   The engineering method for this is the application of form-finding supports. Due to deflections of the structure during installation caused by membrane forces, the resulting prestresses in the membranes in reality are (in most cases) lower than the defined ones in the software form-finding process.
2) Execution of a precambered structure and membranes according to the original geometry together with achieving the set prestresses:
   Therefore, no form-finding supports are used in the calculations and the structure and its rigidity are included in the form-finding process. Consequently, the structure is built pre-deformed against the deflections that occur during the installation and prestressing process. After the installation, the geometry of the structure is the original one and the prestresses are the ones set in the computational form-finding.
3) Execution of a non-precambered structure and achieving the prestresses according to the defined form-finding parameters:
   To achieve this, precambering of the structure is required, but not physically rather in the calculations. In short, the procedure would be that no form-finding supports are used initially. Then an “empty load case” is calculated, which thus only includes the prestresses of the membranes. Against the deflections of this load case, the model is pre-deformed in the calculations. In the final calculations at the very end, the deflections caused by the prestress bring the structure to its original shape. Thereby, also the prestresses are achieved according to the form-finding settings. A major issue of this procedure is its iterative character since each individual, dimensioned structure before precambering against the deformations caused by the prestress result in different stiffnesses and deflections and thus result in different

calculations. Any changes in the model, such as cross-sections, require a new precambered model. When doing so, it is not possible to "just change something quickly". The amount of work required for changes is high due to all the required adjustments.

4) Execution of a non-precambered structure and achievement of the prestresses by manufacturing the membranes according to the deflected model under the prestresses:
   This is practiced sometimes, but results in an installed structure being the deformed geometry that may not be the intended one. This can be done when the deflections are small or inconspicuous.

In practice, it is often neglected or even not understood that a mixture and thus an error is carried out. The mixing often consists of the fact that a non-precambered structure is realised together with membranes on the basis of the original form and the calculations are carried out with the inclusion of the structure in the form-finding, meaning that no form-finding supports are used. The error here is that the (full) membrane forces/prestresses are used for calculation. This is not correct but often negligible and structures are (mostly) over-dimensioned, however, due to this effect often only to a small extent. Sometimes this method causes defects such as wrinkles since the prestress ratios specified in guidelines such as the European Design Guide for Tensile Surface Structures [4] for the avoidance of wrinkles may be taken into account in the calculations, but are not kept in the realised physical structure then.

The most precise and at the same time cost-effective procedure is No. 3, as long as the engineering costs do not increase disproportionately compared to the overall project costs. It does not lead to over-dimensioning of the described nature and also does not require very complicated and cost-intensive production such as doubly curved, three-dimensionally bent components of a pre-deformed structure. But it is also the by far most engineering-intense and challenging one. Procedure No. 1 is usually even more cost-effective with regard to the required cross-sections and the overall tonnage of the substructure, as it allows higher deflections due to the lower prestresses and therefore requires smaller cross-sections. However, due to the risk of errors of any kind, this needs to be considered carefully.

It should be mentioned that in other software this issue may be different. In the software used here it is the case as described. The easiest way to find out is to calculate the structure "in an empty load case", which means that then only prestress is calculated in the load case after the form-finding. If this empty load case shows no deflections (they are only found in the form-finding case) and the structure shows stresses and internal forces, then it is the case as described.

Another thing which is often underestimated and done the wrong way when calculating separate is to apply loads from membranes caused by load cases like wind or snow unfactored to the STR model and later factorising per load case combination factors. This procedure disregards the fact that the influence of loadings in lightweight structures is mostly non-linear to a high degree. In the comparative calculations of this thesis, the loads on the structure caused by the load cases are factorised in the separate MEM model and the forces are transferred then to the STR model accordingly. A comparative calculation shows the difference in these methods with regard to the non-linearity of load effects. This can be seen in Diagram 12 and Diagram 13 and the descriptions in the respective paragraphs. This non-linearity issue in lightweight structures and related requirements is exemplarily mentioned in Section 3.6.4 of the "Prospect for European Guidance for the Structural Design of Tensile Membrane Structures. …" [7]. It is mentioned as a requirement: "The combination of actions will be adjusted to the basic rules on EN 1990. Due to the nonlinearity of membrane structures, preassigned load combinations have to be established and analysed in order to identify the decisive ones for the verification of the structure." (Forster & Mollaert, 2004).

Despite the fact that the wind load determination is not the central focus of this work, however, important in this context, a further criticism of today's wind load handling should be mentioned here, as this also strongly influences the dimensioning. The criticism is aimed towards the wind load handling mostly used nowadays. Wind in its nature is a very dynamic load, but in practice today it is usually used as a static substitute load. The core issue that the author aims to address is the special one of the different response of structures on a dynamic strain and the potential that the wind is able to achieve, performing physical work. For example, the wind is able to deflect a very light structure like a membrane to a very large amplitude. For structures of the same size, but of a very heavy inertial nature, the wind cannot deflect to the same amplitude when speaking of the acceleration of a mass. A wind gust being often the governing load is of very short duration. In this very short time, a membrane can be accelerated and moved easily, whereas this cannot be achieved for a structure of very high mass. And, simplified expressed, since stresses are not caused by loads, but by deformations which loads are able to achieve, this is of high importance and should therefore be covered adequately. When a specific load is able to deflect a structure to a high amplitude this leads to higher stresses than with a structure that cannot be deflected to the same amplitude. Jewel Changi Airport, mentioned in Chapter 1, may be used as an example. As described, this structure shows to a high degree the load-carrying behaviour of a lightweight structure. But the mass per area compared to a membrane structure is extremely high, some thousand times the mass. But the static substitute wind loading is the same. This should illustrate that there is something to be improved in this regard. The static substitute load and the structural calculation methods will certainly be subject to developments in the future. For high mass structures the static substitute load is assumed to be on the safe side since the origin of the static substitute load lies in the real statics. Statics, according to its definition, is the science of resting systems that do not accelerate and remain static. Therefore, the static equivalent wind load should be on the safe side for systems that react favourably under considerable dynamic, thus non-static, behaviour. A real rating of this topic should not be given here, however, the topic should be raised. Dynamic effects like unwished vibrations, galloping effects or the carman vortex street are unfavourable dynamic effects. Most codes handle such dynamic effects, but not the static substitute load satisfactorily for structures of different inertial behaviour.

On the other hand, there is also a very unfavourable effect influencing the wind load on structures of high deflection, which lightweight structures are. This effect is also not sufficiently covered by static equivalent wind loads. There may be the case that under wind conditions a membrane deflects so significantly that its surface exposed to the wind increases like a sail catching more wind. This effect was very clearly visible during a storm event over northern Germany in 2017. In a video taken in the football arena in Wolfsburg, Germany, the lightweight structure of the roof deformed tremendously up and down, altering the area exposed to the wind and thus the load immensely. Two pictures taken from this video are those of Figure 66, showing the maximum amplitudes of the deflecting roof.

7 Conclusion and Perspective

First of all, as this is a strong attitude of the author, the same statement as in Chapter 6 should be mentioned again: The author prefers the attitude not to interpret results too much and to draw conclusions. Instead he rather considers it the better way to present results without influencing the thoughts and impressions too much. The figures and graphs presented speak for themselves. An interpretation is to a special degree a matter of opinion and a subjective classification. Engineers should always gain own impressions and draw own conclusions. Own experiences and conclusions resulting from own investigations and calculations are the best way and not to follow the opinion of others. Nevertheless, it is somehow impossible to refrain entirely from conclusions and ratings in such a paper. In the following, conclusions of the author should always be considered as such, subjective assessments as some amongst many. Others certainly interpret things differently and on most issues there is simply no ultimate truth.

The general conclusion to which all this work leads is certainly that the differences between separate and hybrid calculation may be tremendous. Furthermore, also under-dimensioning and consequently safety issues are to be found in multiple results. Exemplarily, the columns of the example in 6.2.4 are stressed 10% higher in the hybrid calculation, so under-dimensioned when calculating separate (Table 6 and Table 7). Further potential under-dimensioned outcomes of separate calculations are exemplarily reflected in results of Table 11 of >The Sea Star<.

Another very obvious thing, which may even be the difference between hybrid and separate calculation is visible in Figure 136 in comparison to Figure 137, respectively Figure 138. Even such differences may occur, in which moment gradients vary essentially. In this example of membranes between three arches, the separate calculation shows a negative moment of the central arch at the connection to the columns and a positive one in the hybrid calculations.

All these findings and the argumentations listed lead to the conclusion that, at best, the separate calculation should simply be abandoned entirely. Since this will certainly not happen soon, the engineers who follow the separate approach should at least always be aware of the consequences and risks. These do not only refer to topics such as waste of material and costs and are also not limited to the visual deterioration caused by unnecessarily massive constructions. But they are also in the important and never to be ignored aspect of safety. Not following items demanded by codes such as appropriate structural modelling as described in Section 4.7 or meeting the demands to cover the effects of Th. III. O. as described in Section 4.6, may result in defects up to harm of human life.

One of the major conclusions of the examples is that to a large extent wide spans and highly divergent deflections resulting from the different approaches are key reasons and indications for the enormous possible reduction of steel masses and costs through hybrid calculation.

A central maxim of one of the initiators of the course, Jürgen Hennicke, is "Let it move". In simple terms: If a structure is too stiff, it may result in massive, less visually attractive and costly structures. This can be improved if a lightweight structure is allowed to deform under load instead of designing it in a too rigid manner. On the other hand, it can also be the exact opposite, should the supporting structure be too soft, the engineer not allowed to take favourable structural adjustments. Very wide-span members subjected to bending from membrane loads may require massive components. This is exemplarily the case for the trussed girders in >The Sea Star< or very wide spanning edge beams. Stiffening members, reducing the structural spans can reduce tonnage and costs. Such designs may be classified as poor for a lightweight construction. However, in the market it is often the case that customers or architects insist on special designs, which in the end have to be managed by the engineer.

In the case of >The Sea Star< not only the optimisations presented in the comparison are to be emphasised, such as the 42% higher steel tonnage separate, already in the first iteration cycle, even increasing when proceeding. It is also worth remembering what the options were when calculating separate using other methods that time. If one doesn't have the opportunity and time to delve so deeply into the subject, the project may result in what were options during the design phase. Options were exemplarily those of Figure 50 and Figure 51. The geometry with much less components that is easily feasible by hybrid procedures stated in this paper is seen in Figure 52 and even much better when continuing the project work. Needless to say that the differences in aesthetics, costs and opportunities in a tender process are immense.

To some extent, the final judgement is certainly a subjective one, depending on experiences and attitudes, but should nevertheless be outlined. The following aspects are considered objective enough to give such a rating.

Among other reasons, the author rejects separate statics due to the following facts:

- Structures in statics should always be modelled adequately enough, which in the author's judgement is absolutely not the case in separate statics of hybrid lightweight structures, at least for those of the types presented and examined.
- The interaction of the components of structures of high deflection is too high, to that immensely simplify calculations by separating conventional from lightweight hybrid structures in calculations.

- It cannot be denied that the obligation to calculate structures of high deflection following Th. III. O. is violated in separate statics. When calculations are carried out separate, it cannot be argued that these follow Th. III. O. It should explicitly be emphasised that they are indeed still not when calculating with software settings of Th. III. O., which someone might argue. It is without question not a calculation according to Th. III. O.

- As it is to be found always and again in comparative calculations, which the author frequently carries out, that the results of the hybrid approach are not only an over-dimensioning of components but often also an under-dimensioning. This can also be found in many figures in this thesis. This issue is clearly judged too risky and unacceptable for structural engineering. Safety is not discussable.

Clear advantages of the hybrid calculation are exemplified by the following aspects:

- Project development: Hybrid models are a powerful instrument for developing a project. Various options can be examined and compared fast and easily, evaluating the appearance of the different options of forms and designs, resulting in different component cross-sections, costs, optics and further.
- Architectural intent: During hybrid calculation, the architectural intent is better to achieve than by separate calculation as this often results in additionally required components and over-dimensioned massive structures.
- Particularly when lightweight components are used as primary structural components, architectural intents are possible hybrid, unlikely separate. But especially in this case it is always important to think about safety aspects, such as safety cables or the like, which avoid a global failure in case of defects.
- Slender, aerial architecture: The reduction in the number of components and their cross-sections allows the realisation of more slender and gracile structures that attract the attention of the spectators. Nowadays, this aspect becomes more and more one of or often even the main intention of architecture.
- Cost reduction: As shown, hybrid statics in most cases require smaller cross-sections and less members. This leads to a reduction of construction costs. In addition, also the engineering hours and thus the costs are possible to minimise further.
- Competitiveness and success of a company: When operating in a competitive market, hybrid statics increase the chance of winning tenders. Lower costs are one argument, but also the possibility of more slender and appealing constructions can be decisive by convincing a client with architectural arguments.

Depending on the project, it is the author's opinion that for the risk factor, the structural system and above all the engineering assessment and following engineering diligence, separate statics can only be carried out under the responsibility of the engineer and the approving authority. But especially because of the violation against Th. III. O. calculation and acting far from modelling a structure as appropriate as possible, it does not correspond to the state-of-the-art. In the author's view, the approving authorities should and often even must reject separate statics based on these arguments.

A further development towards a more accurate calculation, which helps hybrid structural engineering of lightweight structures to optimise the tonnage and design, reduce costs and realise aerial structures, is seen in the CFD wind load determination technology. In the lightweight branch wind tunnel studies are often not executed, resulting in further over-dimensioned structures. This could soon be omitted by CFD, despite the fact that it is often still not accepted for project realisations. The development in this field is immense. CFD will be more and more accepted as the technology evolves and accuracy and reliability are better verifiable and more reliable. It will increasing become an alternative to wind tunnel studies. Even if CFD is not accepted for project realisations, it is a very powerful tool in practice. It helps engineers and companies in the tendering process as they will no longer have to be too conservative, which is fatal with regard to competitiveness. This development is considered to be a very important topic in the field of accurate hybrid structural calculation of lightweight structures. Today, in the best case, the loads of the CFD wind load calculation results are transferred directly to the structural software by means of an interface. But the best solution for wind load determination and the impact on the dimensioning, the membranes and the supporting structure, is seen in the future, when the evolution of simulations and calculations merge to a joint computational solution. Such developments have already started exemplarily in the software Rhino with its Grasshopper and plug-ins. Such procedures are able to cover changes in the design of a structure or the change of the wind load due to a deformed structure and adapt the calculations to the new situation. Different for the case of wind tunnel studies, which only allow limited adjustments without the need for a new study. One example of interactive simulations is the doctoral thesis of Alexander Michalski, which focuses exactly on this issue. The topic of his dissertation, translated into English, is: "Simulation of lightweight surface structures in a numerically generated atmospheric boundary layer" (German original: "Simulation leichter Flächentragwerke in einer numerisch generierten atmosphärischen Grenzschicht"). The following Figure 65 shows such interactive simulation results for the wind loading on the undeformed and deformed shape of umbrellas.

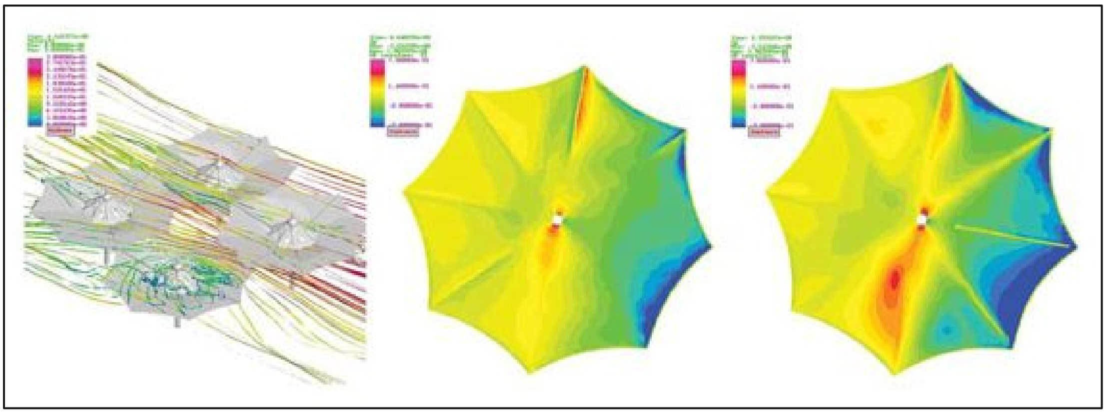


Figure 65: Wind loads of an undeflected and deflected umbrella
(doctoral thesis Alexander Michalski [5])

An example of substantial changes in wind loads under high deflections on an existing structure is shown in Figure 66, visualising the highest and lowest amplitudes of a deflecting football stadium roof during a storm event. Under the high amplitude it gives a much bigger wind-exposed area, so the wind loading is higher.

Figure 66: Roof of football stadium Wolfsburg, Germany – during storm event – Lowest and highest amplitude (website: stadiumdb.com)[19]

[19] http://stadiumdb.com/news/2017/10/wolfsburg_see_volkswagen_arena_roof_dance_with_the_wind – retrieved on 02 June 2018

Nowadays wind loading is typically handled as static substitute load, which is only an approximation. In order to improve the accuracy of dynamic influences, that should no longer be the case in the future. On one hand dynamic simulations and calculations should reflect the character of the wind load and on the other hand cover the behaviour of the lightweight structures, which respond to the load and change their form, which in turn changes the wind load again. Thus, the aforementioned obligation is fulfilled even more to model a structure in the calculation process as realistic as possible. In addition, the rule of Third Order calculation of structures of high deflection would be fulfilled even more. In this system complicated issues such as unwished vibrations, the galloping effect and others could then also be examined better rather than with today's simplified methods. All this would not only enhance the possibility of optimising structures, but also reduce the risk of defects or even danger to life. The implementation of such computer-based systems is certainly a big challenge, but the development of technologies is fast and will open up new opportunities. Future technologies will easily be able to cover all technical effects much easier and more realistic than today. Artificial intelligence will certainly soon also be integrated in this area, not only to assist in the design process and engineering, but also as a contribution to error prevention, perhaps comparable to today's driver assistance systems.

Finally, in order to complete the hybrid holistic theme, it should be completed to a real one. As an essential requirement for a structural analysis it is often stated that a structural model should be very accurate and reflect the real conditions as realistic as possible. In order to extend the already mentioned well rated methods, it should also be pointed out that modern software packages should be able to and already can include also details in a holistic model. A detail calculation like a support in a separate FEM software may seem to reflect absolutely precise results in relation to this isolated problem. But one should always consider the complete problem. If such a detail can be included in a holistic model, this is always more accurate and safer. The key word in this respect is stiffness. In models, supports are often defined to be rigid. Defining rigid here means infinitely stiff. But infinite stiffness does not exist. No support is infinitely stiff, but always shows some flexibility. Supports of already very little flexibility can lead to significantly deviating results compared to models with rigid ones. This is often the case with supports which in practice are eye bars. Utilising a rigid support for eye bars typically gives considerabe deviating results in the structure than in the calculation including the detail or the stiffness of it. Very significant differences between these two often result under temperature load. An engineer should always carry out such investigations when not having the opportunity of including everything in one holistic model. Also connection details or membrane/substructure interface details like keder profiles, line-supporting profiles of membranes, upstands and the like should be considered and in the most accurate case everything included in a holistic model. There are already software packages able to achieve this, however, at present the problem then often is still the required computing time of the currently available hardware. For big models this is not yet efficient enough, but will certainly be soon with the evolution of technologies.

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List of Abbreviations and Symbols

BL	Bottom layer of a cushion
CFD	Computational fluid dynamics A computer-based method of calculating fluids, wind in this context, to determine wind loading per computer without a physical wind tunnel study
CHS	Circular hollow section (cross-section of structural members)
DL	Dead load in general/combined of substructure and membrane (load case)
DLm/DLmem	Dead load membrane (load case)
DLs	Dead load structure (load case)
d_s	Cable nominal strand diameter
ETFE	Ethylene tetrafluoroethylene
FF	Form-finding
FTC	Abbreviation for in this thesis investigated basic system of a Flat Triangular Cushion
HY	Hybrid model
Hypar	Hyperbolic paraboloid One of the basic shapes in lightweight structural design
Hypar Type A	In this paper so-called type of a hypar with axial-forces only structural behaviour; with four struts and eight cables
Hypar Type B	In this paper so-called column bending type of a hypar; with four columns under bending
IP	Internal pressure of a cushion
I_y	Moment of Inertia [cm^4]
LC	Load case
LCC	Load case combination
LL	Live load (load case)
MEM	Membrane partial model (substructure deleted; membranes supported fix)

MbtA	Abbreviation for in this thesis investigated basic system of Membranes installed between three Arches
MiAF	Abbreviation for in this thesis investigated basic system of a Membrane installed in an Arched Frame
M_{yd}	Design bending moment around y axis (y-axis in direction of adjacent membranes)
M_{zd}	Design bending moment around z axis (z-axis perpendicular to surface of adjacent membranes)
N_d	Design axial force
n_x	Membrane internal force in x-direction = warp direction
n_y	Membrane internal force in y-direction = weft direction
P	Prestress (load case)
SecSame	Comparative calculations using the same sections in all of the models compared
SecDim	Comparative calculations with dimensioned sections in all models compared
SL	Snow load (load case)
STR	Substructure partial model (membranes deleted, support forces of the MEM partial model imported for dimensioning)
Th. III. O.	Theory Third Order A structural calculation theory/method
TL	Top layer of a cushion
u	Utilization of members in stress design
URS	Updated Reference Strategy A numerical method for form-finding by K.-U. Bletzinger and E. Ramm
u_y'	Deflection (u) in local y-direction
u_z'	Deflection (u) in local z-direction
WL	Wind load
WL+/-y	Wind load for +y respectively -y wind direction
WP	Wind pressure (load case)

WS	Wind suction (load case)
x'-direction	Local x-direction (not global)
>	Symbol in the appendix for next step

List of Software Used

Rhinoceros 6.4	3D graphics design software especially for free-form surfaces (Robert McNeel & Associates)
RFEM, ver. 5.16	3D Finite Element Software (Dlubal Software GmbH, Tiefenbach, Germany)
RFEM ad-on modules:	
• RF-FORMFINDING	Form-finding module (method used: Updated Reference Strategy)
• RF-STEEL	Dimensioning module investigating stresses/ utilisations, etc.
• RF-LIMITS	Module for checking limits like max. forces/stresses
RStab, ver. 8.14	3D static software for the calculation of frameworks (Dlubal Software GmbH, Tiefenbach, Germany)
RStab ad-on modules:	
• RS-STEEL	Dimensioning module investigating stresses/ utilisations, etc.
FEMAP with NX Nastran	3D Finite Element Software (SMART Engineering GmbH, Marburg, Germany)

Appendix

The appendices present various results of the diverse investigations and calculations. For a better overview, the comparative colour plots of the calculations are usually arranged on one page. Without always mentioning this explicitly, all models and images in the appendices are by the author, with the exception of two CFD wind load determination result colour plots of >The Sea Star<.

Appendix A Membrane Installed in an Arched Frame (MiAF)

In the following, the results of the different calculation methods are always arranged on one page for better comparability. The influence of the rigidity respectively flexibility of the membrane edges can be identified very clearly, which is the governing influence here.

All figures in Appendix A are by the author.

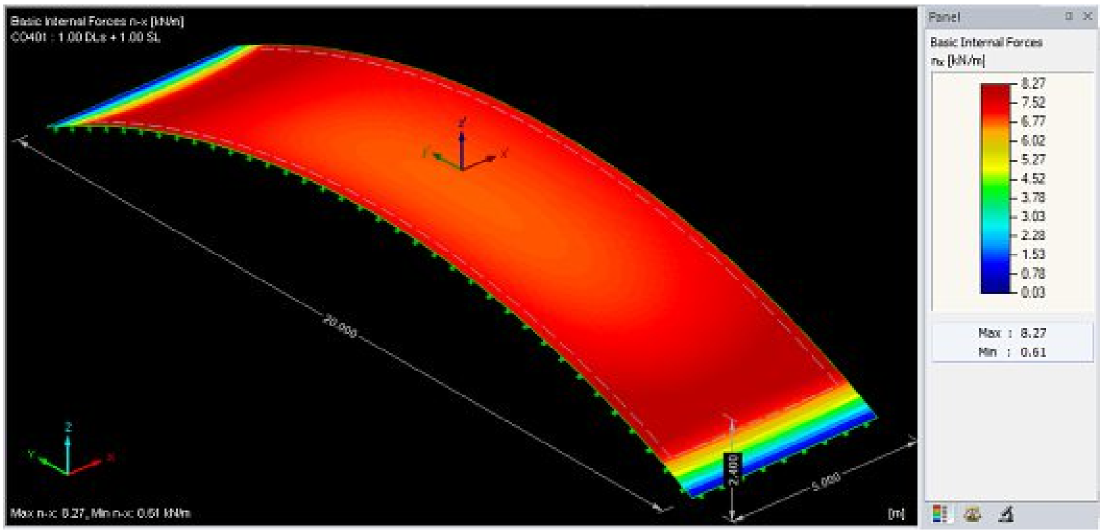

Figure 67: MiAF – Separate MEM – 1.0 DL + 1.0 SL – Membrane internal forces n_x – Model 20 m

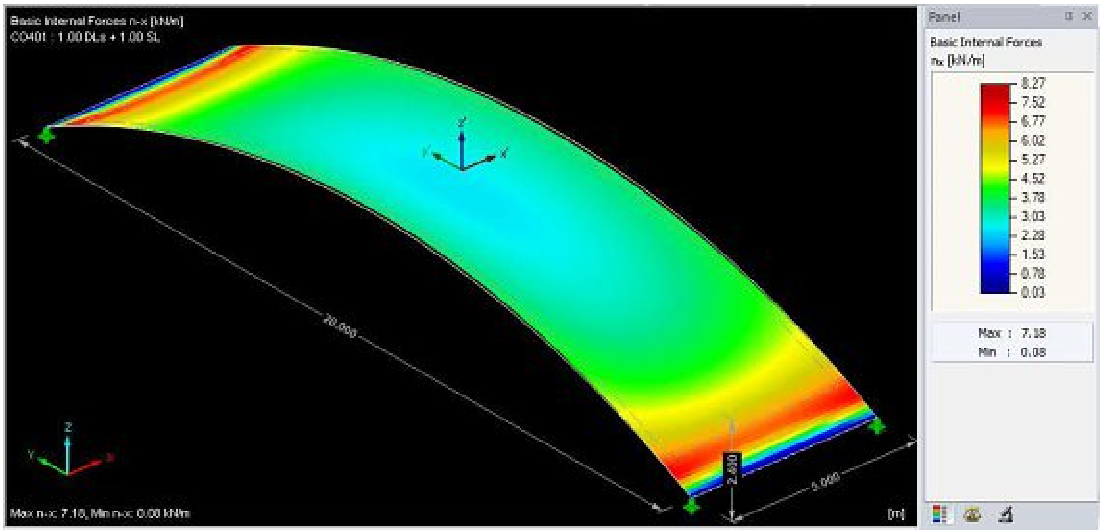

Figure 68: MiAF – Hybrid without – 1.0 DL + 1.0 SL – Membrane internal forces n_x – Model 20 m

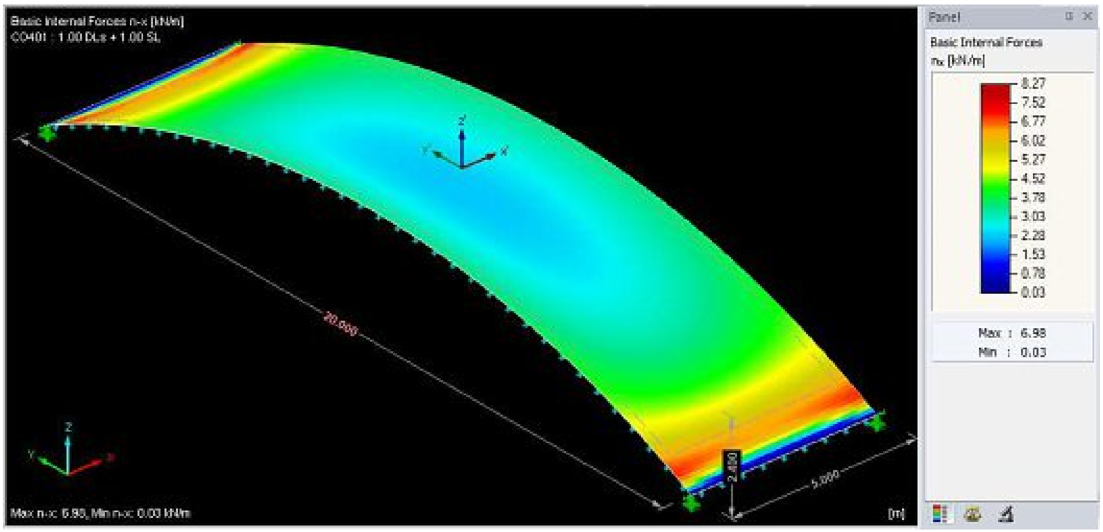

Figure 69: MiAF – Hybrid with – 1.0 DL + 1.0 SL – Membrane internal forces n_x – Model 20 m

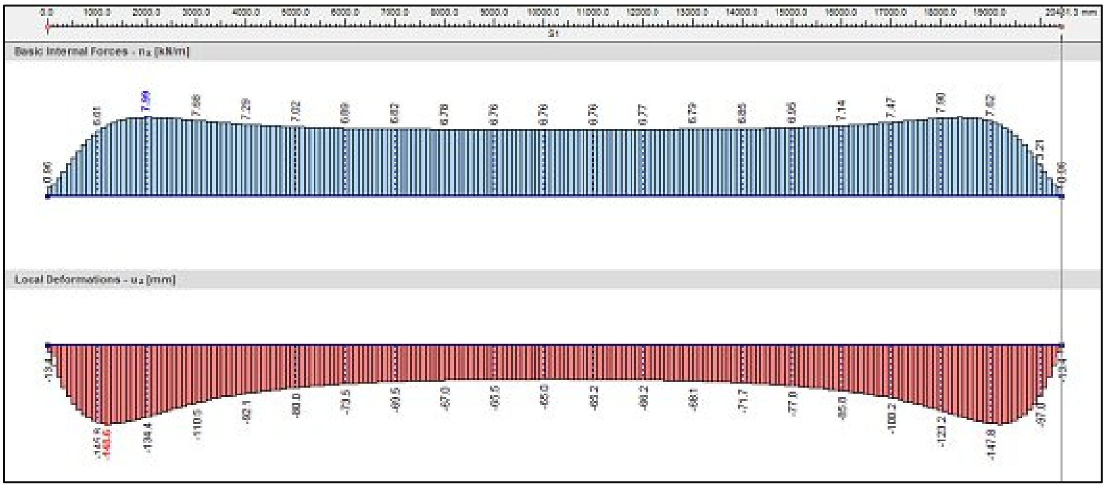

Figure 70: MiAF – Separate MEM – 1.0 DL + 1.0 SL – Membrane forces n_x, local deflections u_z' – Model 20 m – Longitudinal section midspan

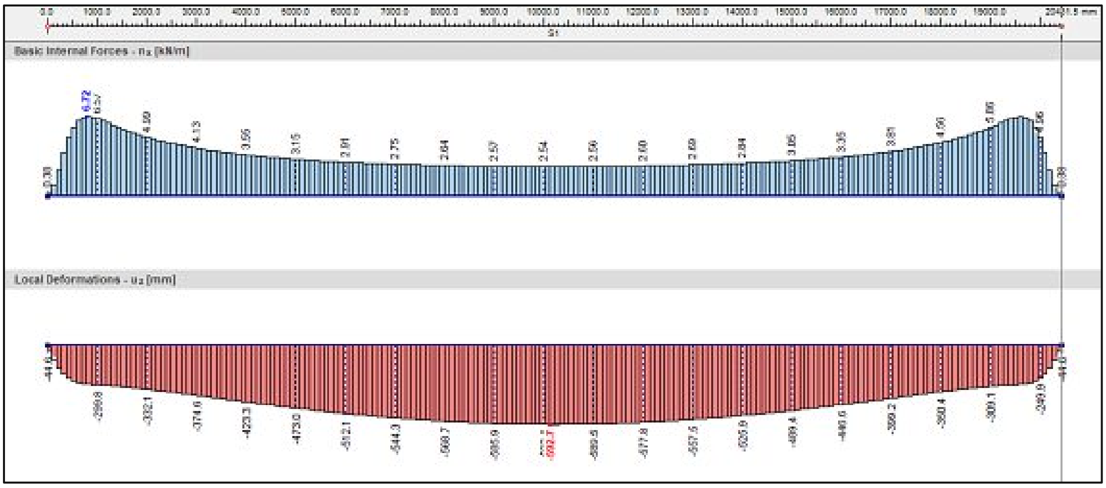

Figure 71: MiAF – Hybrid without FF supports – 1.0 DL + 1.0 SL – Membrane forces n_x, local deflections u_z' – Model 20 m – Longitudinal section midspan

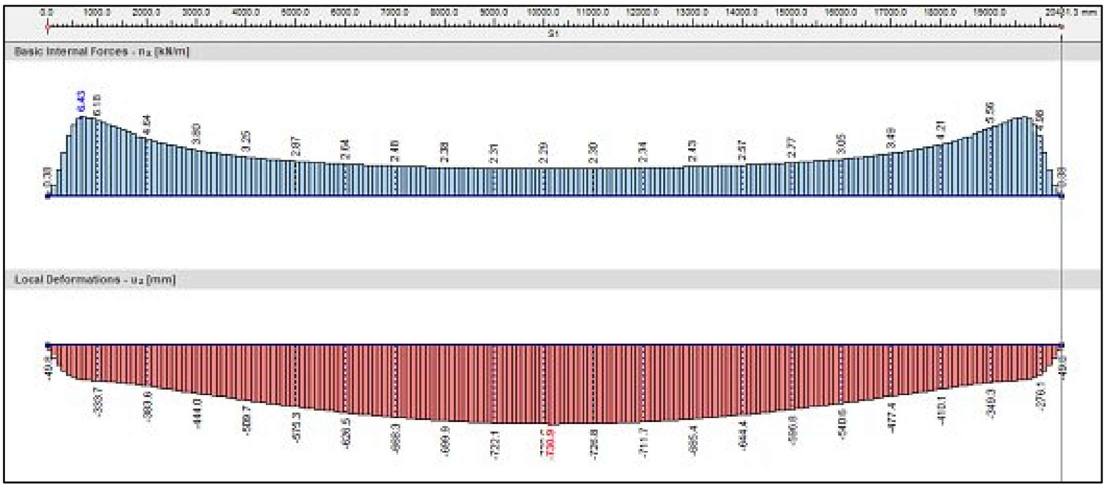

Figure 72: MiAF – Hybrid with FF supports – 1.0 DL + 1.0 SL – Membrane forces n_x, local deflections u_z' – Model 20 m – Longitudinal section midspan

The main influences here are the deflecting arches, strained by the membrane.

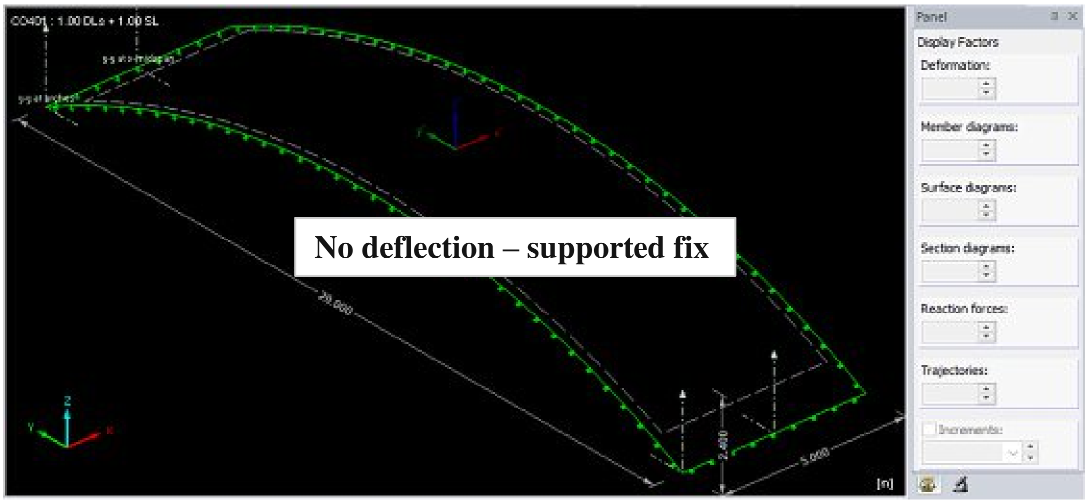

Figure 73: MiAF – Separate MEM – 1.0 DL + 1.0 SL – Local member deflections u_y' – Model 20 m

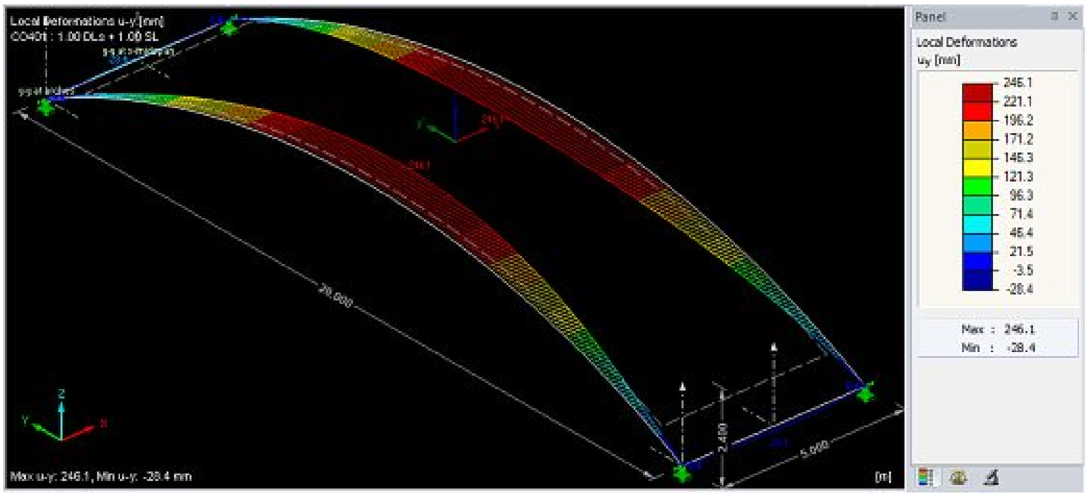

Figure 74: MiAF – Hybrid without – 1.0 DL + 1.0 SL – Local member deflections u_y' – Model 20 m

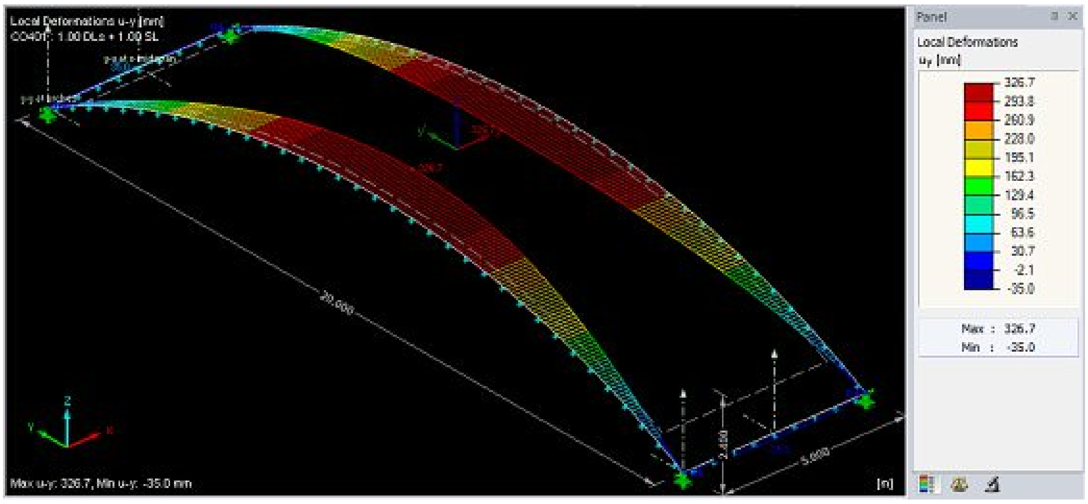

Figure 75: MiAF – Hybrid with – 1.0 DL + 1.0 SL – Local member deflections u_y' – Model 20 m

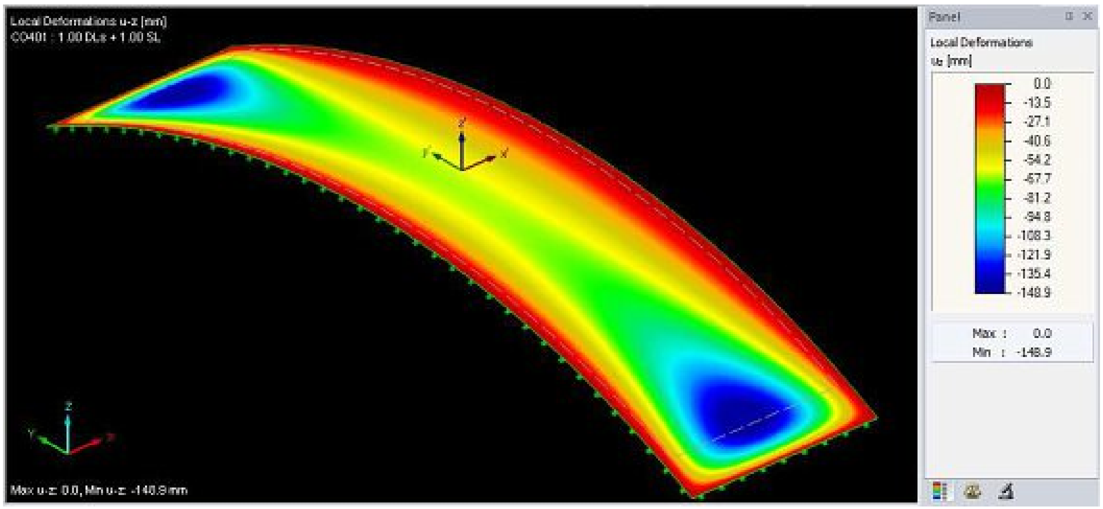

Figure 76: MiAF – Separate MEM – 1.0 DL + 1.0 SL – Local membrane deflections u_z' – Model 20 m

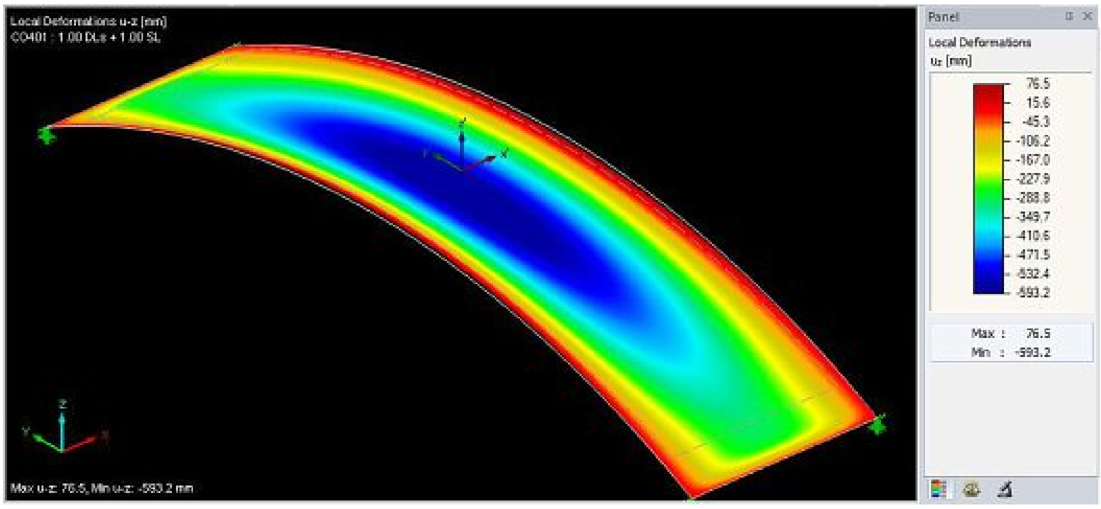

Figure 77: MiAF – Hybrid without – 1.0 DL + 1.0 SL – Local membrane deflections u_z' – Model 20 m

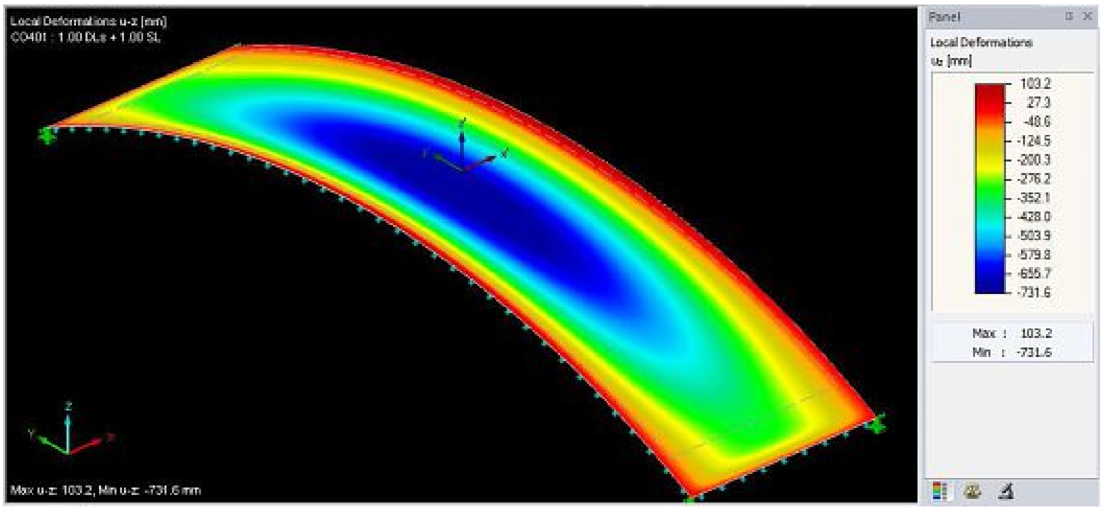

Figure 78: MiAF – Hybrid with – 1.0 DL + 1.0 SL – Local membrane deflections u_z' – Model 20 m

Appendix B Hypar

B.1 Hypar Type A – With Four Struts and Eight Cables

The results of the comparative calculations of the three types are always arranged on one page in the following order:

1. Separate
2. Hybrid without form-finding supports
3. Hybrid with form-finding supports

The colour scale of the results is always set manually to be identical for all three cases, thus the same colour stands for the same result.

All figures in Appendix B.1 are by the author.

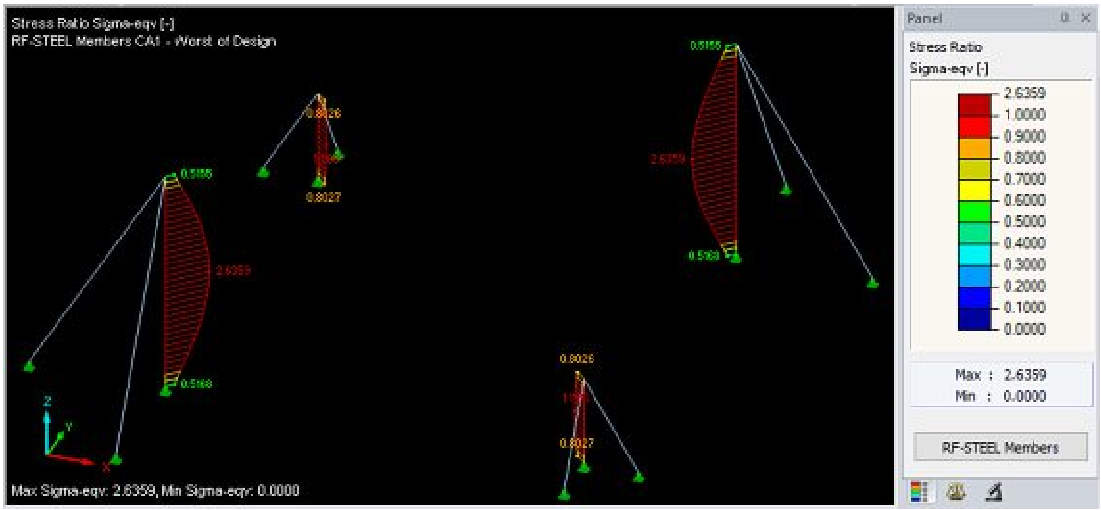

Figure 79: Hypar type A – Separate – Utilisation struts – Worst of design

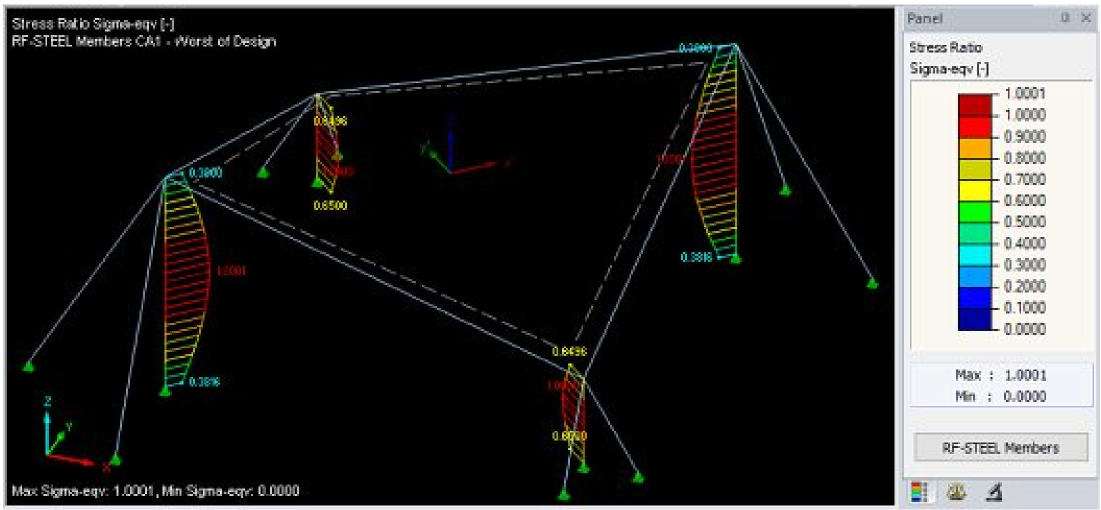

Figure 80: Hypar type A – Hybrid without FF supports – Utilisation struts – Worst of design

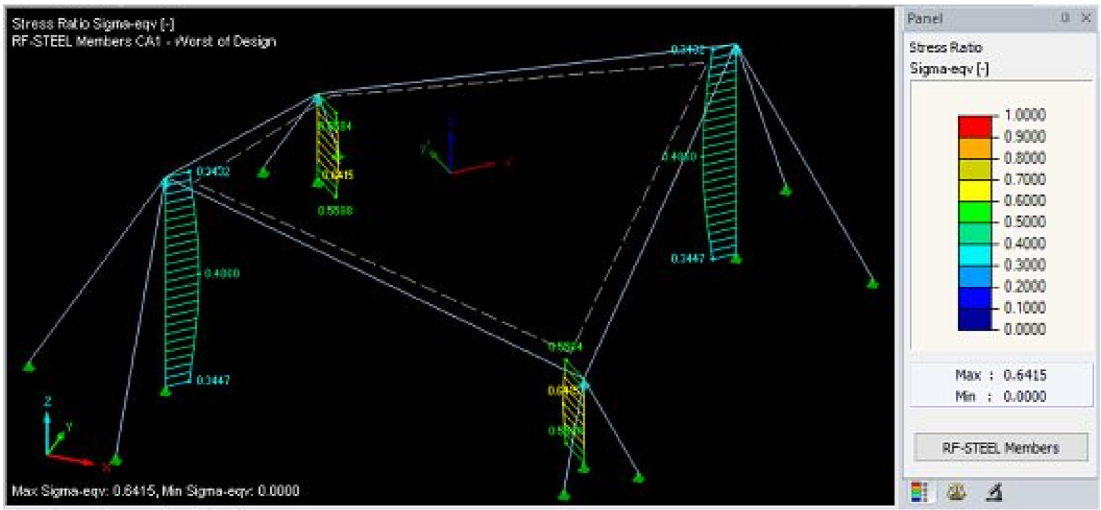

Figure 81: Hypar type A – Hybrid with FF supports – Utilisation struts – Worst of design

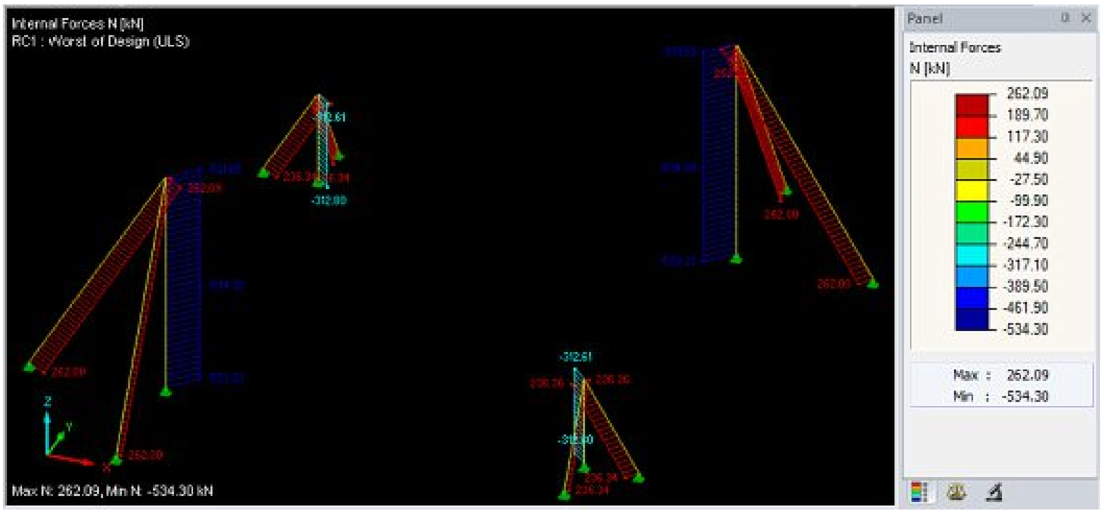

Figure 82: Hypar type A – Separate – Member internal forces – Worst of design

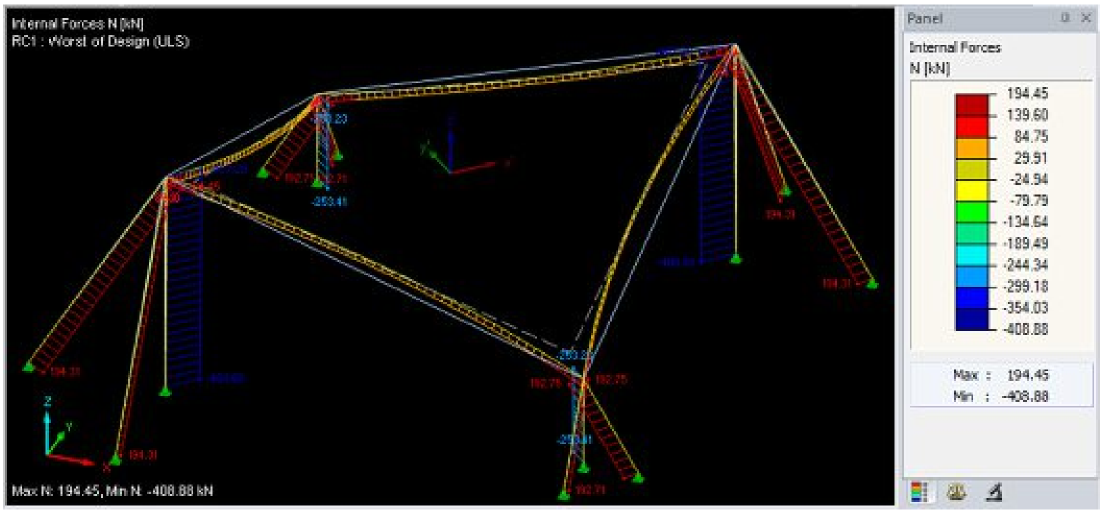

Figure 83: Hypar type A – Hybrid without FF supports – Member internal forces – Worst of design

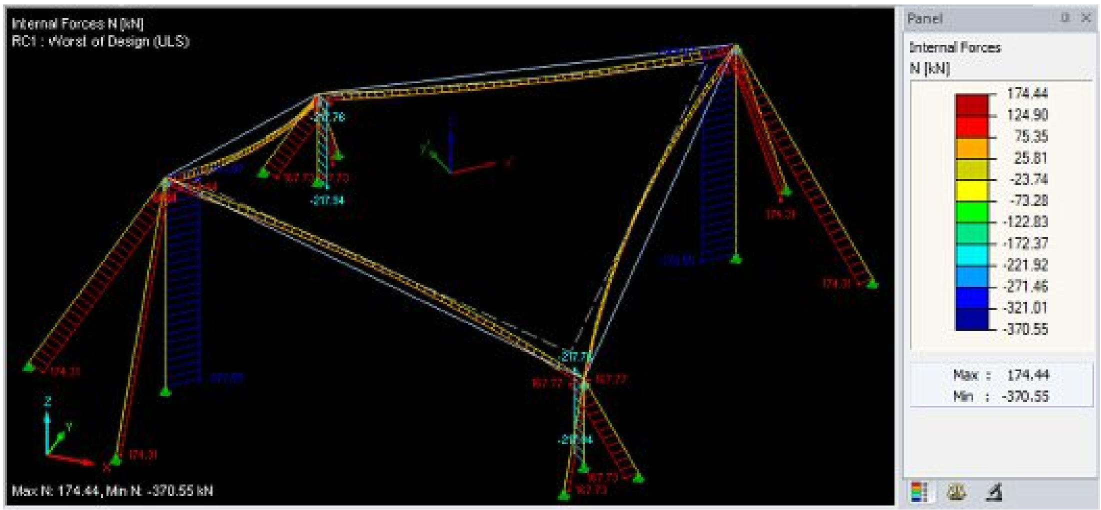

Figure 84: Hypar type A – Hybrid with FF supports – Member internal forces – Worst of design

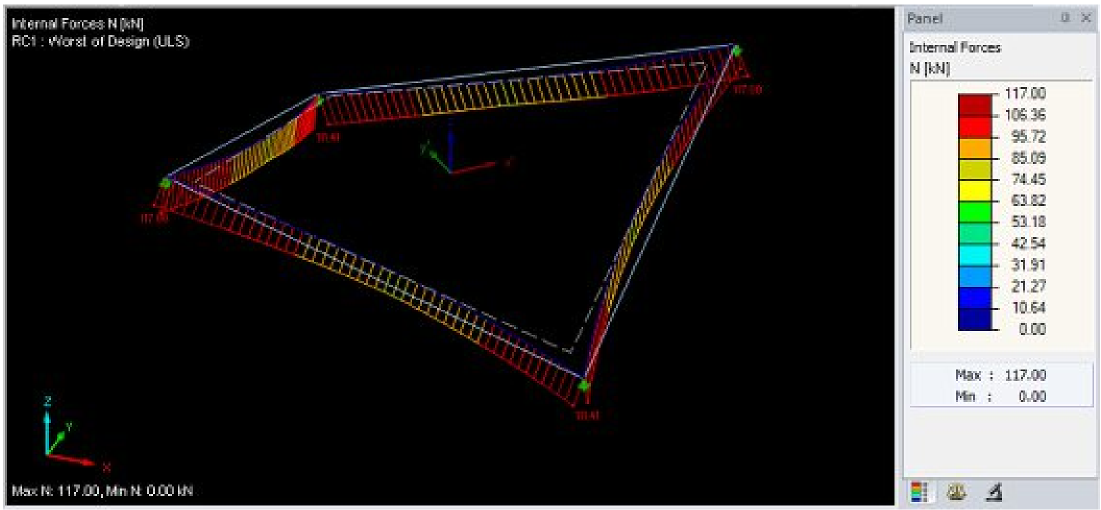

Figure 85: Hypar type A – Separate – Max. forces edge cables – Worst of design

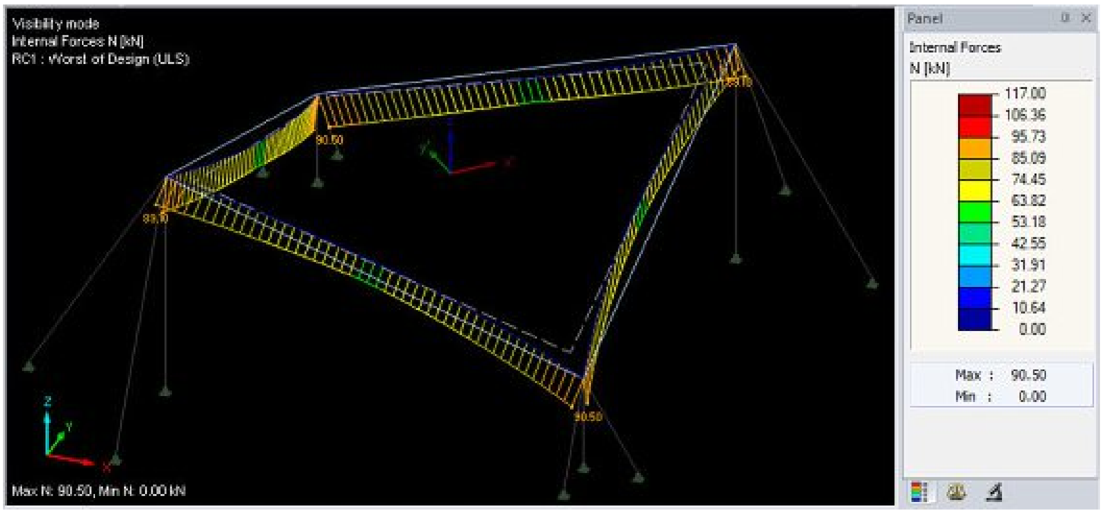

Figure 86: Hypar type A – Hybrid without FF supports – Max. forces edge cables – Worst of design

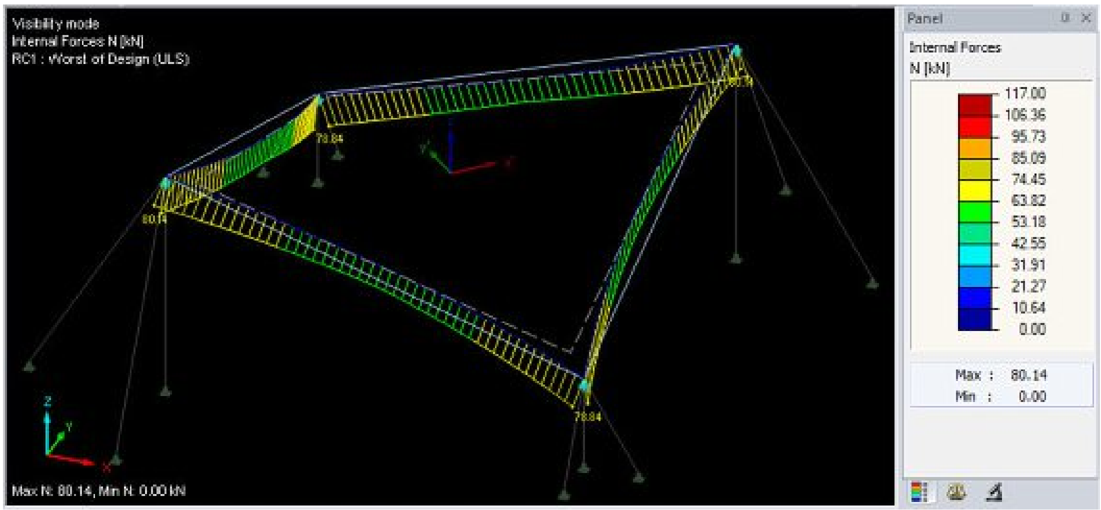

Figure 87: Hypar type A – Hybrid with FF supports – Max. forces edge cables – Worst of design

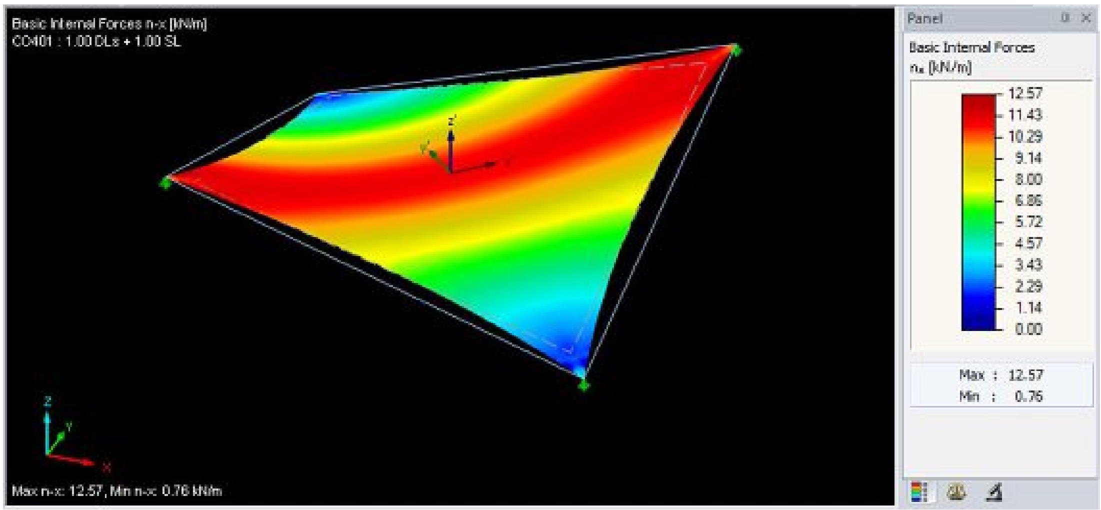

Figure 88: Hypar type A – Separate – Membrane forces 1.0 DL + 1.0 SL

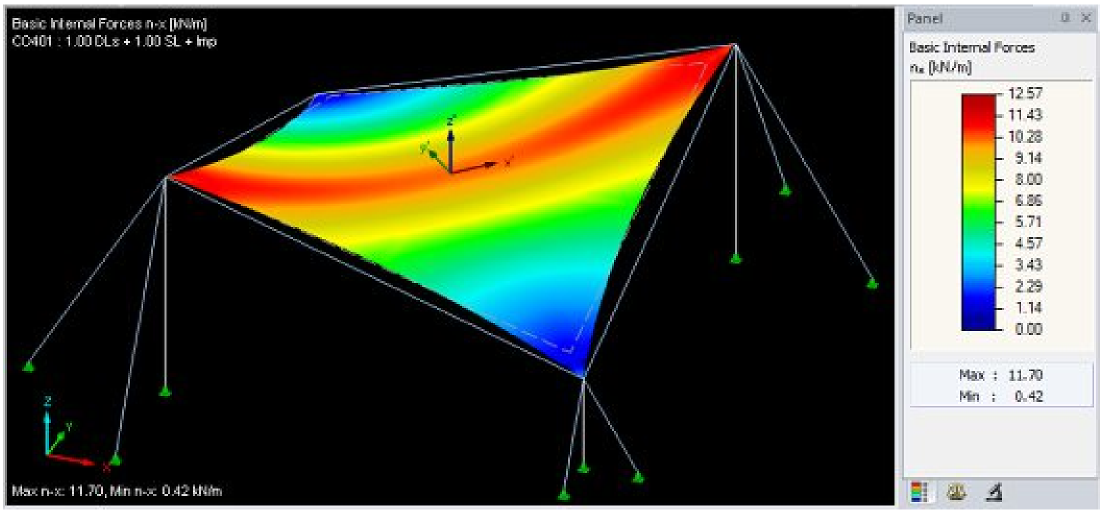

Figure 89: Hypar type A – Hybrid without FF supports – Membrane forces 1.0 DL + 1.0 SL

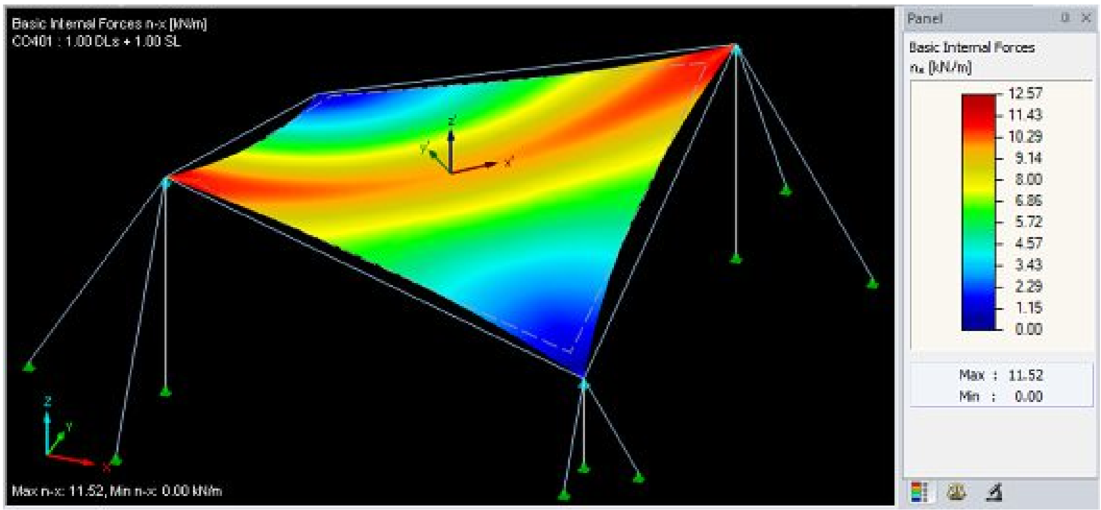

Figure 90: Hypar type A – Hybrid with FF supports – Membrane forces 1.0 DL + 1.0 SL

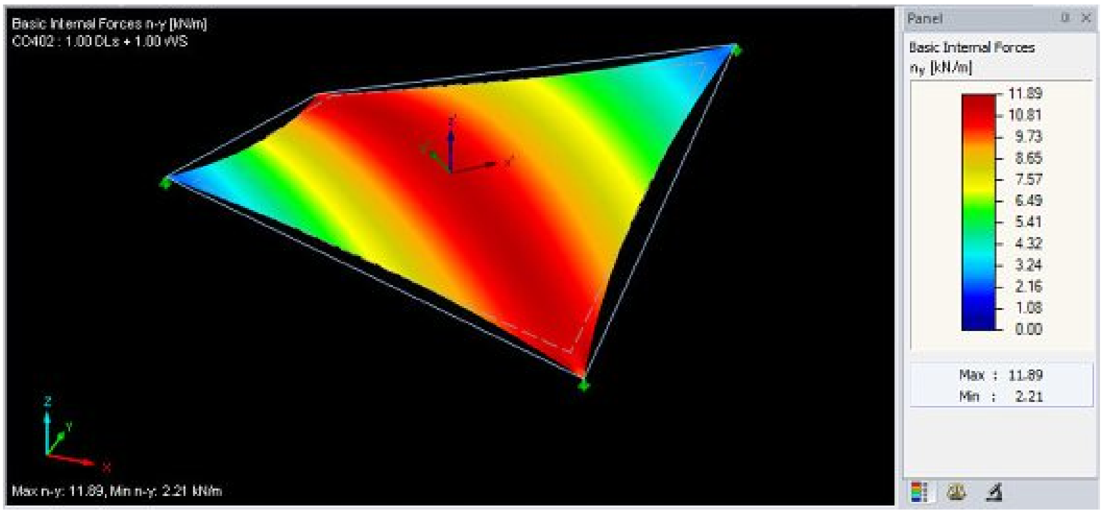

Figure 91: Hypar type A – Separate – Membrane forces 1.0 DL + 1.0 WS

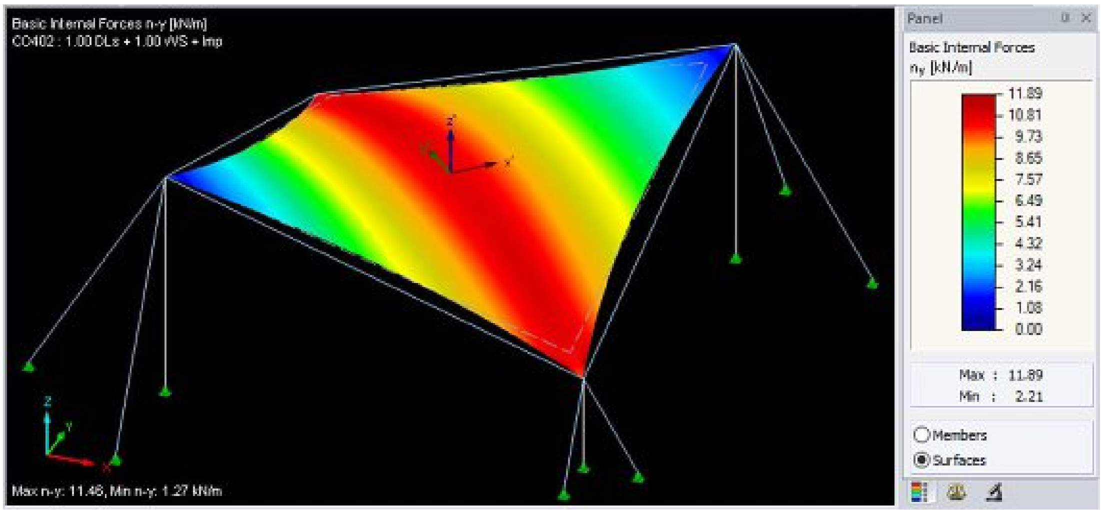

Figure 92: Hypar type A – Hybrid without FF supports – Membrane forces 1.0 DL + 1.0 WS

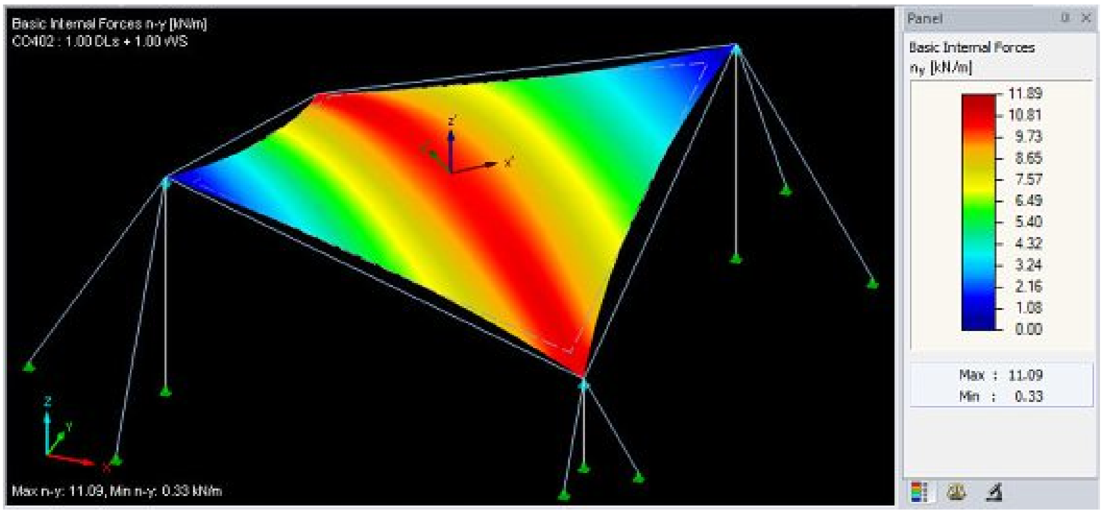

Figure 93: Hypar type A – Hybrid with FF supports – Membrane forces 1.0 DL + 1.0 WS

B.2 Hypar Type B – Column Bending Type

The results of the comparative calculations of the three types are always arranged on one page in the following order:

1. Separate
2. Hybrid without form-finding supports
3. Hybrid with form-finding supports

The colour scale of the results is always set manually to be identical for all three cases, thus the same colour stands for the same result.

All figures in Appendix B.2 are by the author.

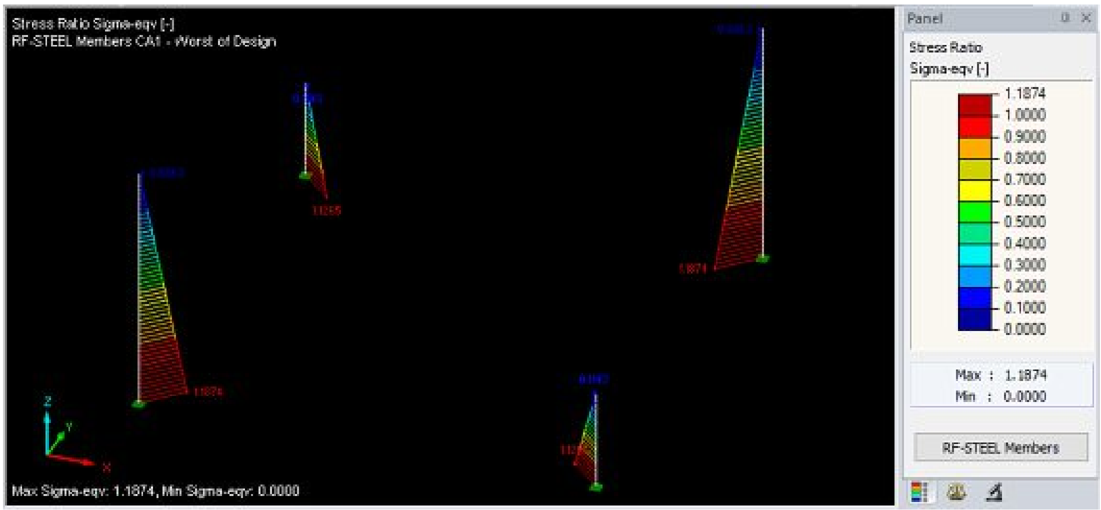

Figure 94: Hypar type B – Separate – Utilisation struts – Worst of design

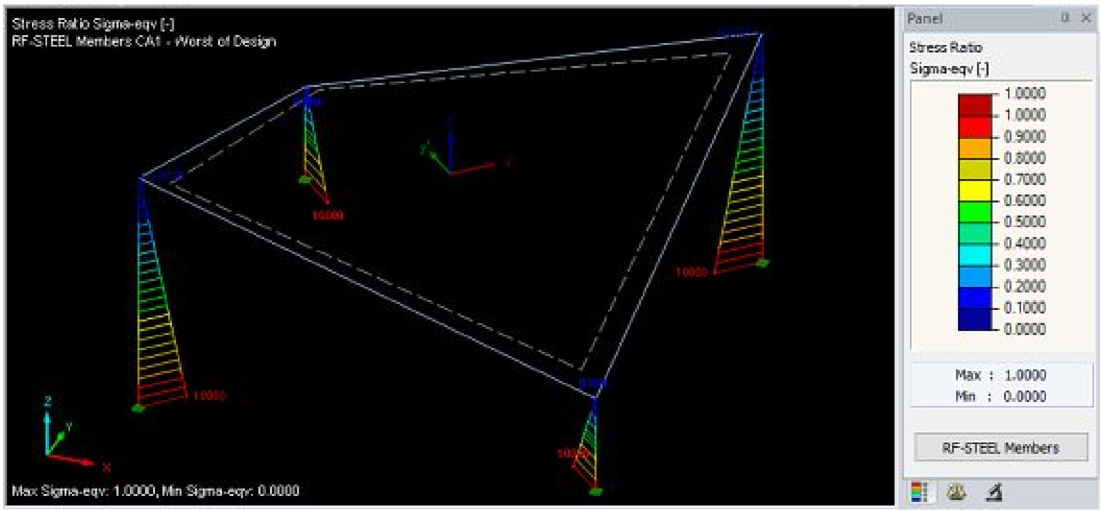

Figure 95: Hypar type B – Hybrid without FF supports – Utilisation struts – Worst of design

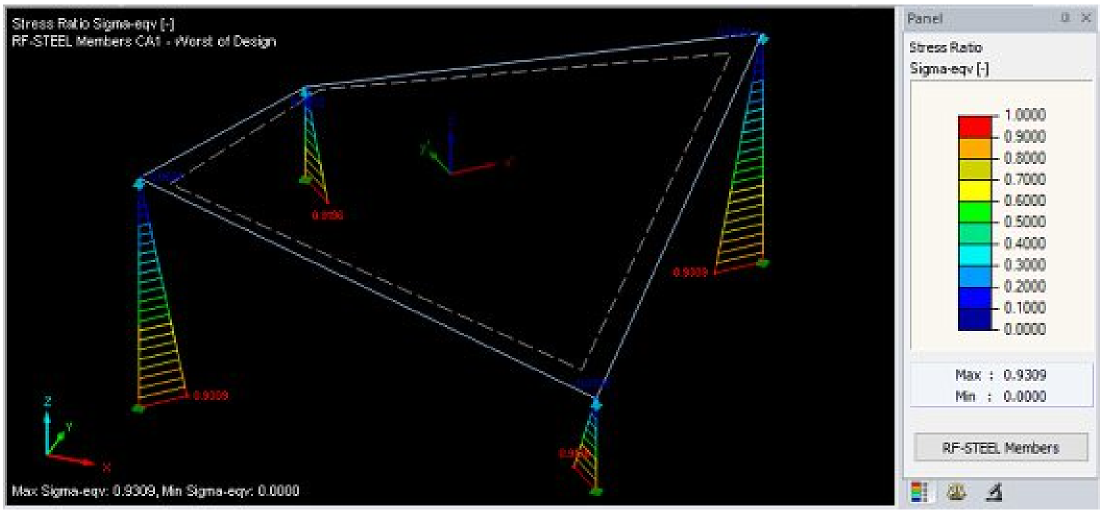

Figure 96: Hypar type B – Hybrid with FF supports – Utilisation struts – Worst of design

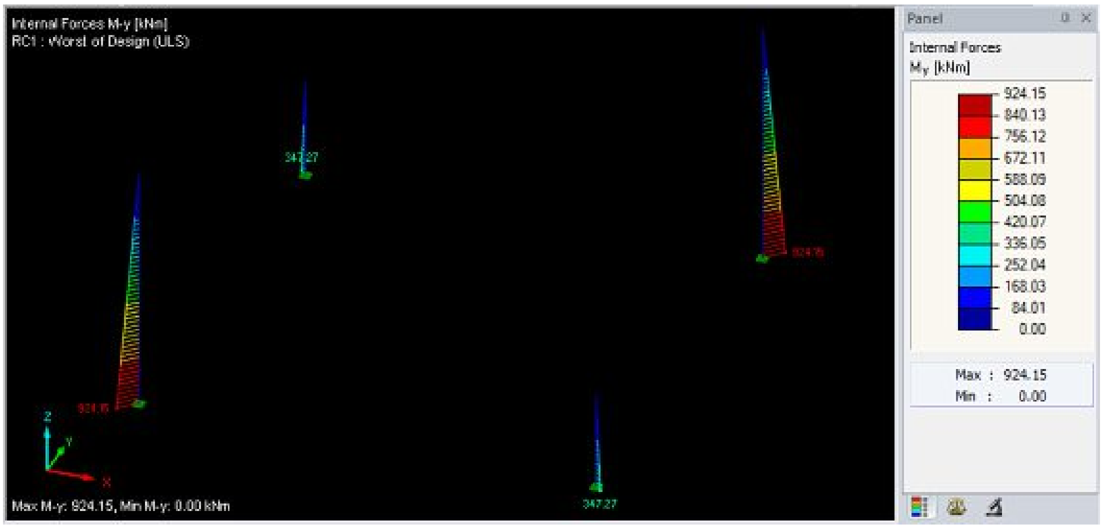

Figure 97: Hypar type B – Separate – Bending moments – Worst of design

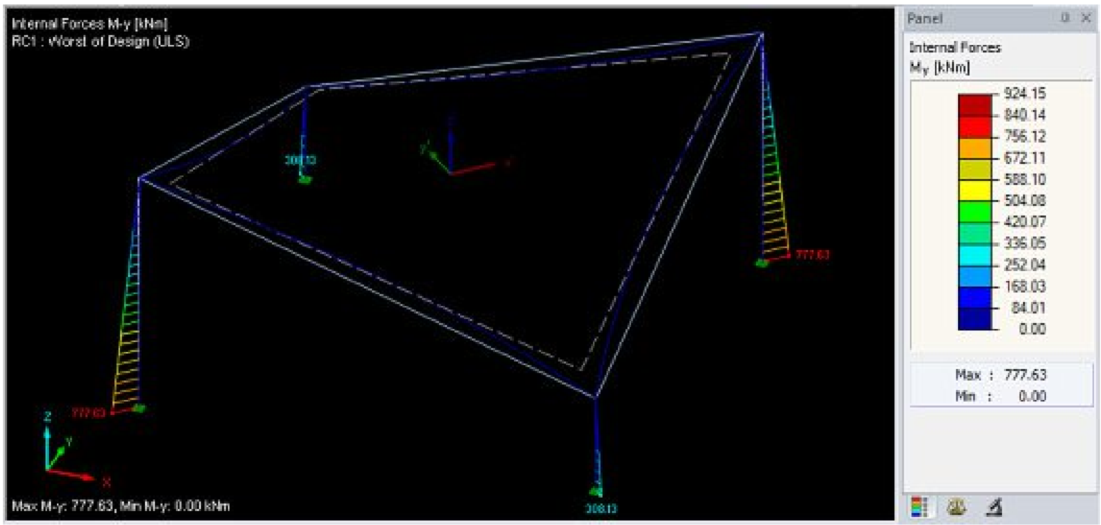

Figure 98: Hypar type B – Hybrid without FF supports – Bending moments – Worst of design

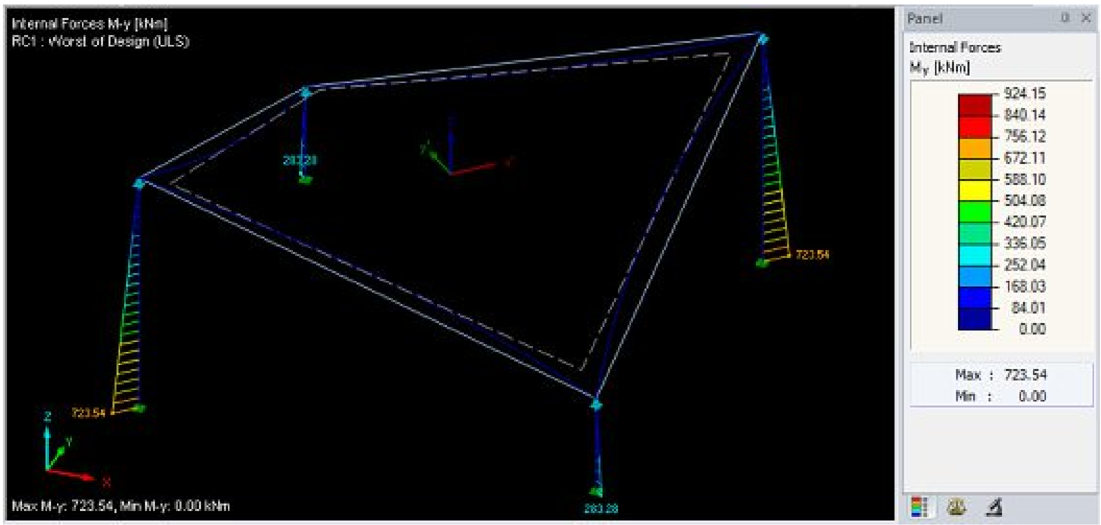

Figure 99: Hypar type B – Hybrid with FF supports – Bending moments – Worst of design

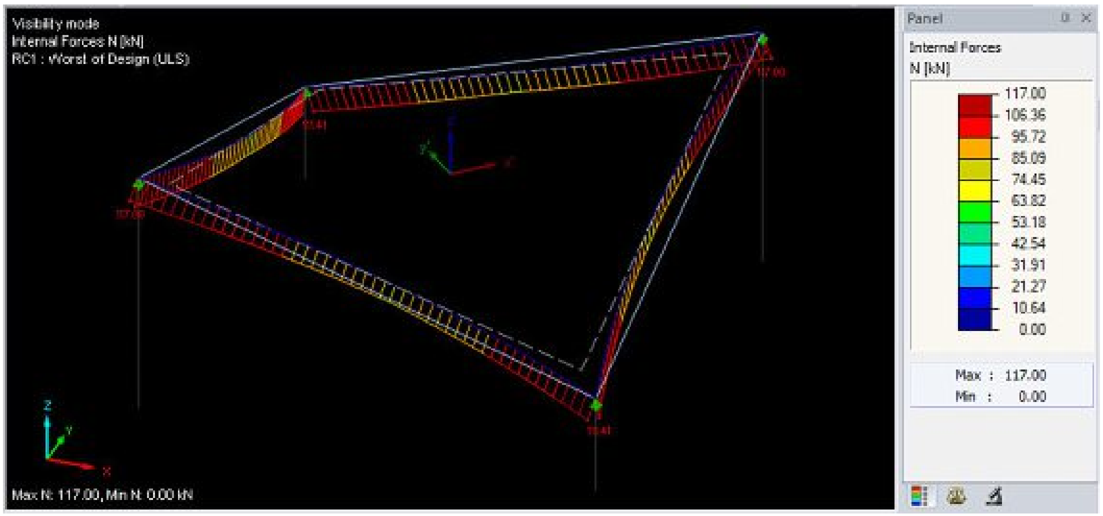

Figure 100: Hypar type B – Separate – Max. forces edge cables – Worst of design

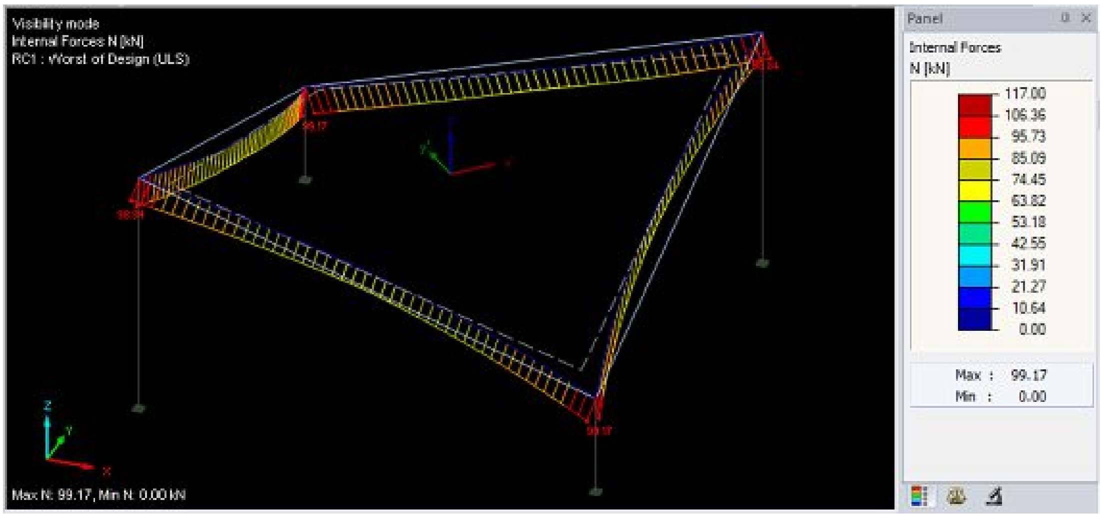

Figure 101: Hypar type B – Hybrid without FF supports – Max. forces edge cables – Worst of design

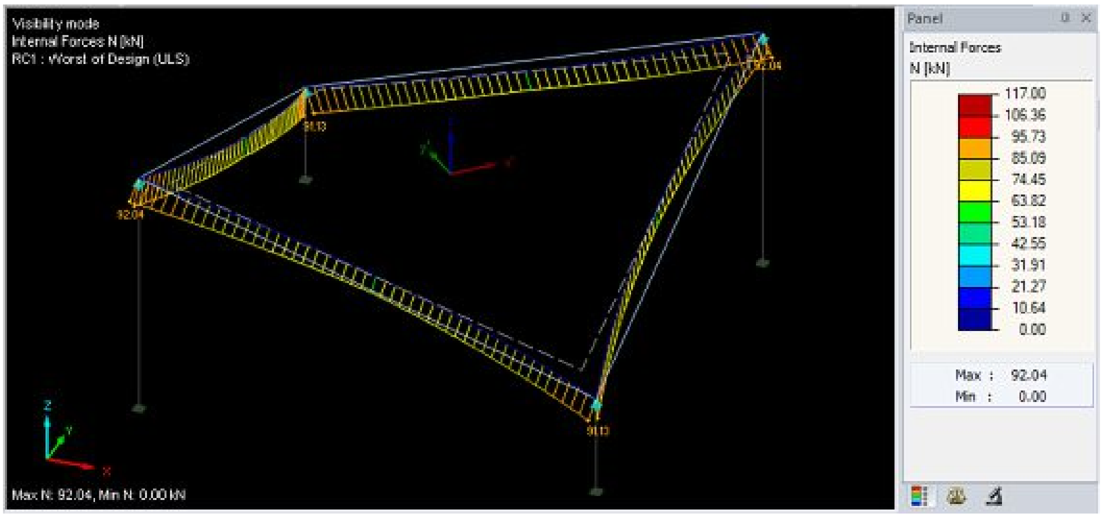

Figure 102: Hypar type B – Hybrid with FF supports – Max. forces edge cables – Worst of design

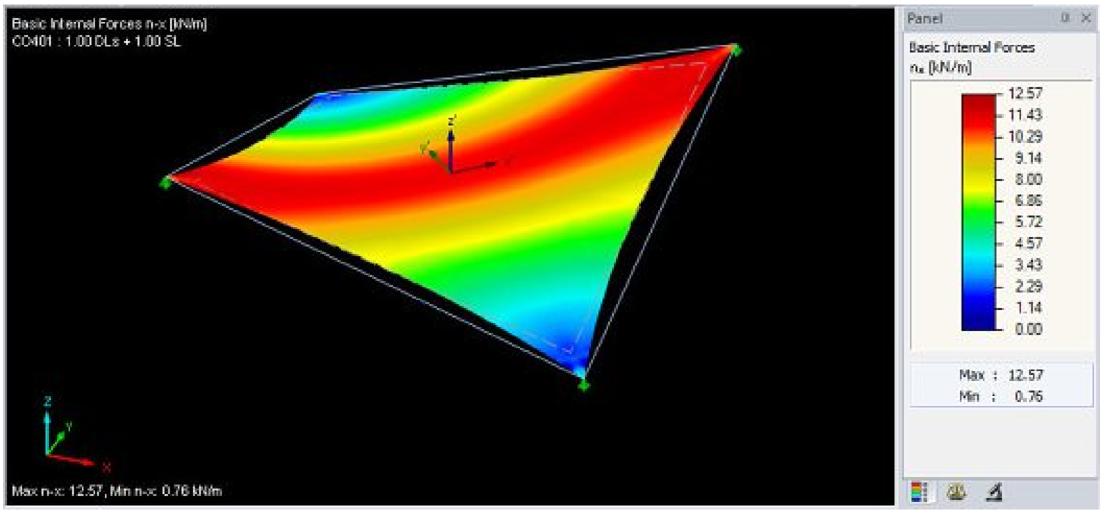

Figure 103: Hypar type B – Separate – Membrane forces 1.0 DL + 1.0 SL

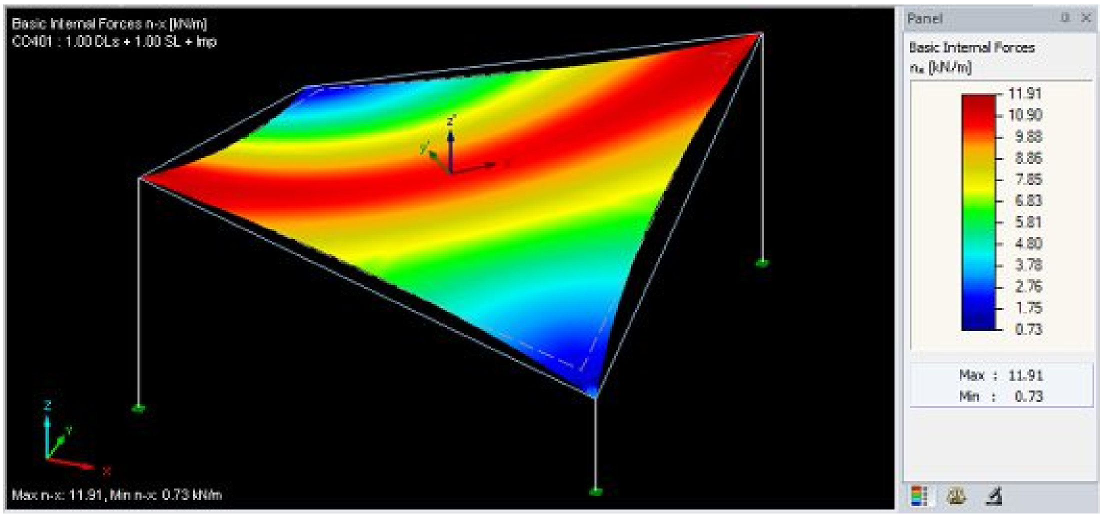

Figure 104: Hypar type B – Hybrid without FF supports – Membrane forces 1.0 DL + 1.0 SL

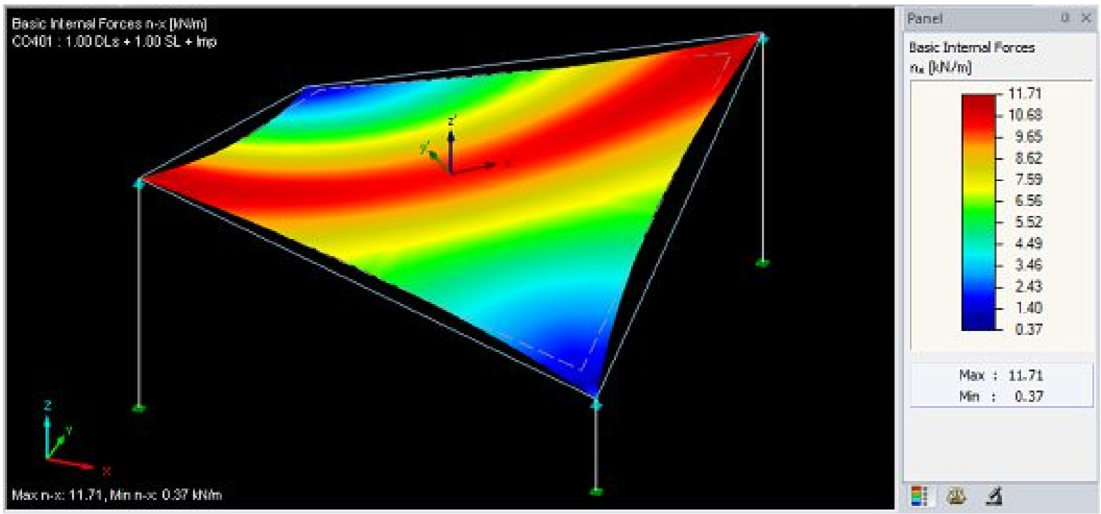

Figure 105: Hypar type B – Hybrid with FF supports – Membrane forces 1.0 DL + 1.0 SL

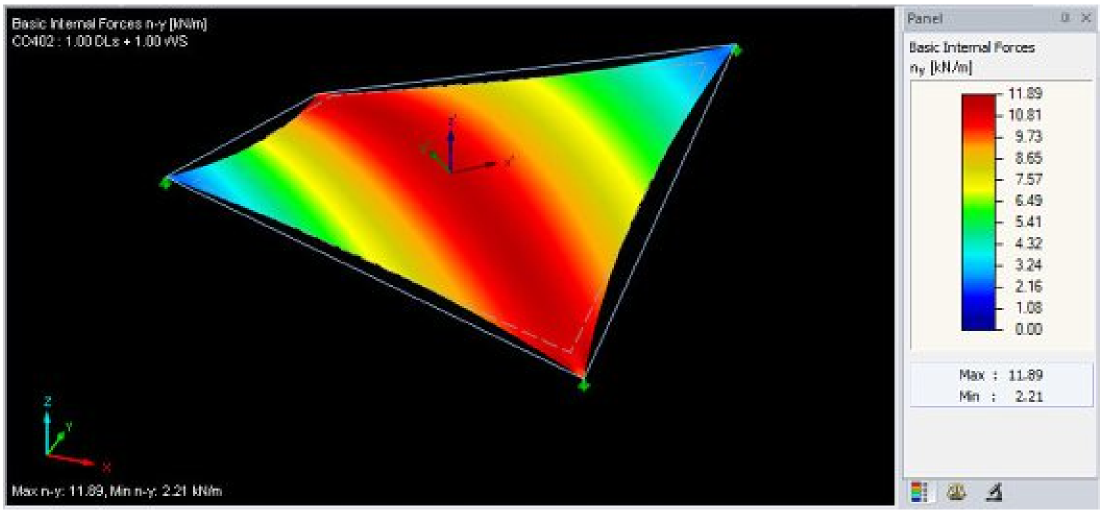

Figure 106: Hypar type B – Separate – Membrane forces 1.0 DL + 1.0 WS

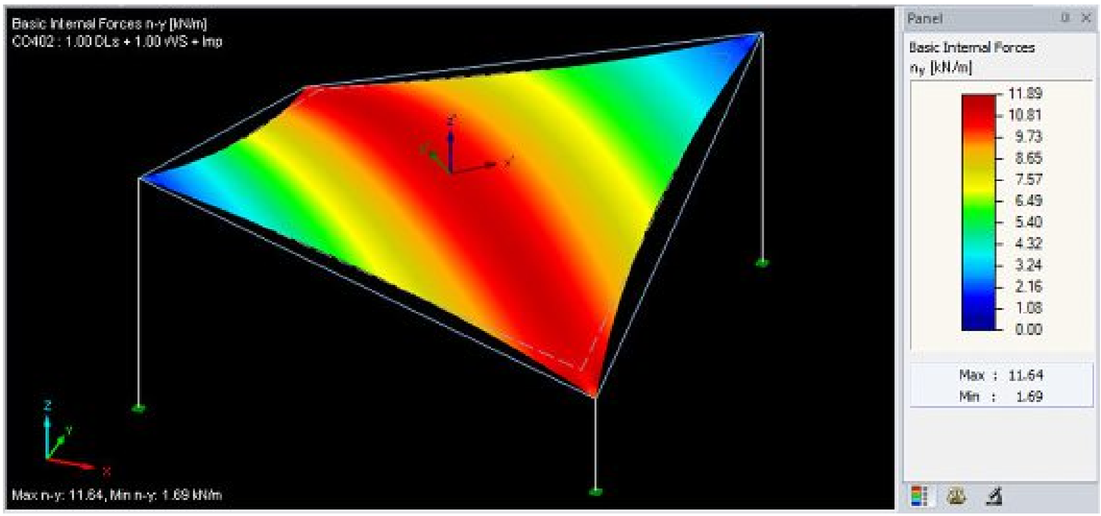

Figure 107: Hypar type B – Hybrid without FF supports – Membrane forces 1.0 DL + 1.0 WS

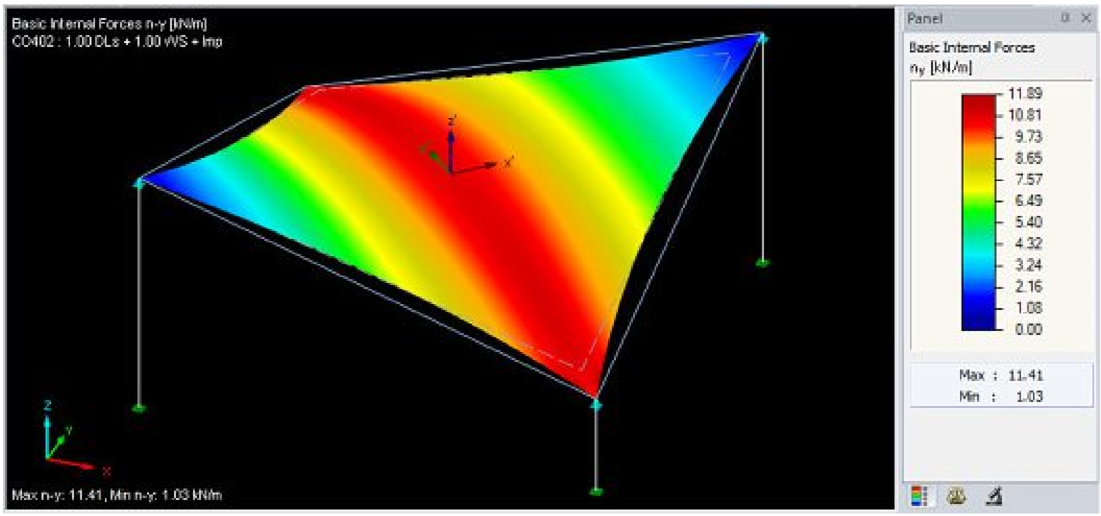

Figure 108: Hypar type B – Hybrid with FF supports – Membrane forces 1.0 DL + 1.0 WS

Appendix C Flat Triangular Cushion (FTC)

In the following, only the relevant layers according to the respective load direction are displayed. For live load and wind pressure the bottom layer, for wind suction the top layer. The order of presented options is:

1) Hybrid including the gas volume in modelling and calculation
2) Separate without gas volume; loading option 1
3) Separate without gas volume; loading option 2

For each load case combination, all three options are always displayed on one page, so that the respective result for all three is at the same position on the respective page. This was done for better comparability on the computer while scrolling. The colour scale of the results is always manually set to be identical, so that the same colour always stands for the same force.

Flat Triangular Cushion is abbreviated as FTC in the following.

All figures in Appendix C are by the author.

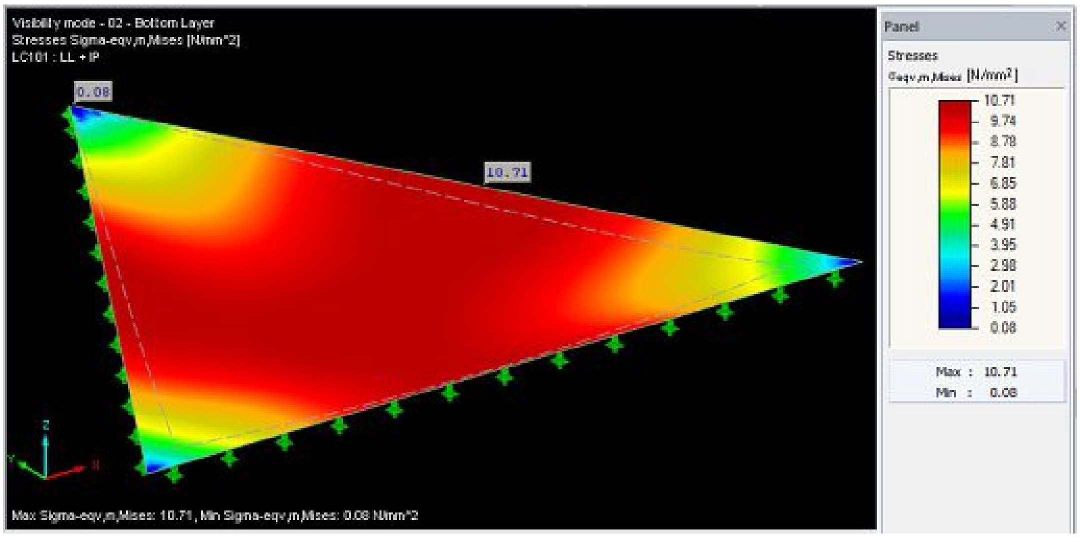

Figure 109: FTC – Stresses – Separate – Loading Option 1 – LL – Bottom Layer

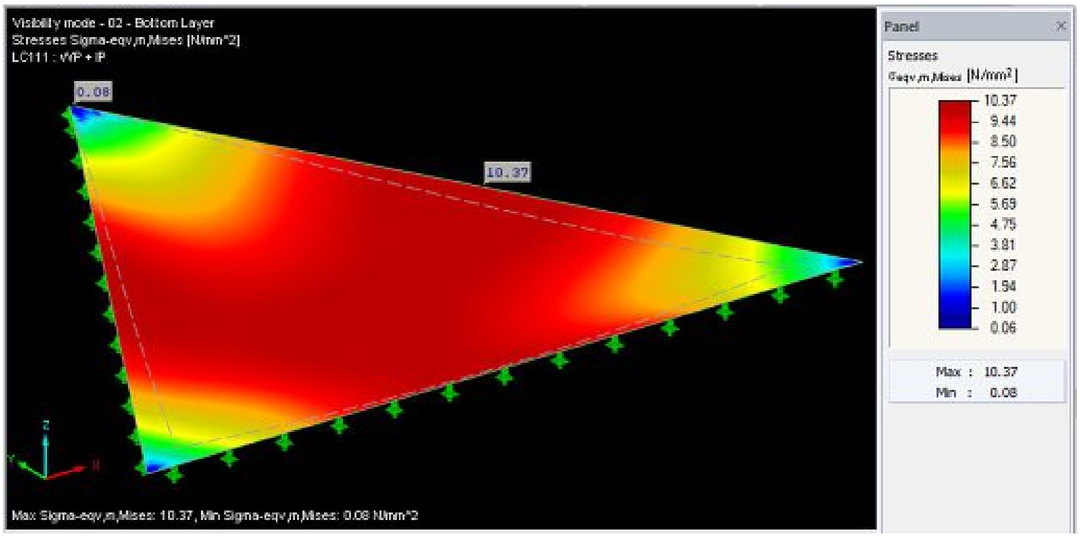

Figure 110: FTC – Stresses – Separate – Loading Option 1 – WP – Bottom Layer

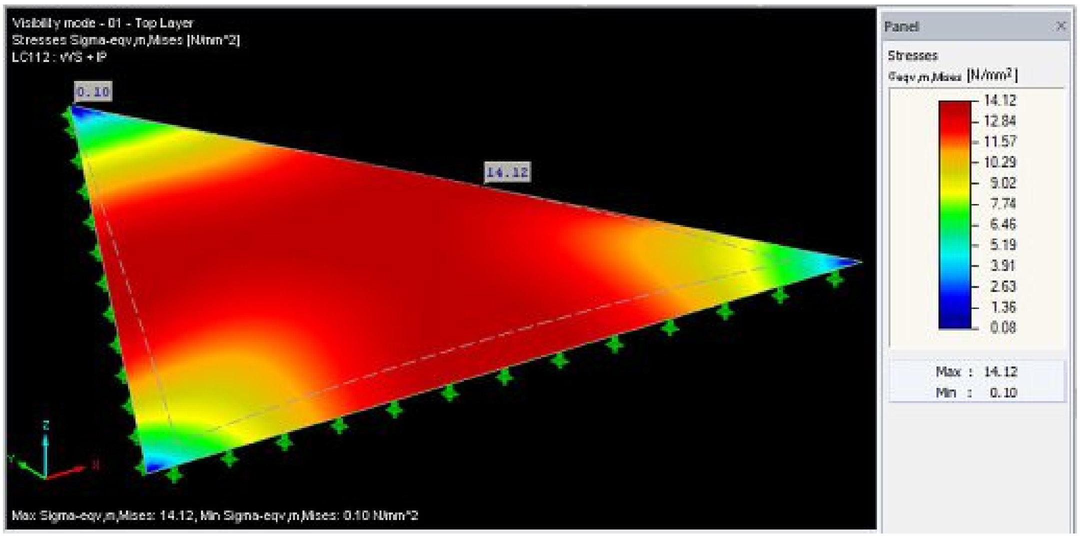

Figure 111: FTC – Stresses – Separate – Loading Option 1 – WS – Top Layer

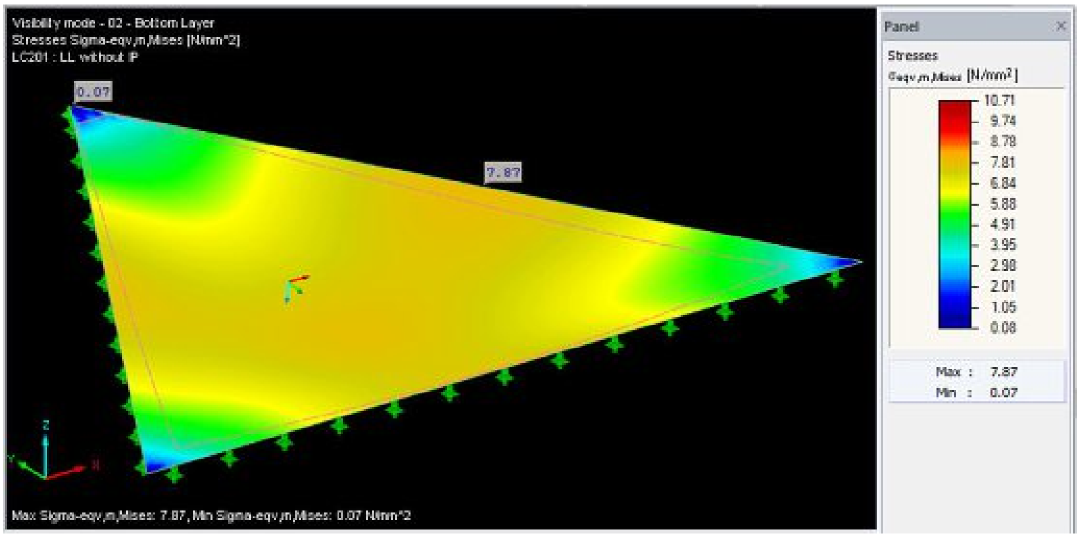

Figure 112: FTC – Stresses – Separate – Loading Option 2 – LL – Bottom Layer

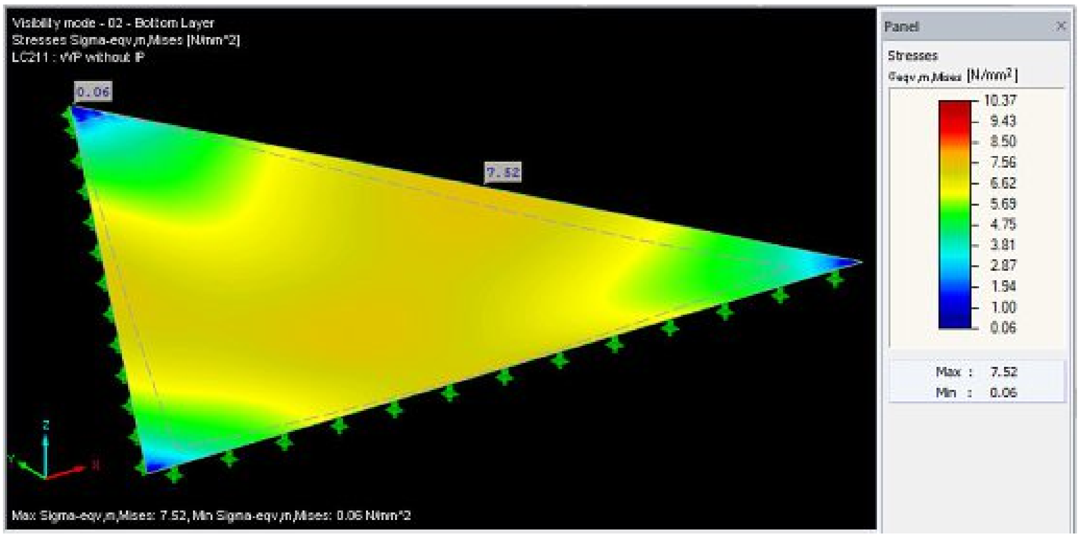

Figure 113: FTC – Stresses – Separate – Loading Option 2 – WP – Bottom Layer

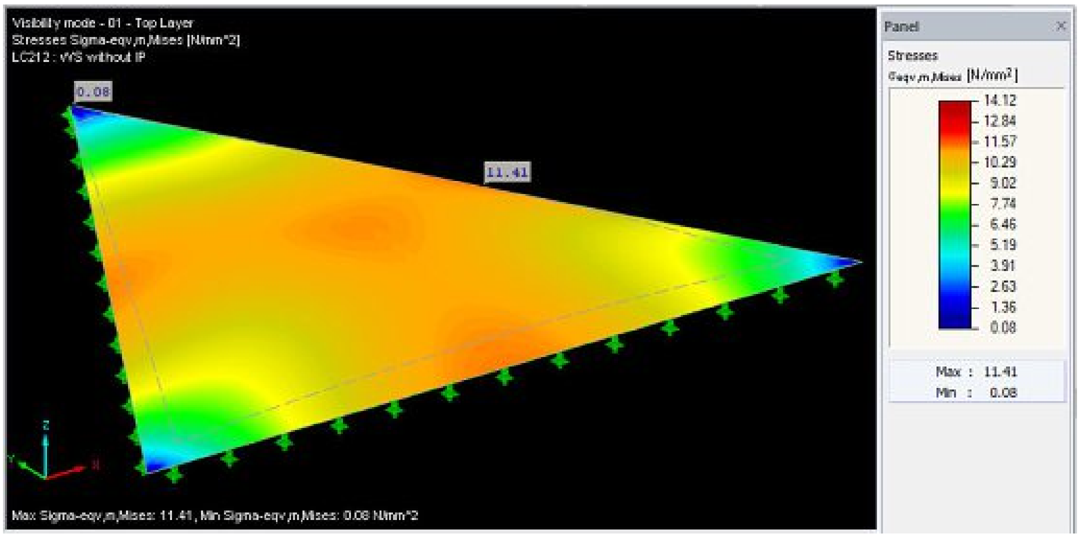

Figure 114: FTC – Stresses – Separate – Loading Option 2 – WS – Top Layer

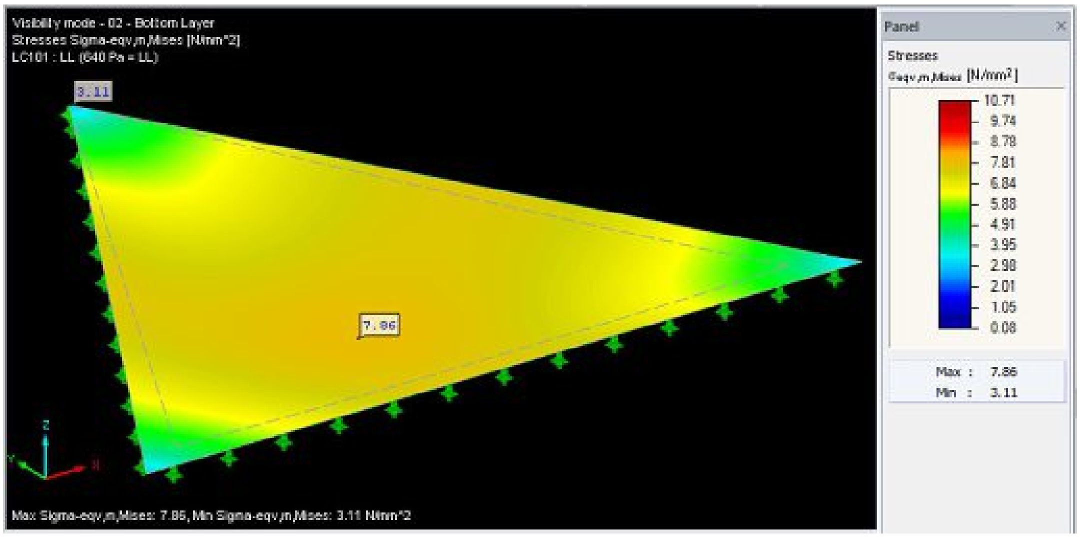

Figure 115: FTC – Stresses – Hybrid – LL – Bottom Layer

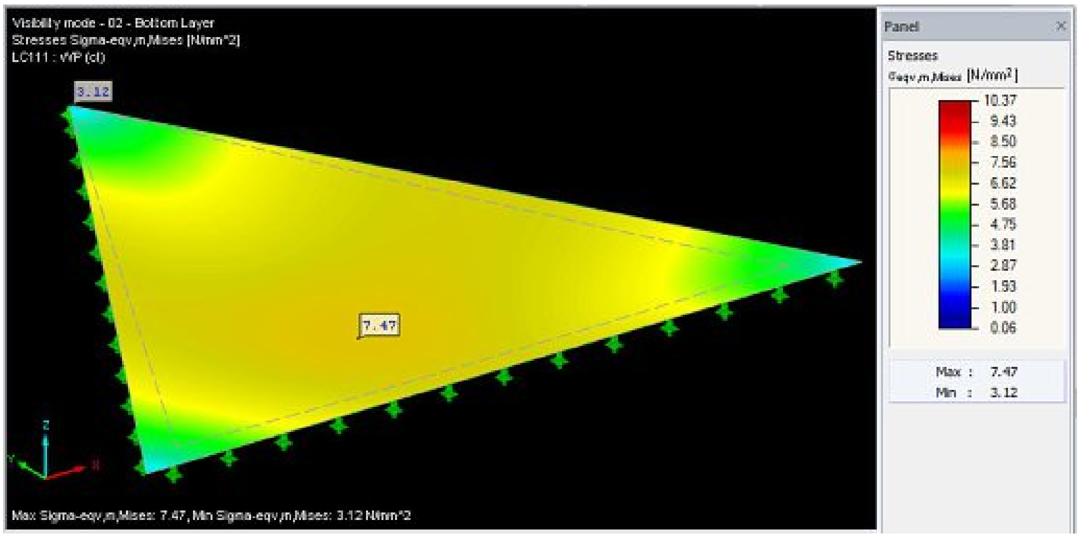

Figure 116: FTC – Stresses – Hybrid – WP – Bottom Layer

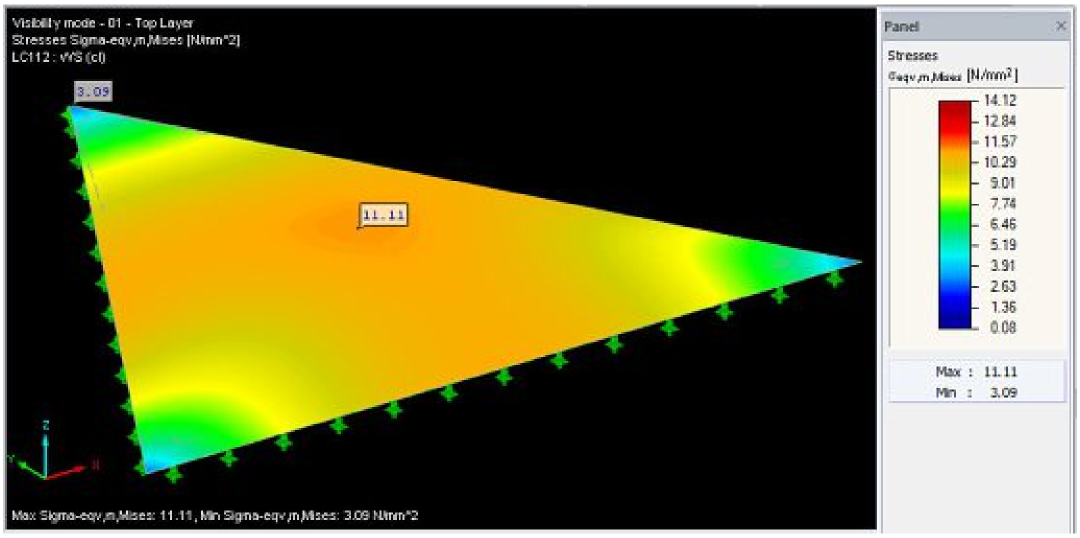

Figure 117: FTC – Stresses – Hybrid – WS – Top Layer

Appendix D Membranes Between Three Arches (MbtA)

The results of the comparative calculations of the three types are always arranged on one page in the following order:

1. Separate
2. Hybrid without form-finding supports
3. Hybrid with form-finding supports

The colour scale of the results is always set manually so that it is identical for all three cases, thus the same colour stands for the same result.

Membranes between three Arches is abbreviated as MbtA in the following.

All figures in Appendix D are by the author.

D.1 MbtA – Same Sections (SecSame)

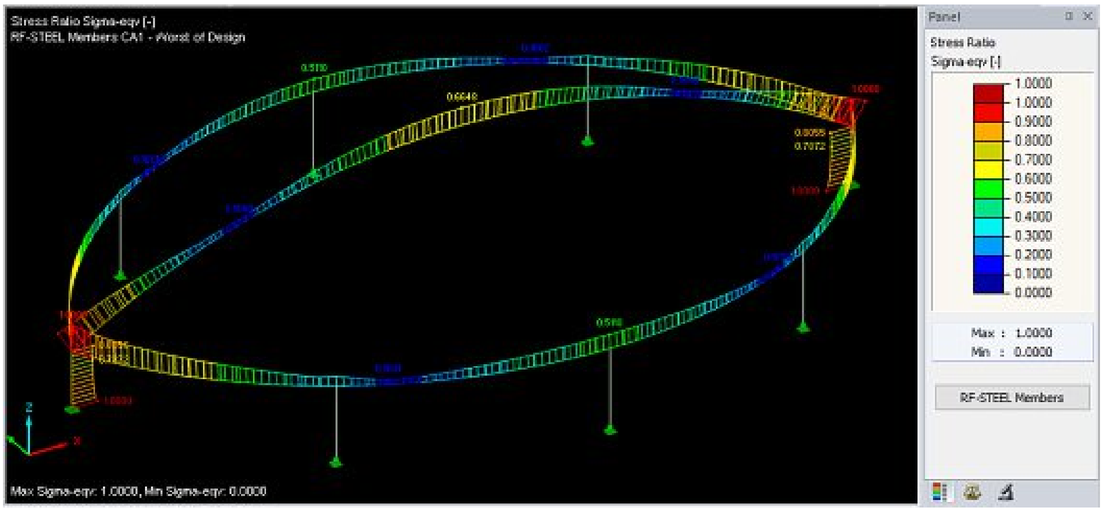

Figure 118: MbtA - SecSame – Separate – Utilisation members – Worst of design

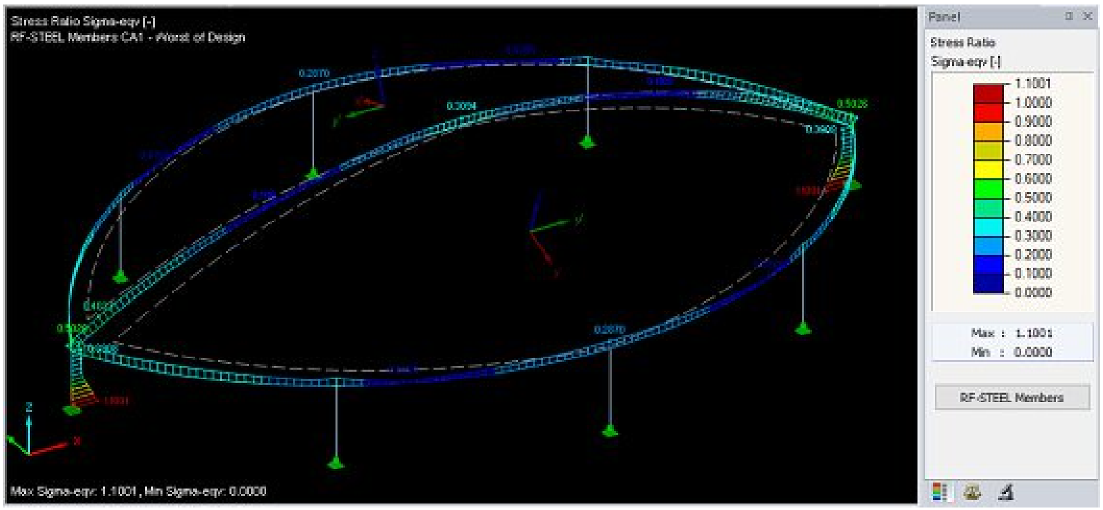

Figure 119: MbtA - SecSame – Hybrid without – Utilisation members – Worst of design

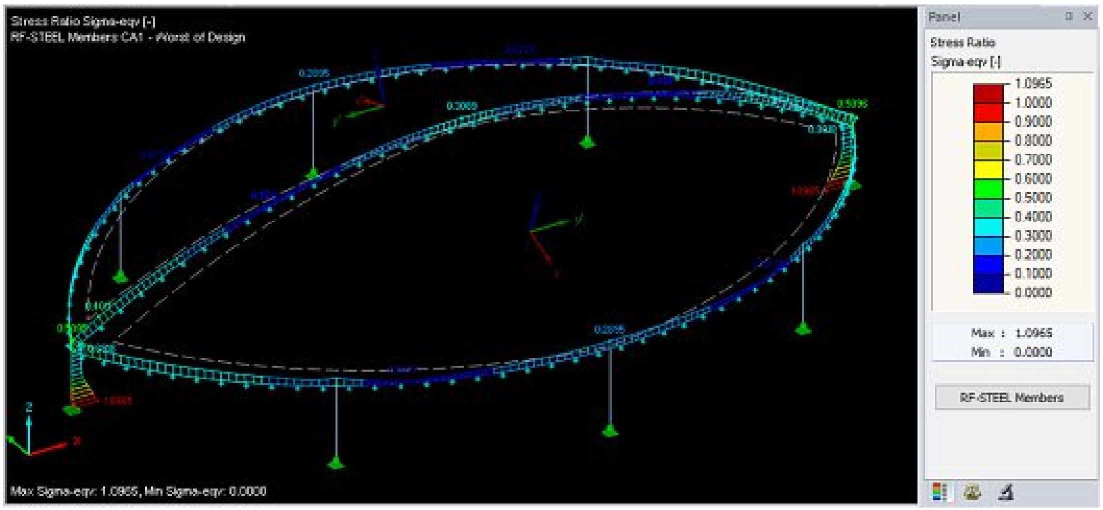

Figure 120: MbtA – SecSame – Hybrid with – Utilisation members – Worst of design

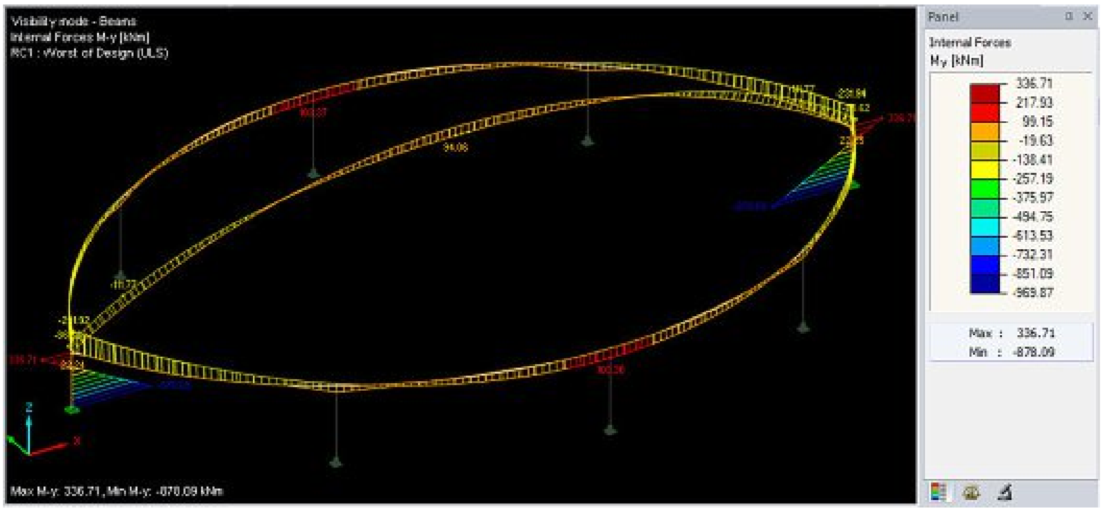

Figure 121: MbtA – SecSame – Separate – Bending moment M_{yd} – Worst of design

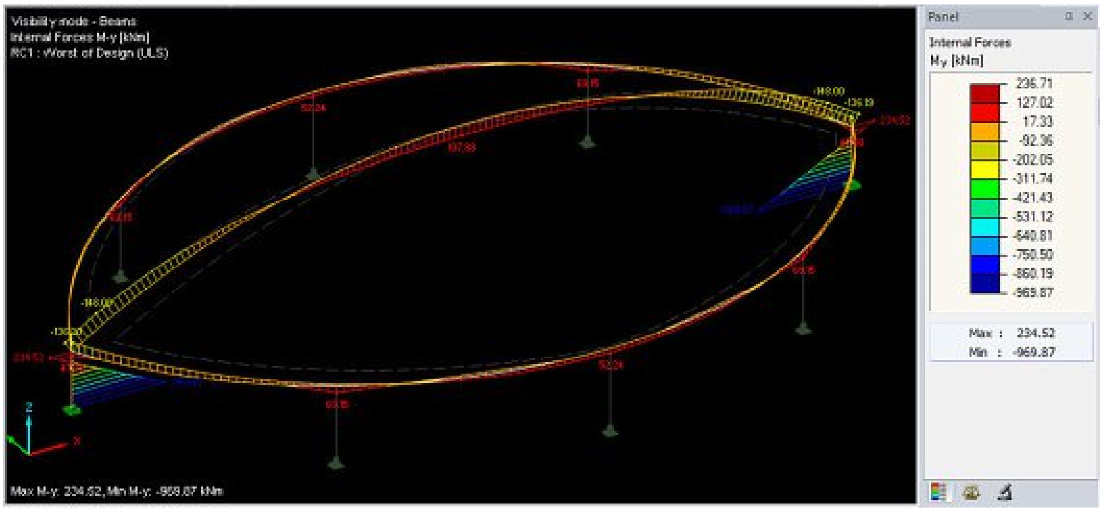

Figure 122: MbtA – SecSame – Hybrid without – Bending moment M_{yd} – Worst of design

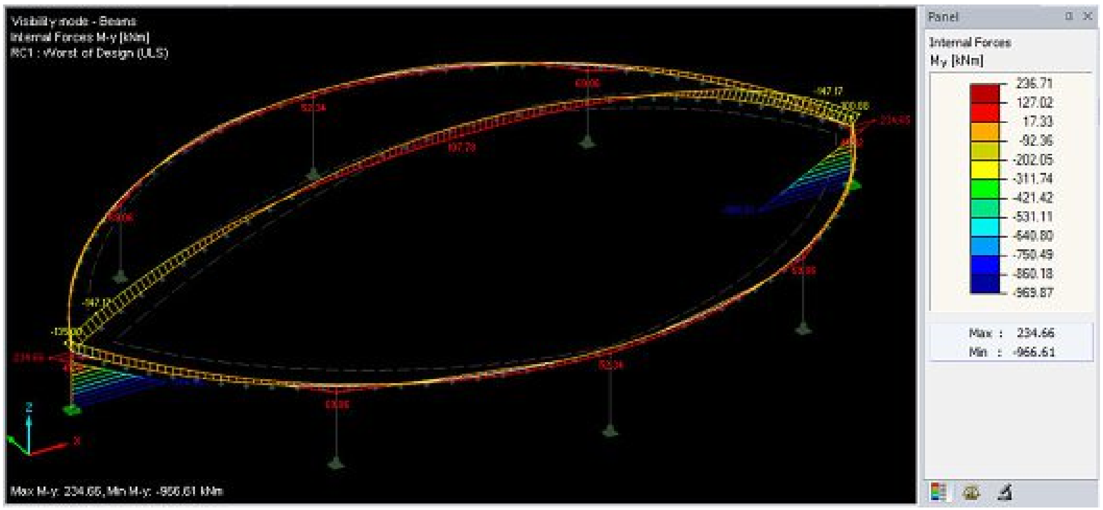

Figure 123: MbtA – SecSame – Hybrid with – Bending moment M_{yd} – Worst of design

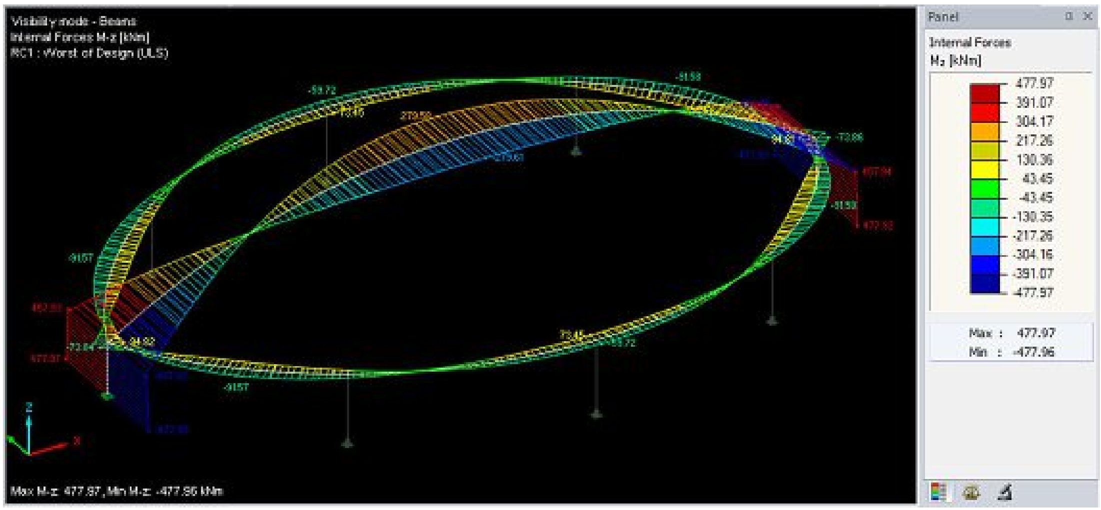

Figure 124: MbtA – SecSame – Separate – Bending moment M_{zd} – Worst of design

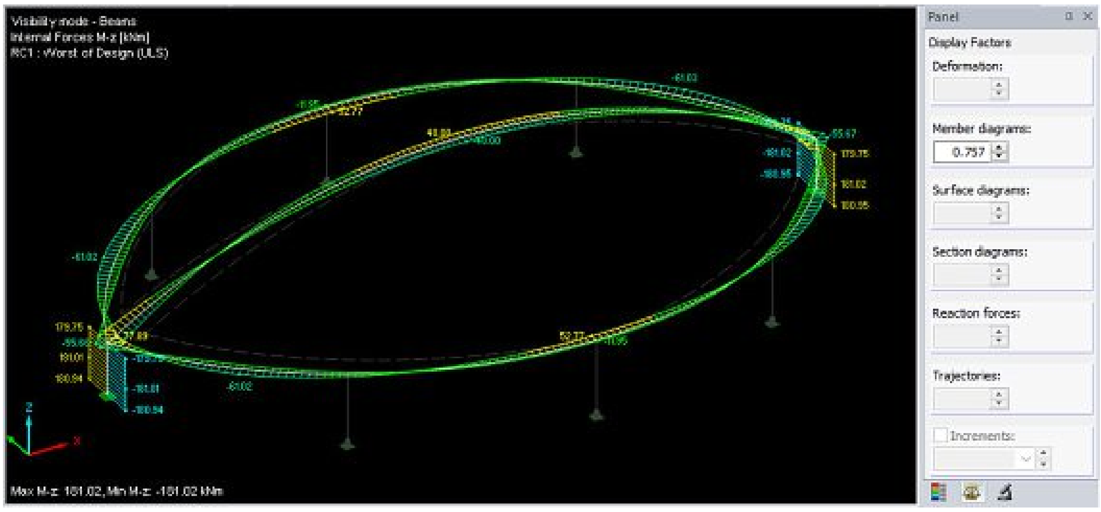

Figure 125: MbtA – SecSame – Hybrid without – Bending moment M_{zd} – Worst of design

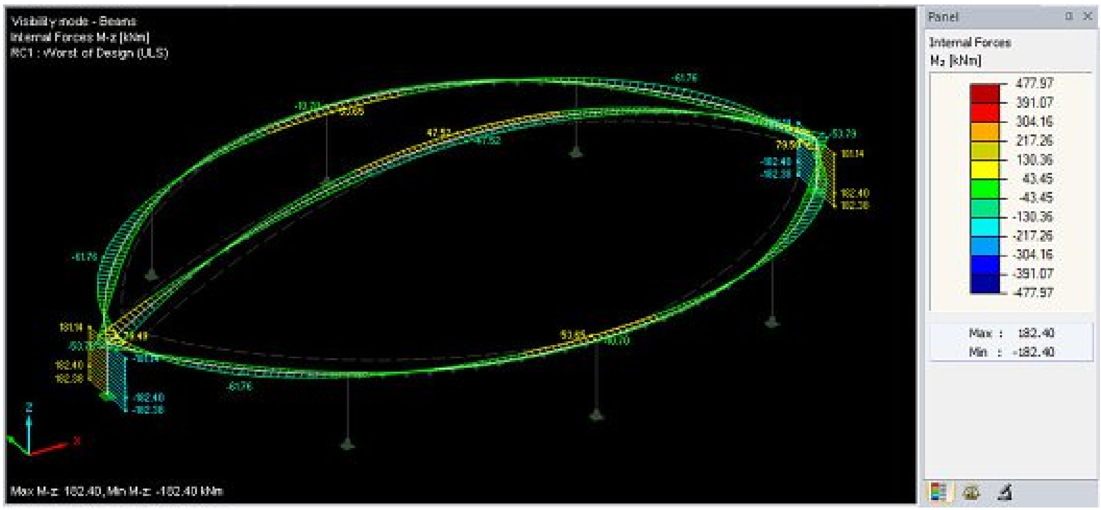

Figure 126: MbtA – SecSame – Hybrid with – Bending moment M_{zd} – Worst of design

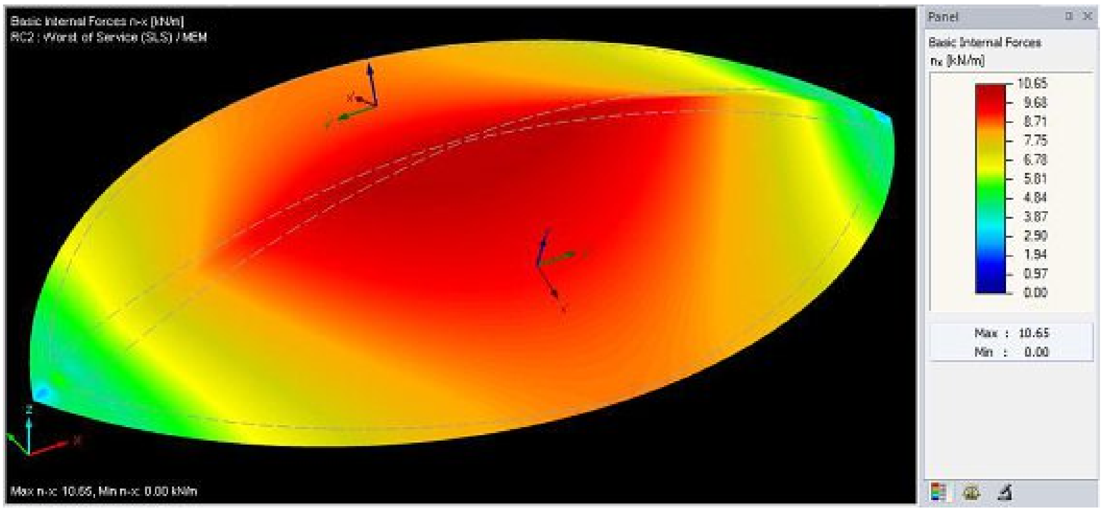

Figure 127: MbtA – SecSame – Separate – Membrane forces n_x – Worst of service/MEM

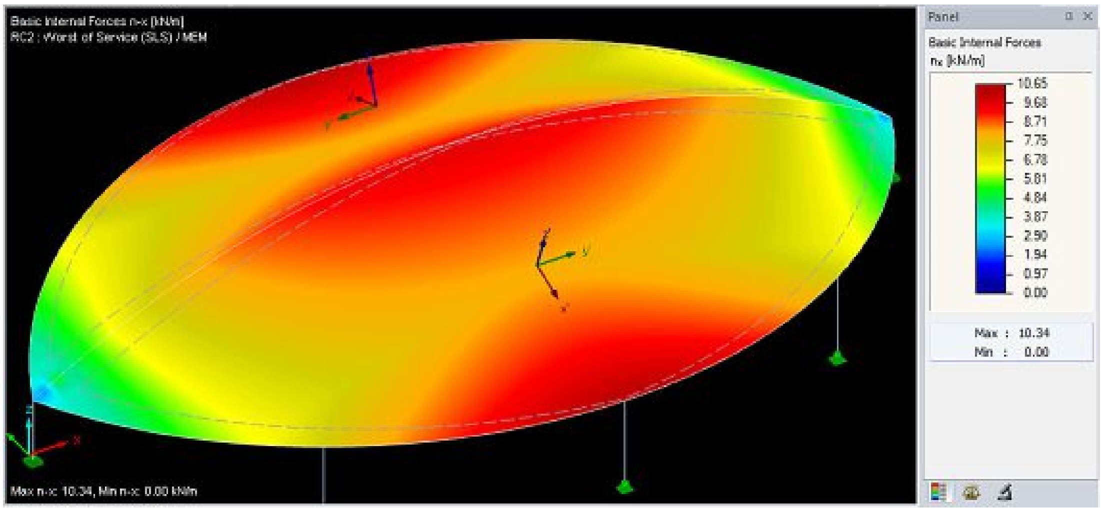

Figure 128: MbtA – SecSame – Hybrid without – Membrane forces n_x – Worst of service/MEM

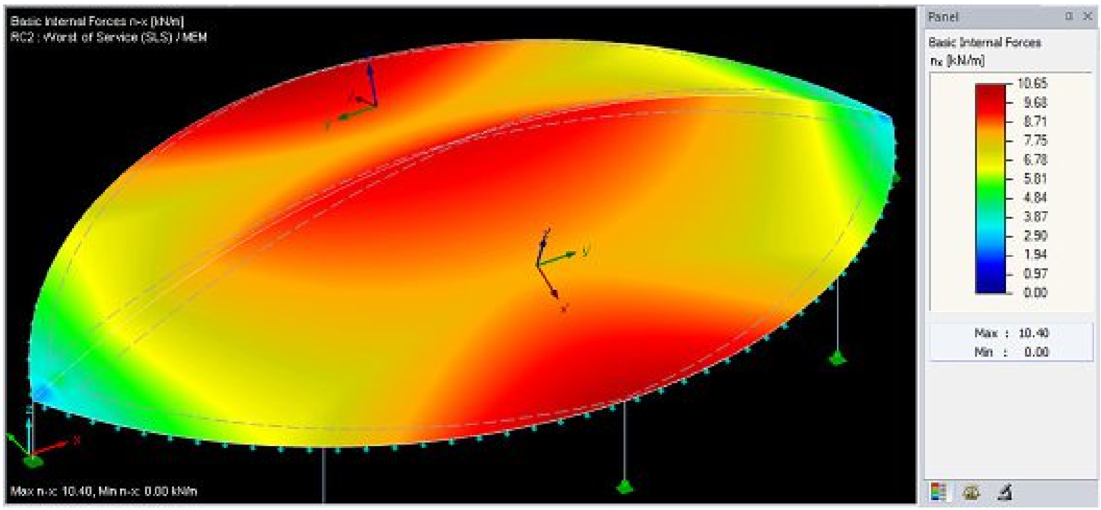

Figure 129: MbtA – SecSame – Hybrid with – Membrane forces n_x – Worst of service/MEM

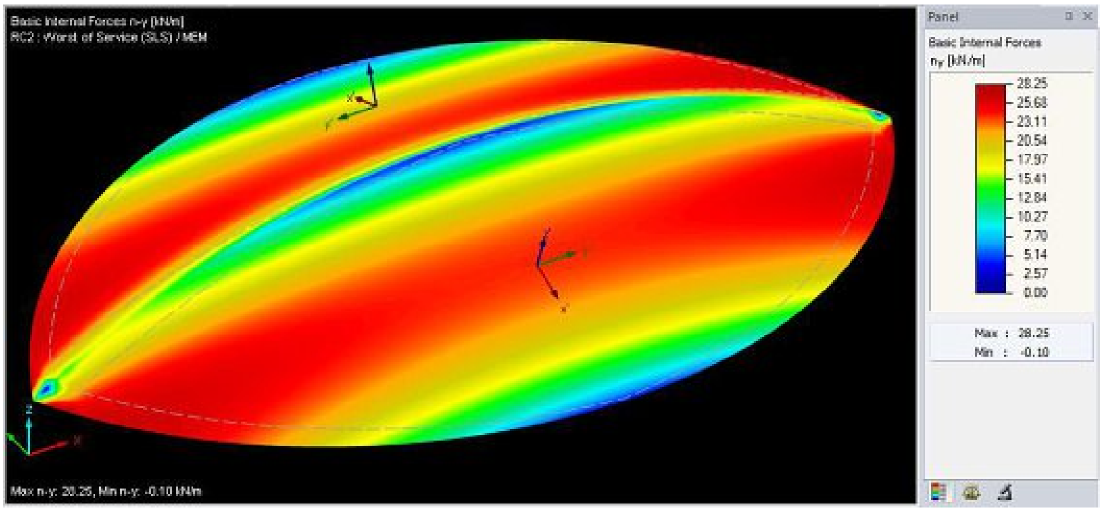

Figure 130: MbtA – SecSame – Separate – Membrane forces n_y – Worst of service/MEM

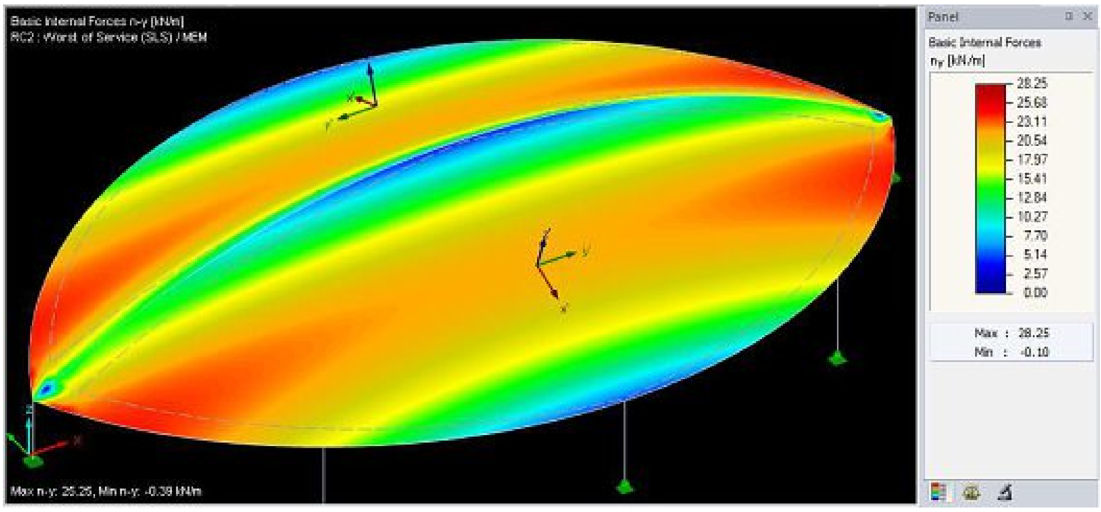

Figure 131: MbtA – SecSame – Hybrid without – Membrane forces n_y – Worst of service/MEM

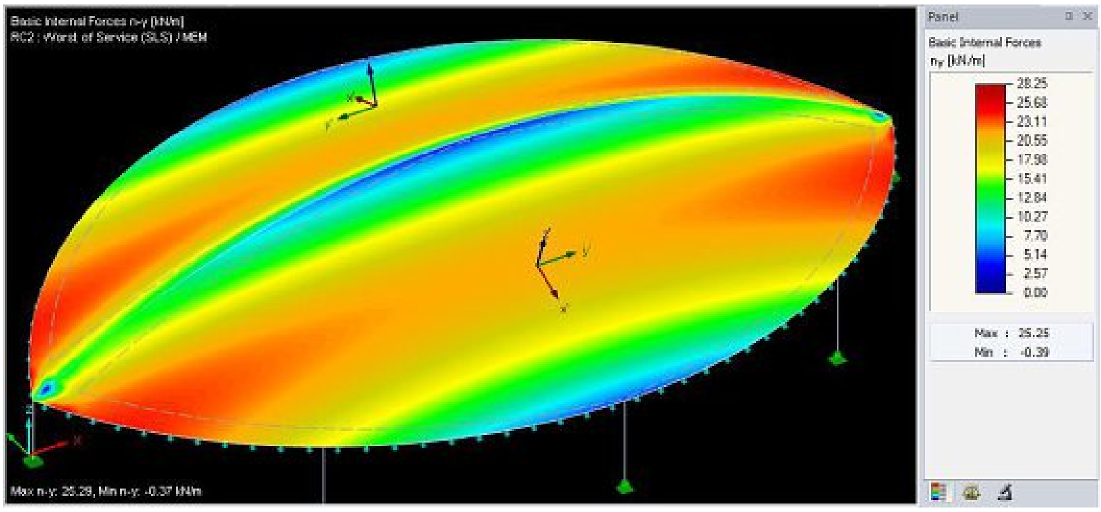

Figure 132: MbtA – SecSame – Hybrid with – Membrane forces n_y – Worst of service/MEM

D.2 MbtA – All Models Dimensioned to u = 100% (SecDim)

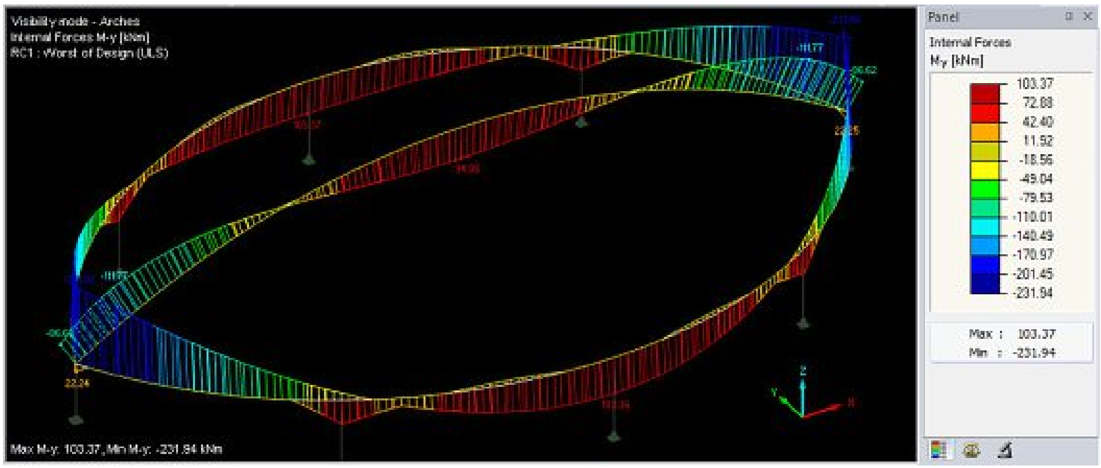

Figure 133: MbtA – SecDim – Separate – Bending moment M_{yd} arches – Worst of design

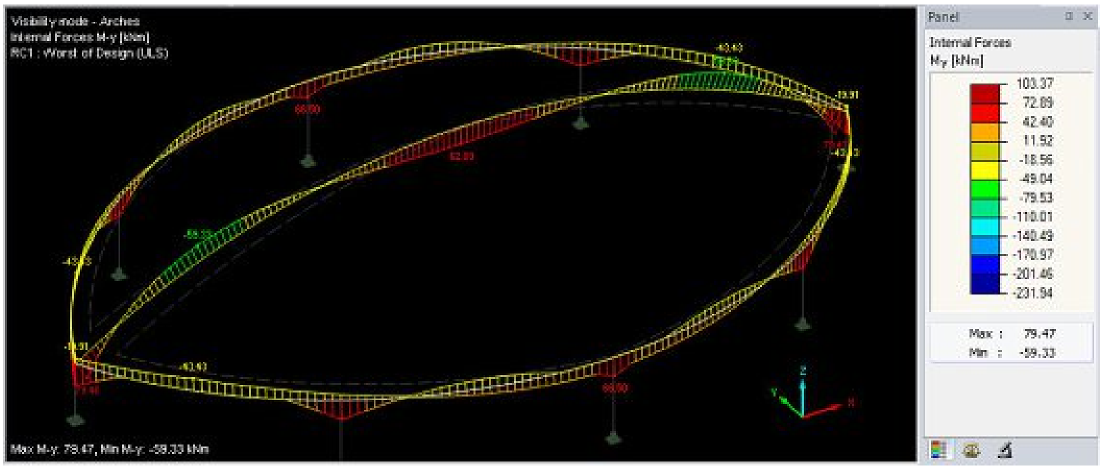

Figure 134: MbtA – SecDim – Hybrid without – Bending moment M_{yd} arches – Worst of design

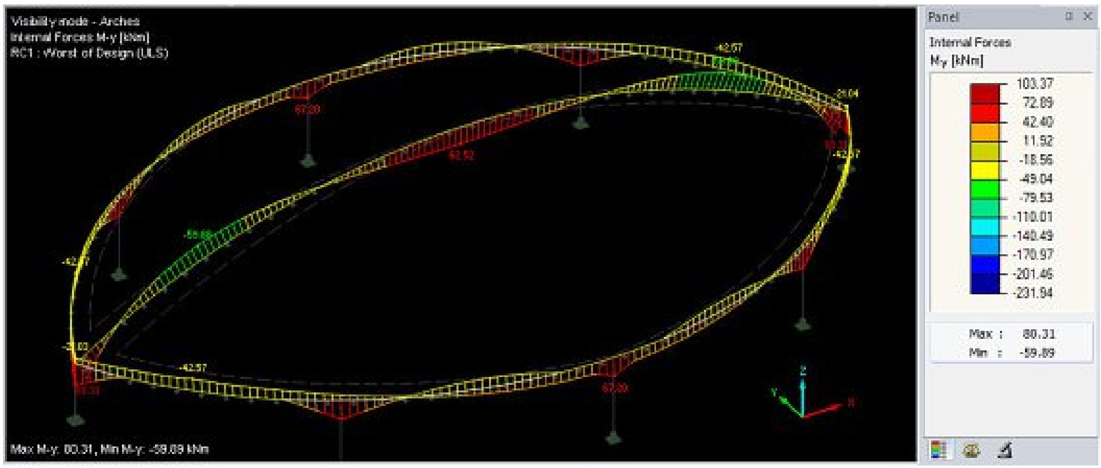

Figure 135: MbtA – SecDim – Hybrid with – Bending moment M_{yd} arches – Worst of design

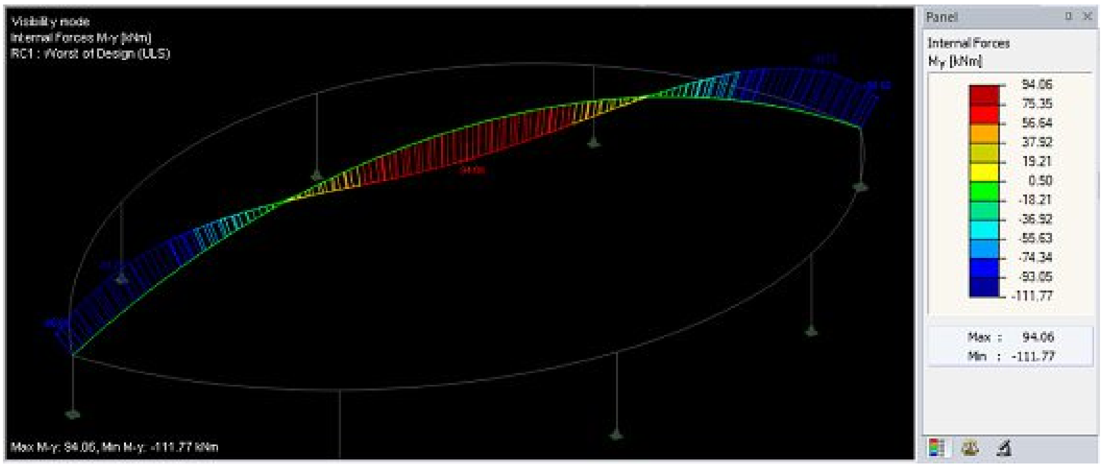

Figure 136: MbtA – SecDim – Separate – Bending moment M_{yd} central arch – Worst of design

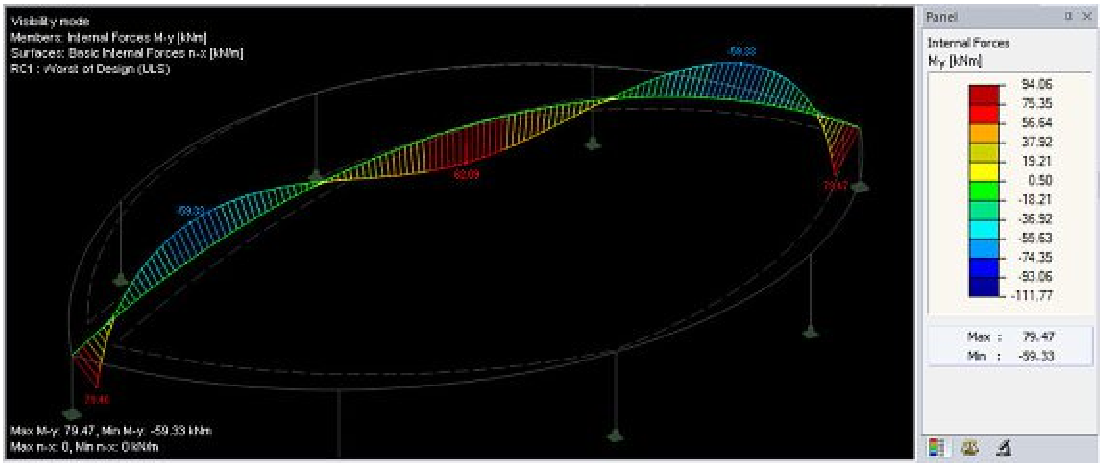

Figure 137: MbtA – SecDim – Hybrid without – Bending moment M_{yd} central arch – Worst of design

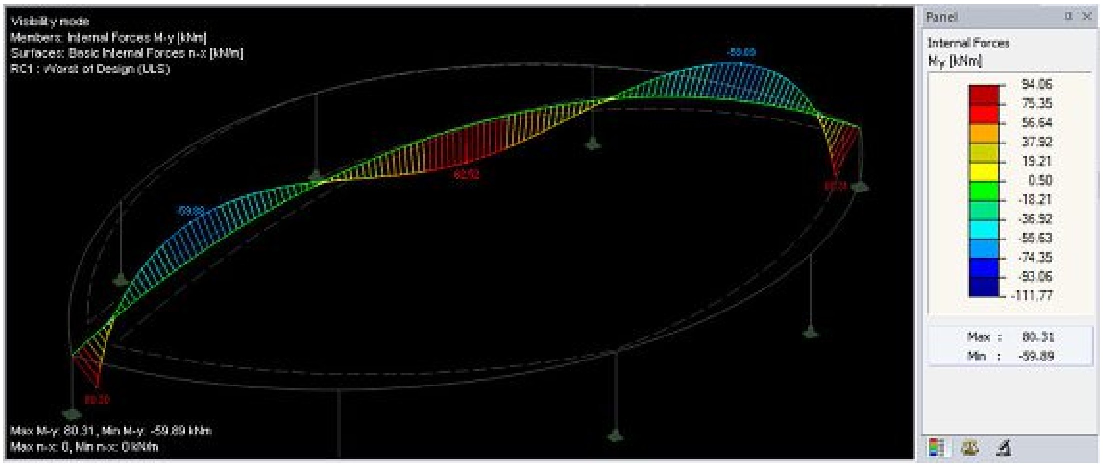

Figure 138: MbtA – SecDim – Hybrid with – Bending moment M_{yd} central arch – Worst of design

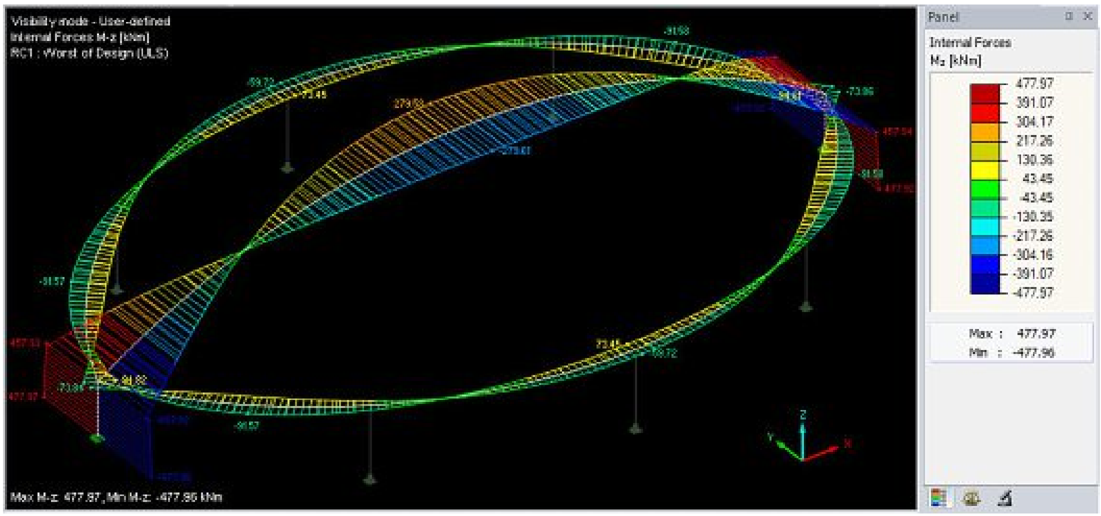

Figure 139: MbtA – SecDim – Separate – Bending moment M_{zd} – Worst of design

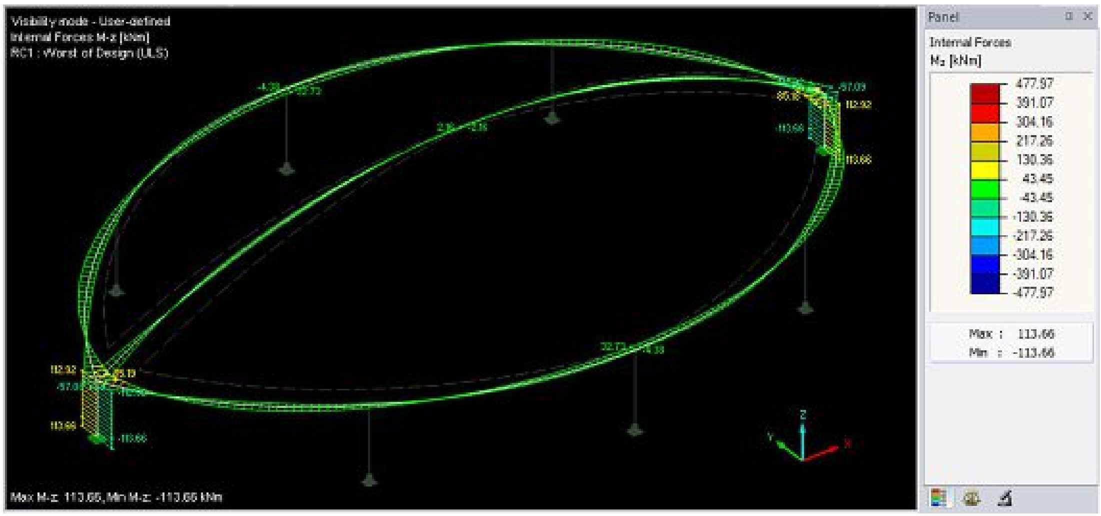

Figure 140: MbtA – SecDim – Hybrid without – Bending moment M_{zd} – Worst of design

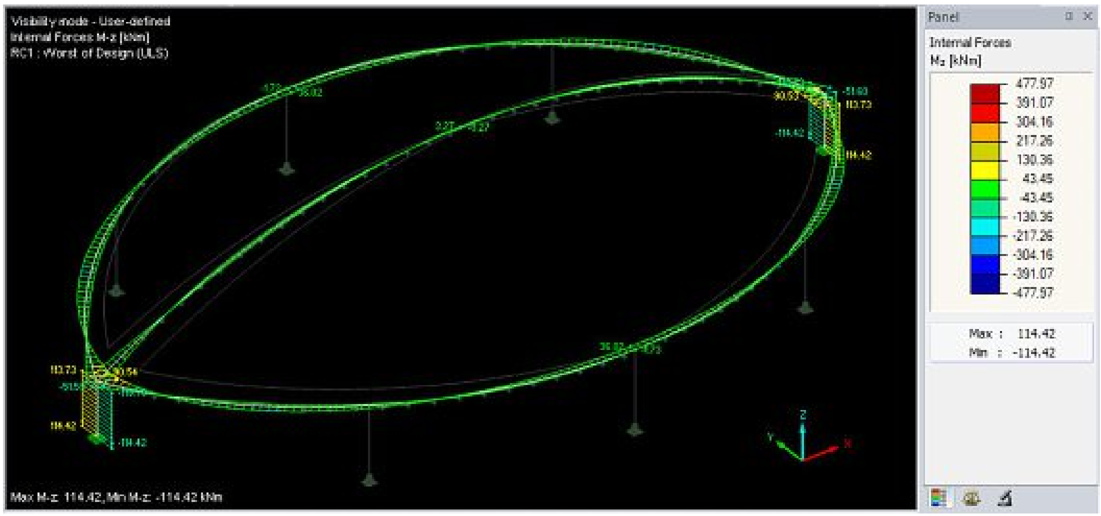

Figure 141: MbtA – SecDim – Hybrid with – Bending moment M_{zd} – Worst of design

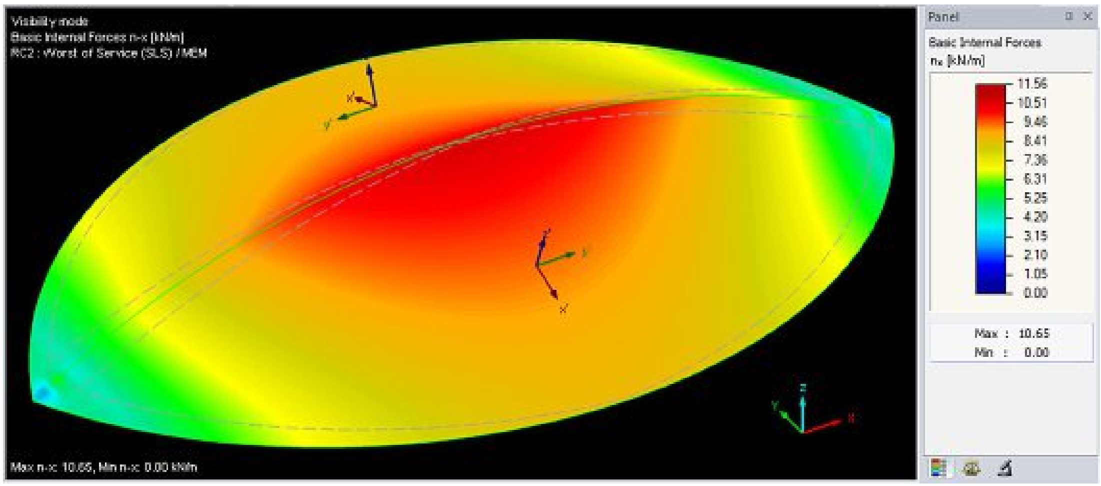

Figure 142: MbtA – SecDim – Separate – Membrane forces n_x – Worst of service/MEM

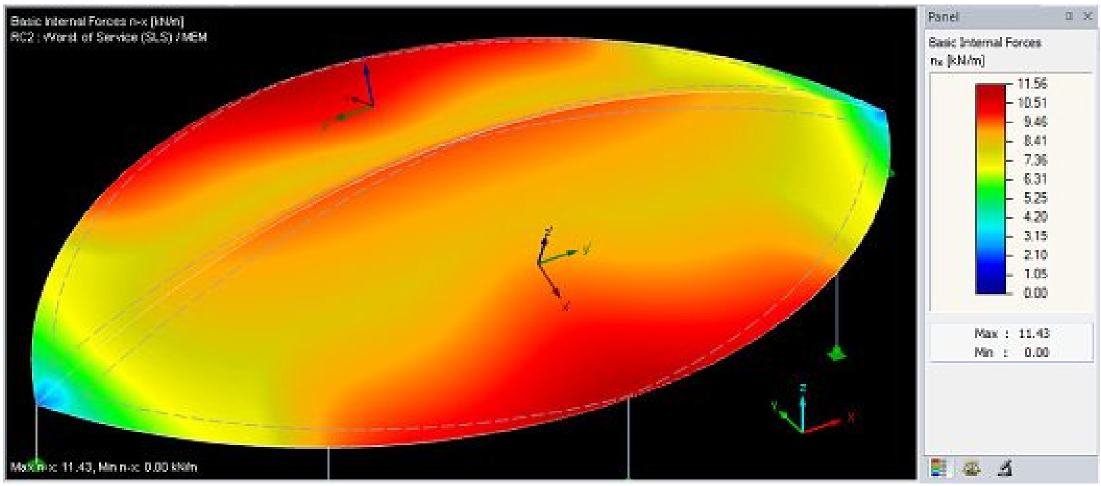

Figure 143: MbtA – SecDim – Hybrid without – Membrane forces n_x – Worst of service/MEM

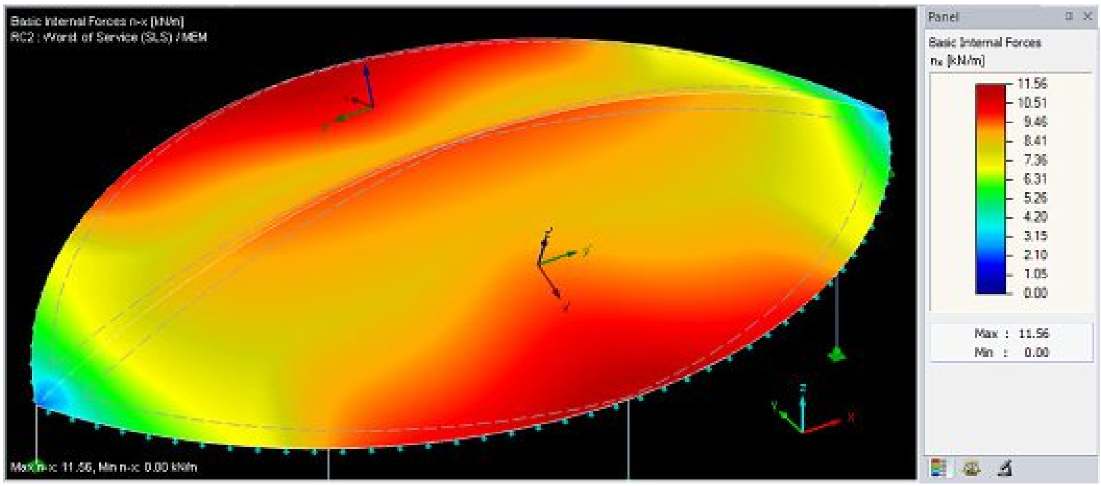

Figure 144: MbtA – SecDim – Hybrid with – Membrane forces n_x – Worst of service/MEM

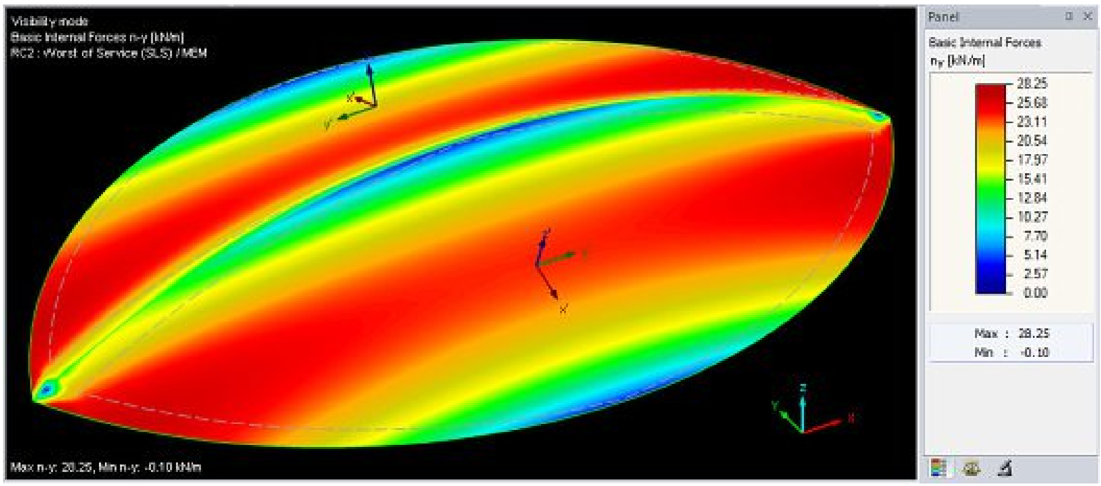

Figure 145: MbtA – SecDim – Separate – Membrane forces n_y – Worst of service/MEM

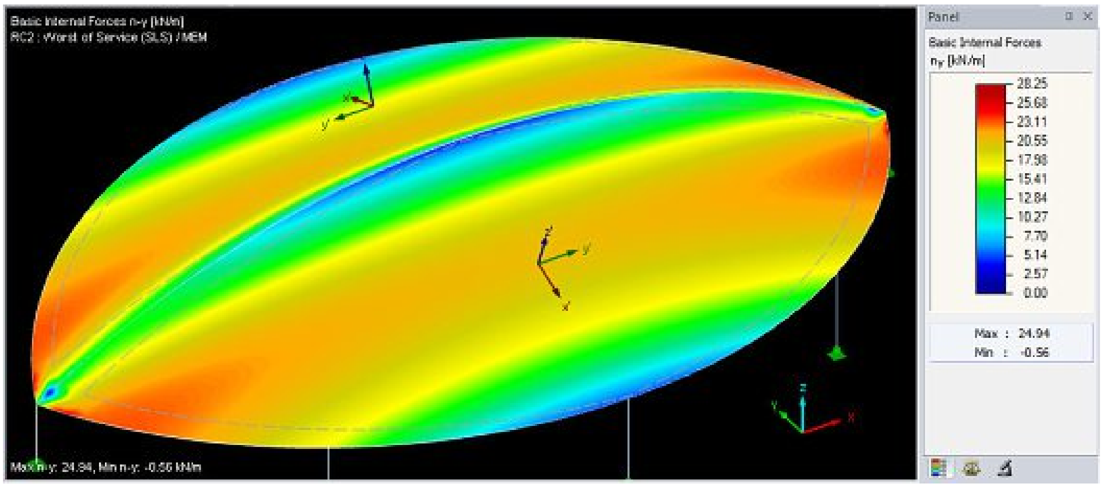

Figure 146: MbtA – SecDim – Hybrid without – Membrane forces n_y – Worst of service/MEM

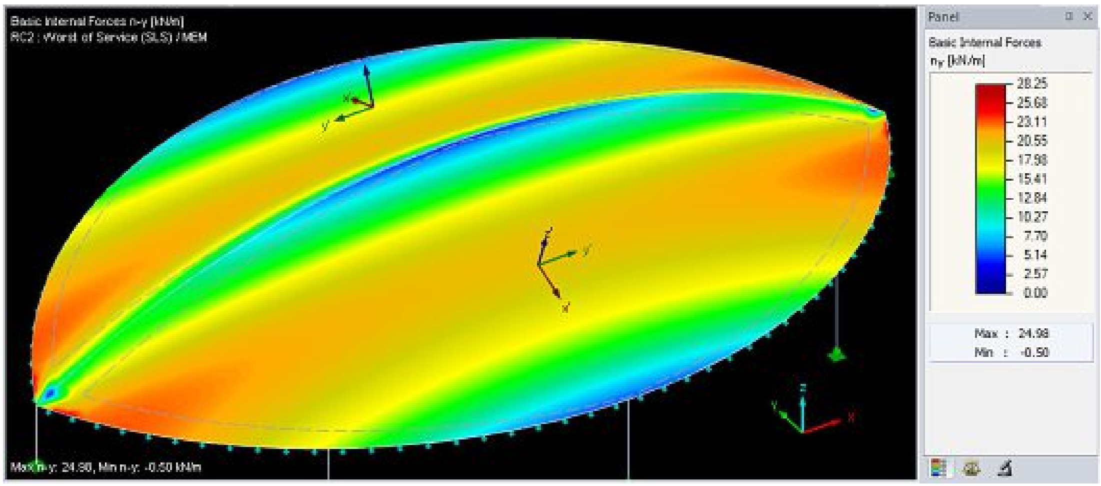

Figure 147: MbtA – SecDim – Hybrid with – Membrane forces n_y – Worst of service/MEM

Appendix E Festival Tents >The Sea Star<

In Appendix E.1 some descriptive screenshots of the workflow of model generation, load application and calculations are presented. Appendix E.2 presents several results.

All figures and tables in Appendix E are by the author, except for the two colour plots of the CFD calculation results, Figure 158 and Figure 159.

E.1 Workflow

- Precise and clean redesign of the intended geometry in Rhino > Changes in the course likely

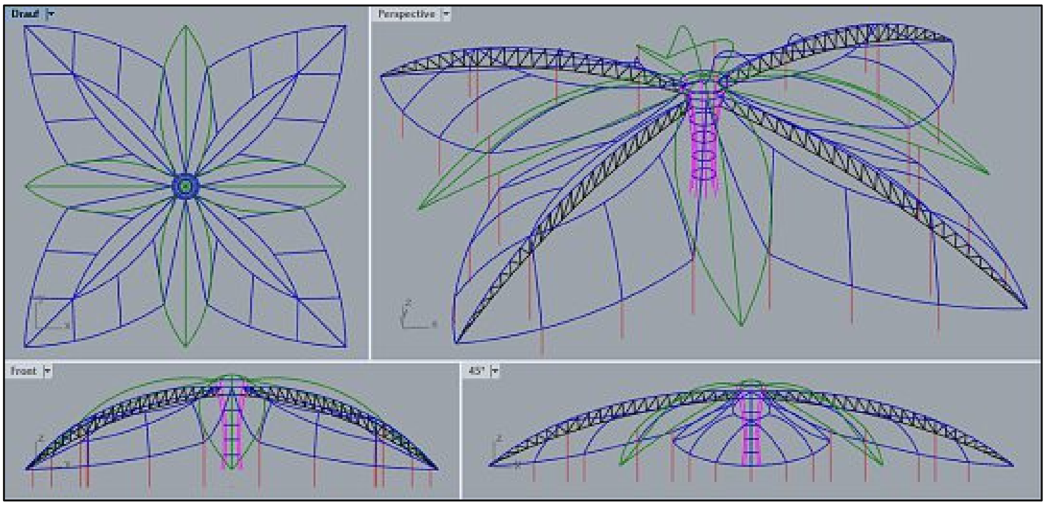

Figure 148: >The Sea Star< Rhino model of intended starting model for design

- Import of the geometry in RFEM > Definition and arrangement of supports > Generation of the surfaces (dashed lines symbolising surfaces), here B-spline surfaces or quadrangles, NURBS also possible, green = lines without surfaces, cyan = lines assigned to surfaces

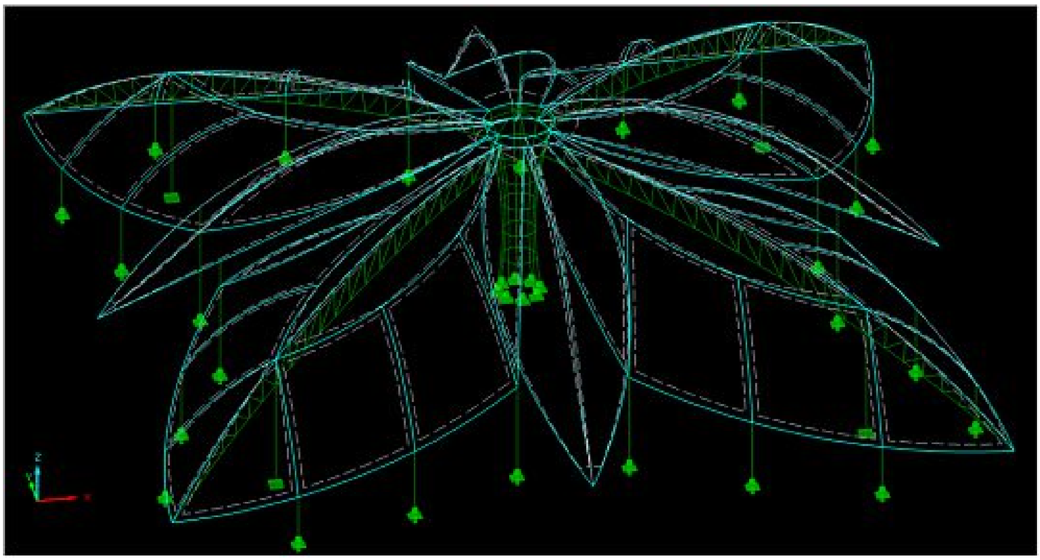

Figure 149: >The Sea Star< RFEM model with supports and membranes

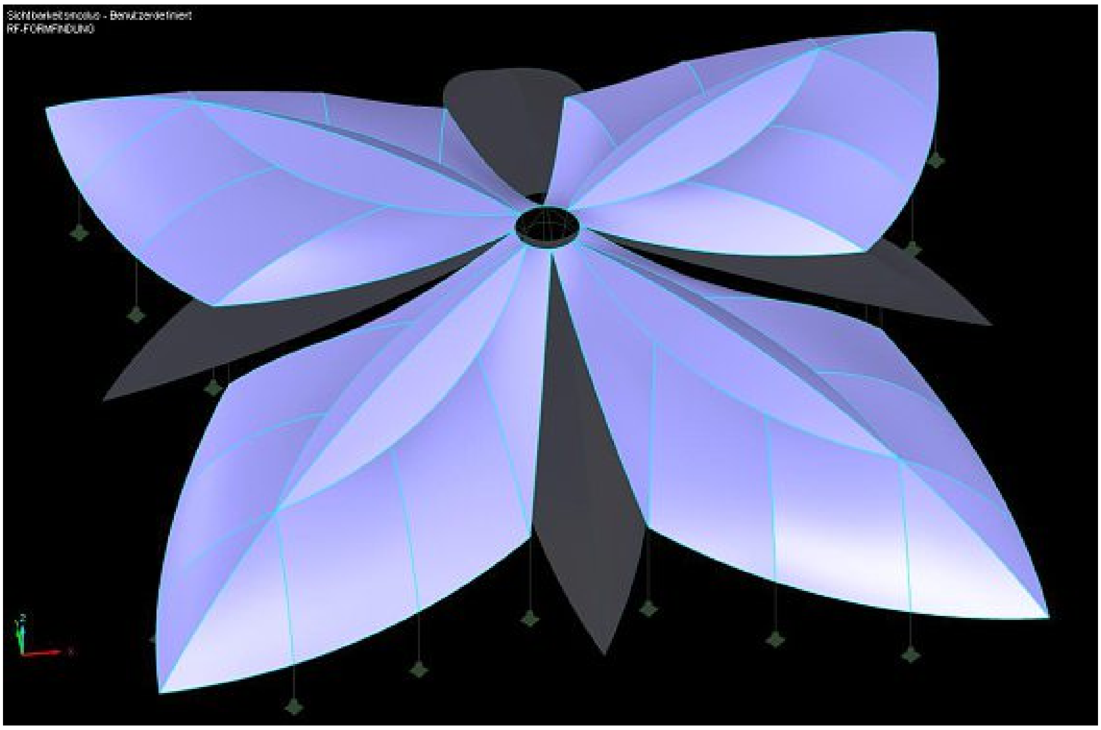

Figure 150: >The Sea Star< RFEM model – membranes “big leaves” – Prior to form-finding

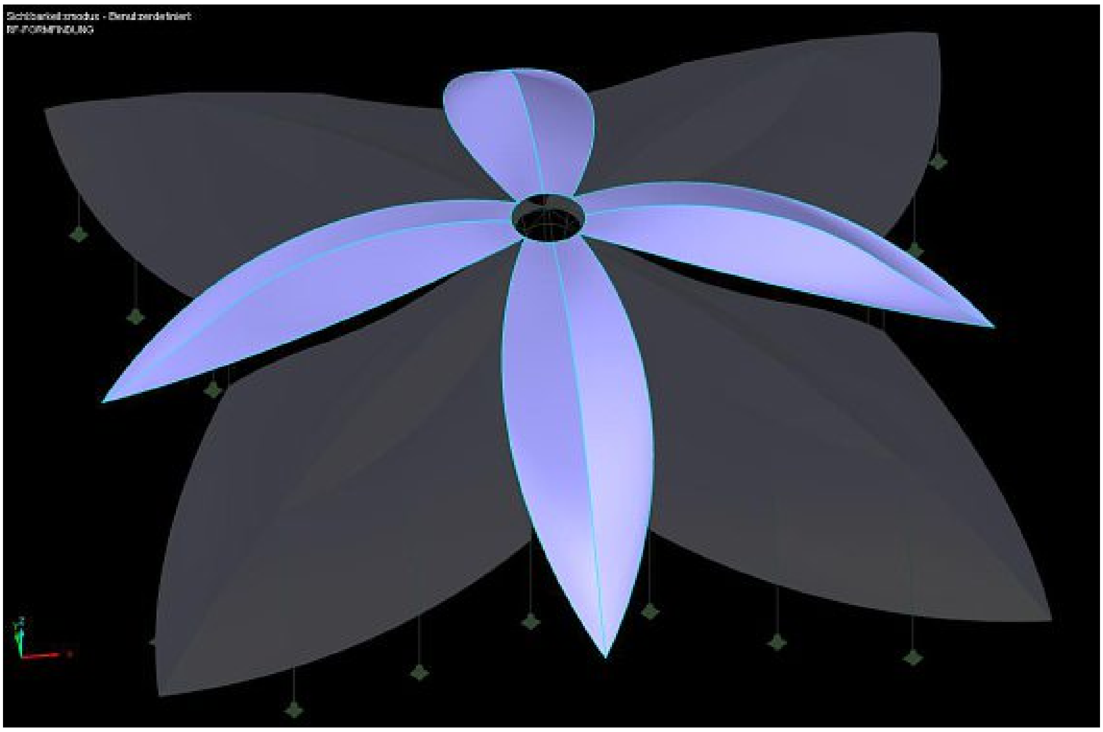

Figure 151: >The Sea Star< RFEM model – membranes “small leaves” – Prior to form-finding

➢ Definition of the membrane material, the membrane warp/weft direction (x/y), etc. > Iteratively setting the prestress ratio for the membranes to achieve the shapes as whished and as structurally favourable > Arrangement of form-finding supports (only active in form-finding)

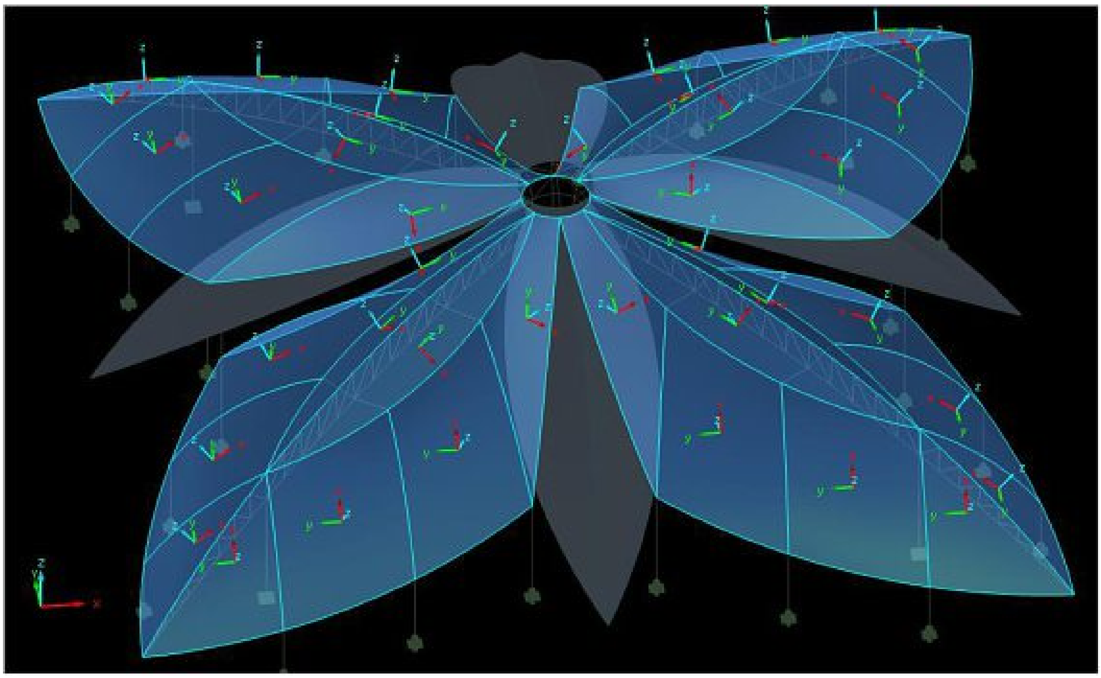

Figure 152: >The Sea Star< RFEM model – Defined axis system membranes (warp/weft) – "Big leaves"

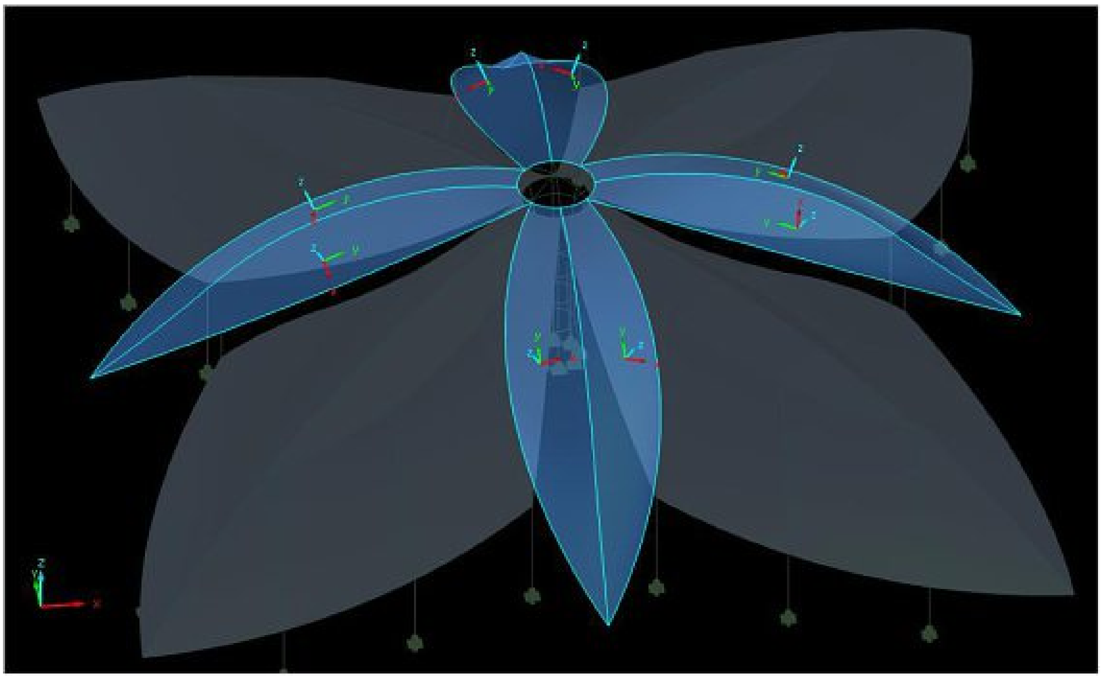

Figure 153: >The Sea Star< RFEM model – Defined axis system membranes (warp/weft) – "Small leaves"

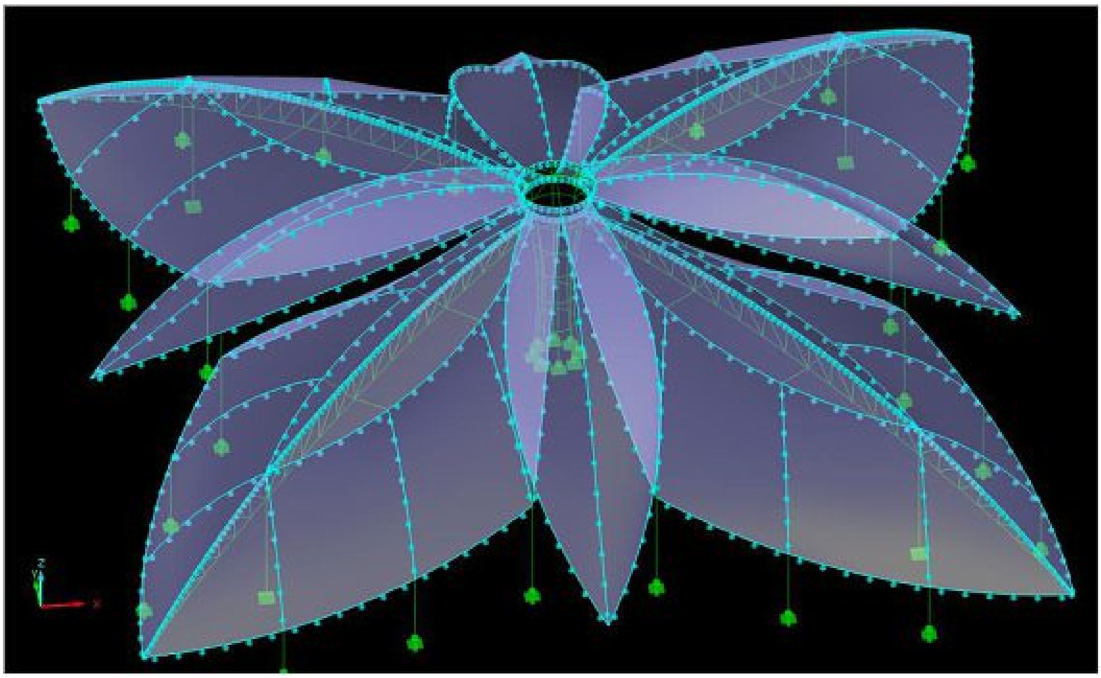

Figure 154: >The Sea Star< RFEM model – Arrangement of form-finding line supports

- FE mesh settings – here mesh refinement at membrane edges for higher accuracy of the membrane support forces for load transfer to the separate substructure partial model STR > Mesh settings for membrane stresses analysis using smaller elements for higher accuracy

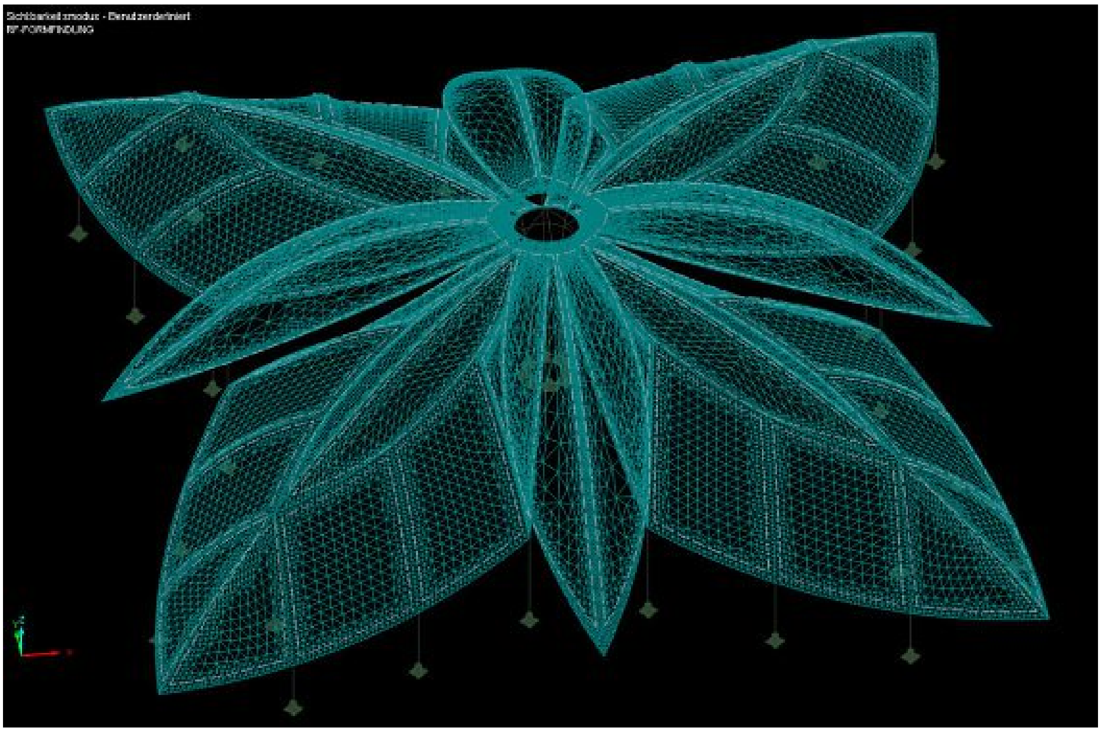

Figure 155: >The Sea Star< RFEM model – FE mesh with mesh refinement at edges

- Work on the form-finding, deciding about the prestress ratio and thus about the shapes. Arguments for e.g. optical appearance and load-carrying behaviour. In the course of project calculations, the prestress ratio and per this the shape is adjusted severally.

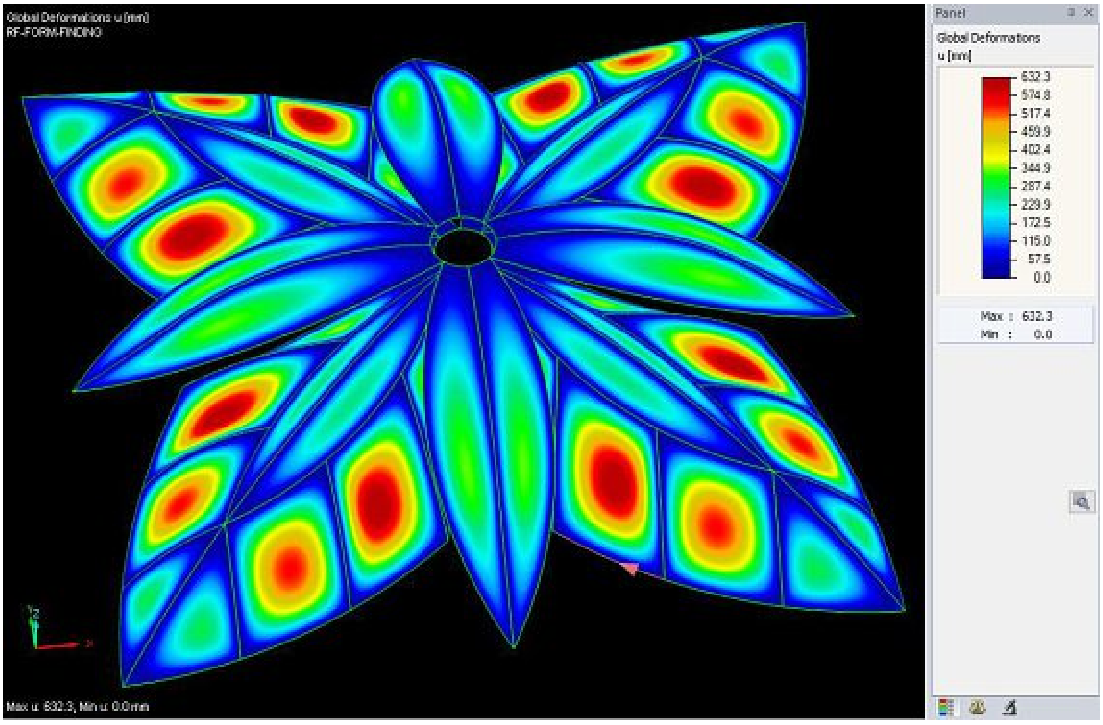

Figure 156: >The Sea Star< RFEM – Form-finding membrane global deformation

- Definition of LCs, LCCs, application of loads, STEEL cases for stress design, etc.
- Important: All loadings are the same for hybrid and separate calculation because for both methods the identical model was used as basis

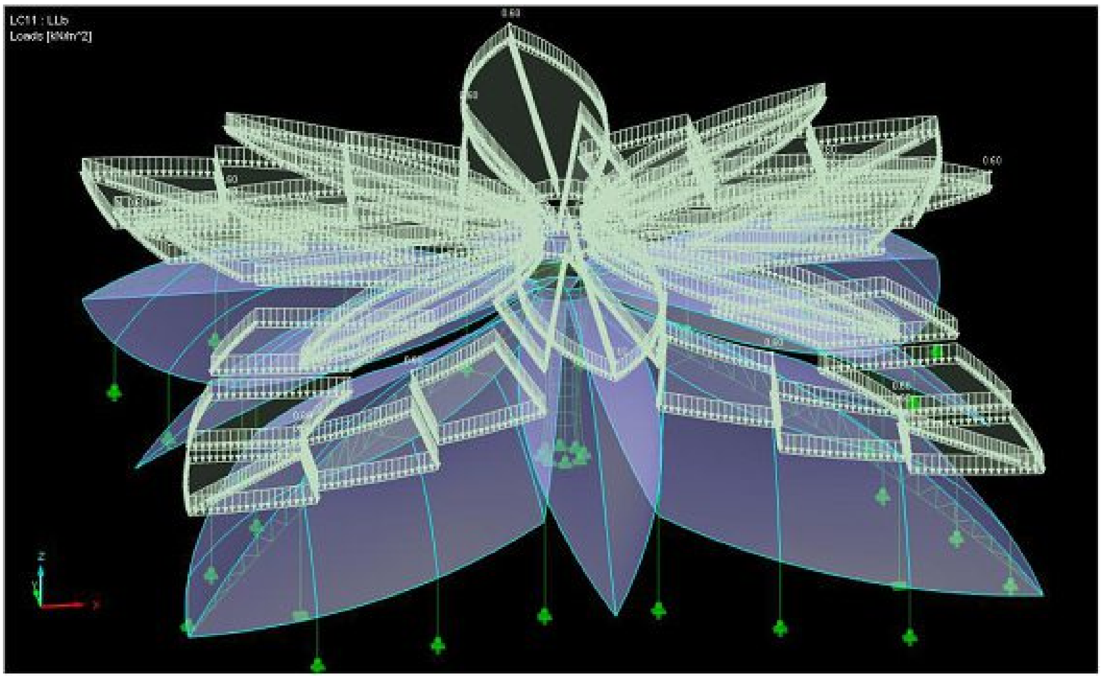

Figure 157: >The Sea Star< RFEM model – Application of live load/sand – Load direction “global related to projected area”

➢ The following CFD wind load calculations were available. Those are incorporated by using the images as background layers in the software used

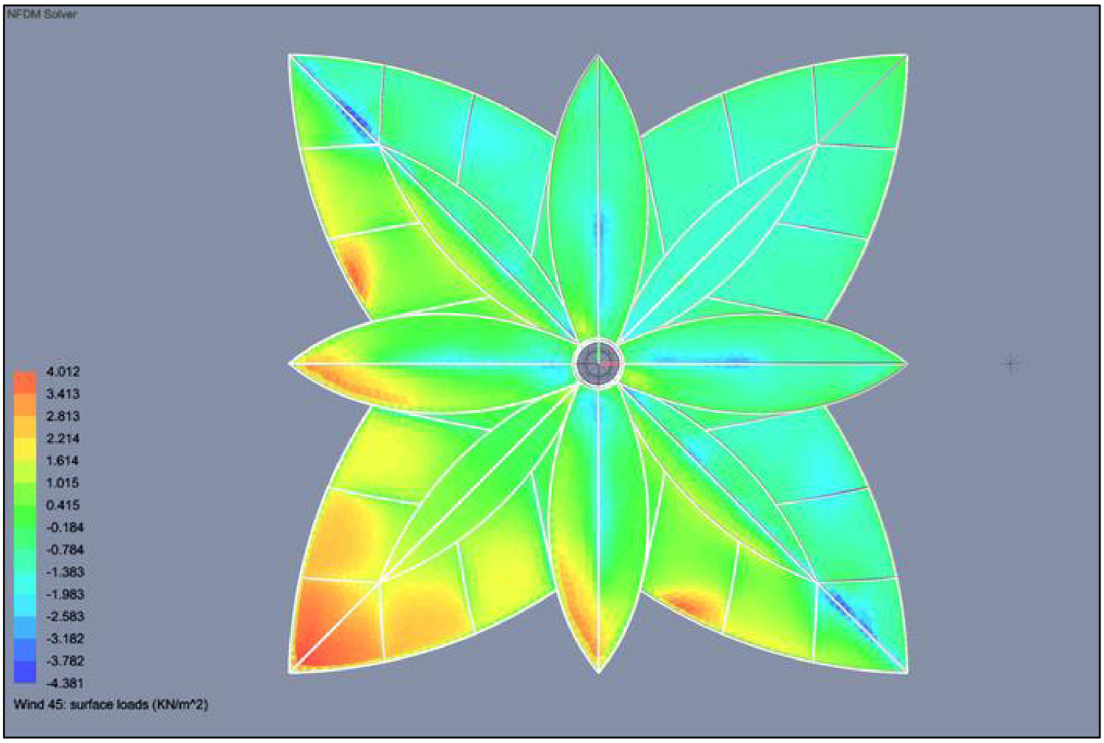

Figure 158: >The Sea Star< CFD Wind Load Determination – Wind Direction 45°
(source: Gerry D'Anza, ixRay Ltd.)

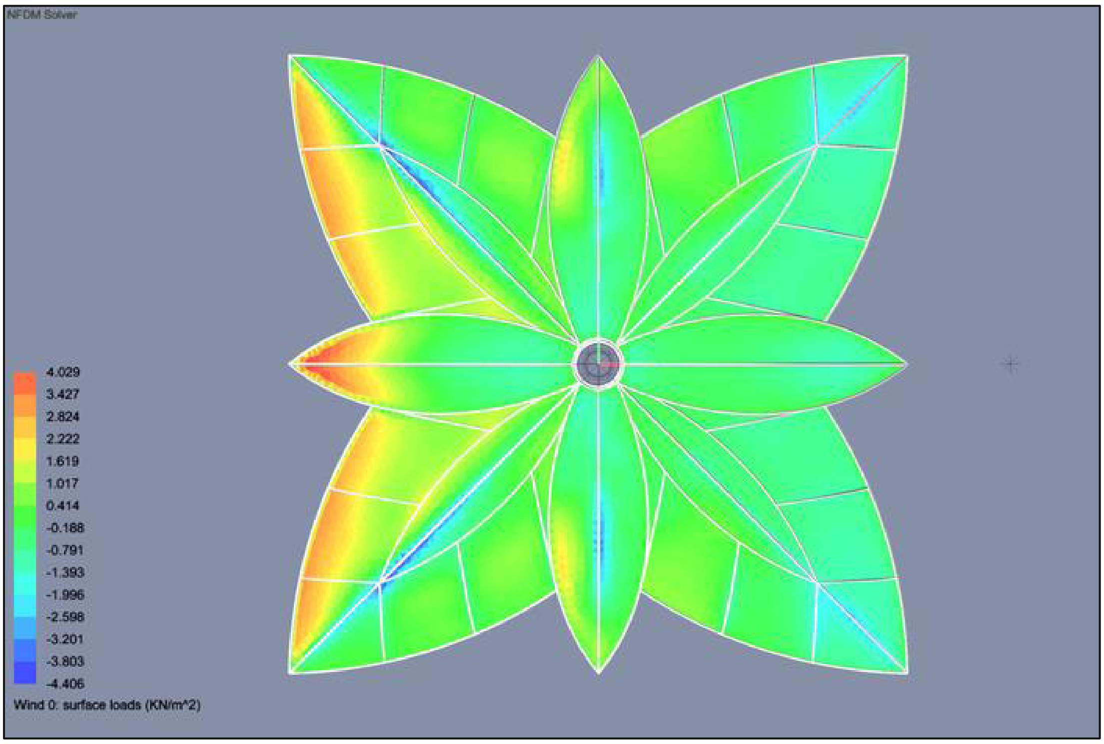

Figure 159: >The Sea Star< CFD Wind Load Determination – Wind Direction 90°
(source: Gerry D'Anza, ixRay Ltd.)

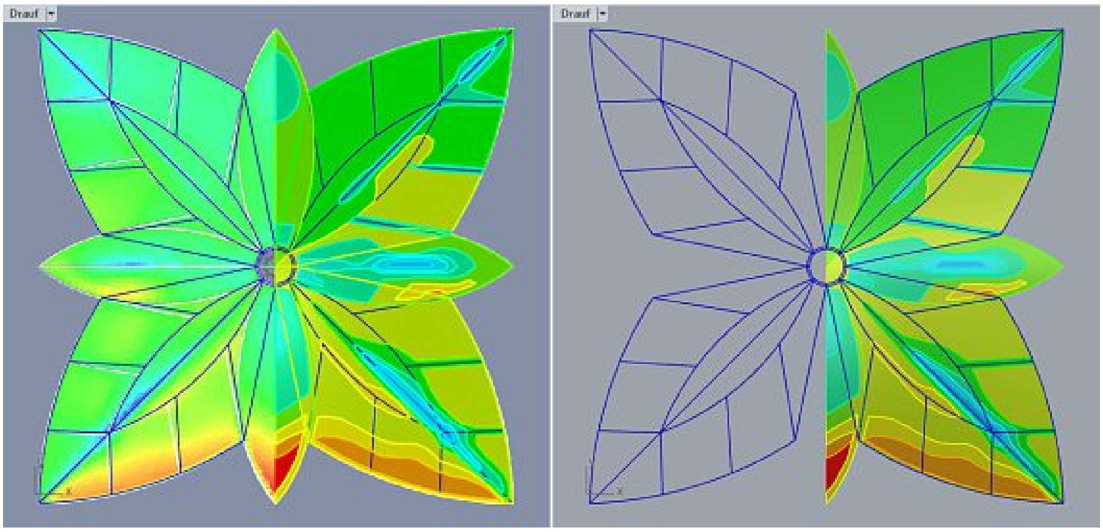

Figure 160: >The Sea Star< Drawing of the load zone separation lines in Rhino for import to RFEM

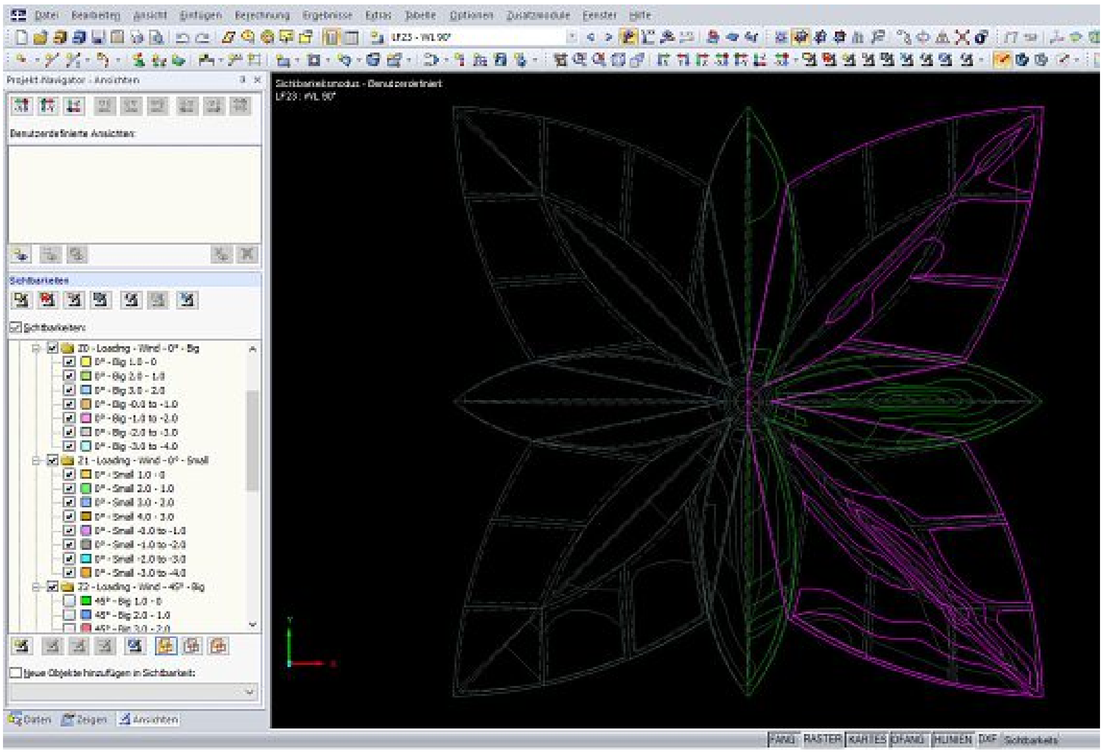

Figure 161: >The Sea Star< RFEM – Wind load zones imported and definition of the loads – Drawn on one half, mirrored then for mirror accuracy

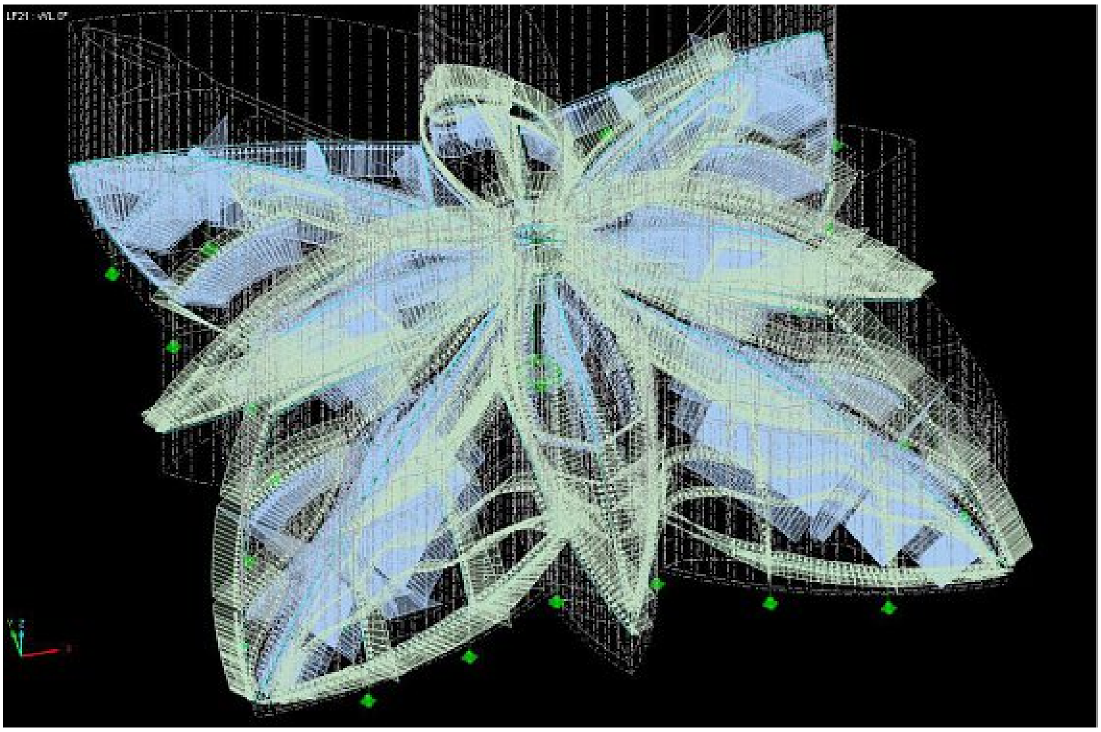

Figure 162: >The Sea Star< RFEM – Applied wind load for +y wind direction – Complete model

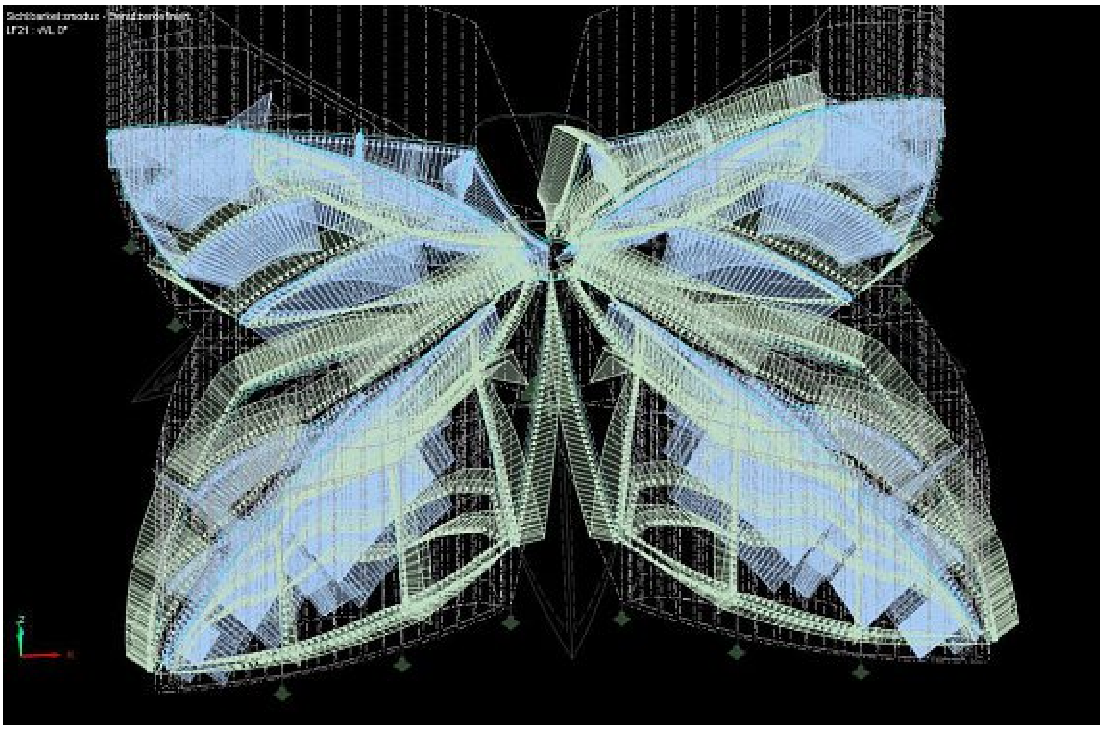

Figure 163: >The Sea Star< RFEM – Applied wind load for +y wind direction – “Big leaves”

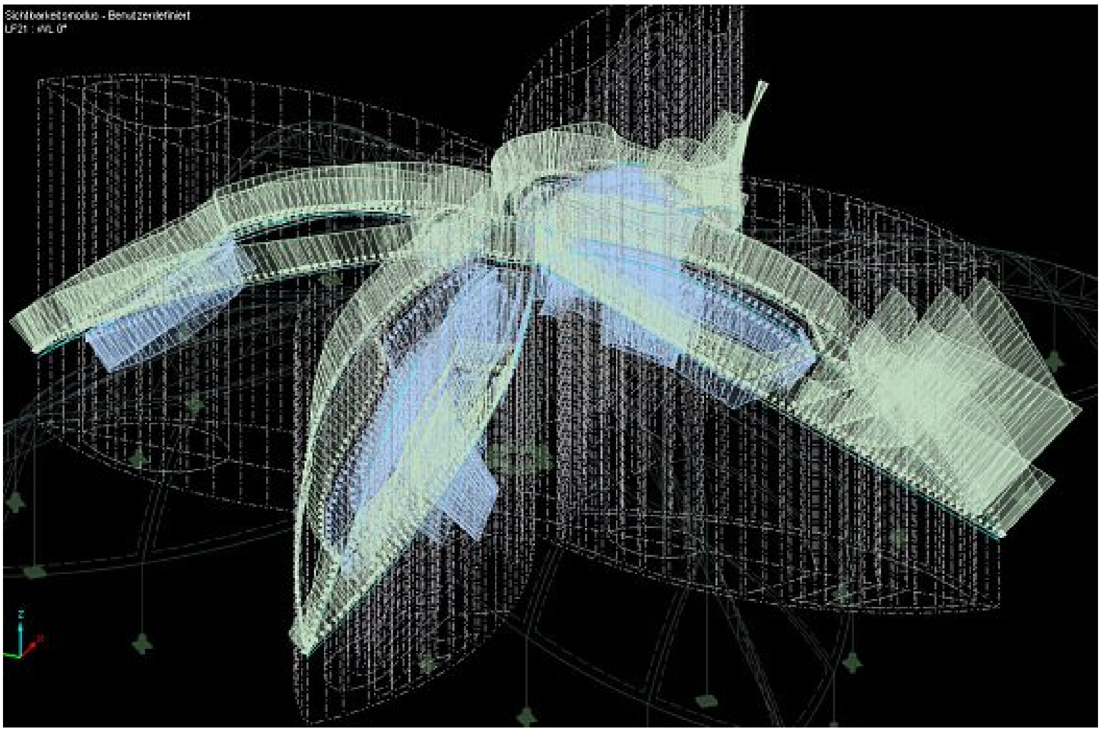

Figure 164: >The Sea Star< HY – RFEM – Applied wind load for +y wind direction – “Small leaves”

- Assignment of the estimated required outer diameters of the various parts of the structure (Colours = same outer dimensions). Adjustments of those during the course of the calculations. The colder the colours below, the smaller the outer diameters, the warmer, the bigger. The four beams at two locations to the lower chord of the trusses (type here: truss, only N) were identified being required in separate calculation (tendency of lateral torsional buckling of the trusses).
  > Database set up for plenty of wall thicknesses for the different outer diameter series
  > Dimensioning of all members in the hybrid model by several iterative calculation cycles.

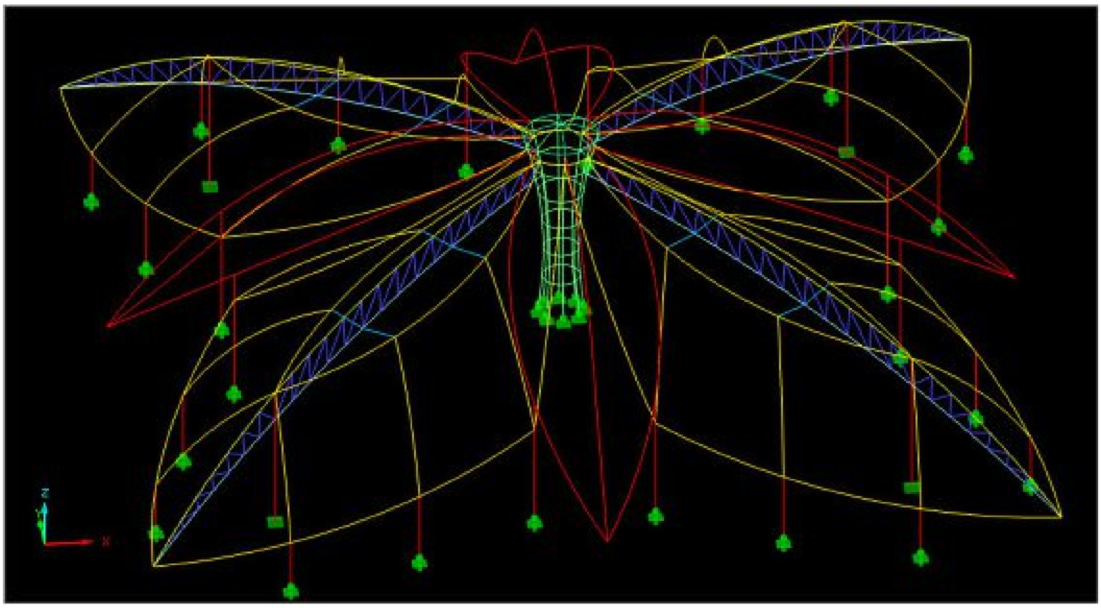

Figure 165: >The Sea Star< HY – RFEM – Final outer sections of the preliminary results, displayed per colours for the different outer diameters

- Separation of the model into the membrane partial model MEM and the substructure partial model STR for the separate calculations approach

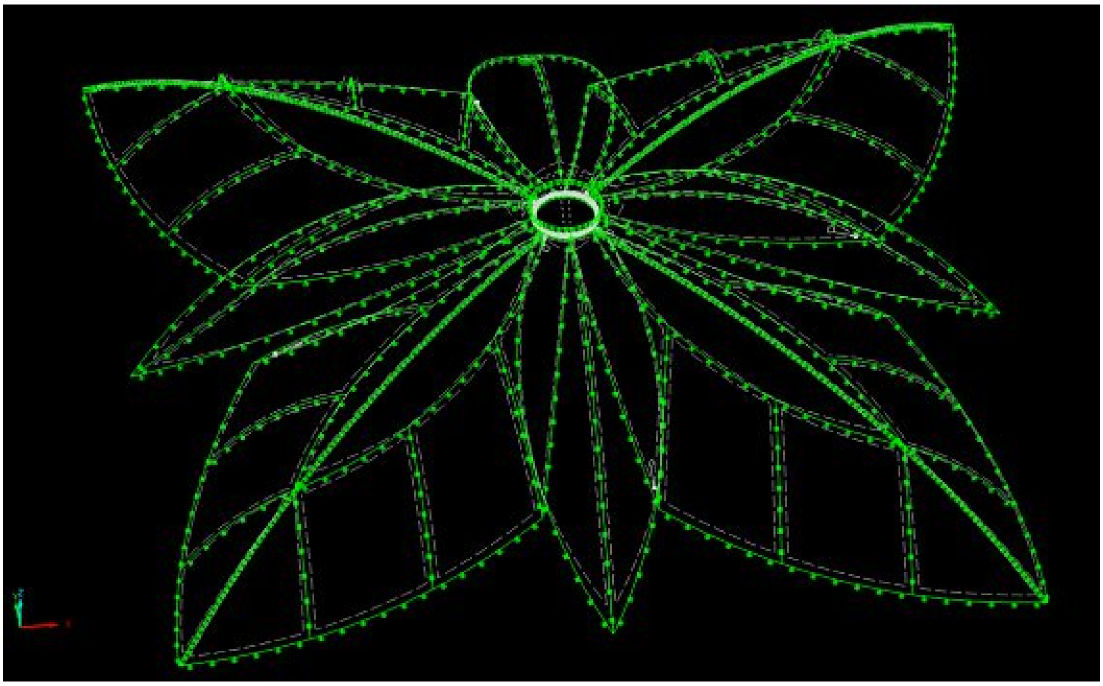

Figure 166: >The Sea Star< MEM – RFEM – Deletion of the structure, fix permanent supports for all membranes

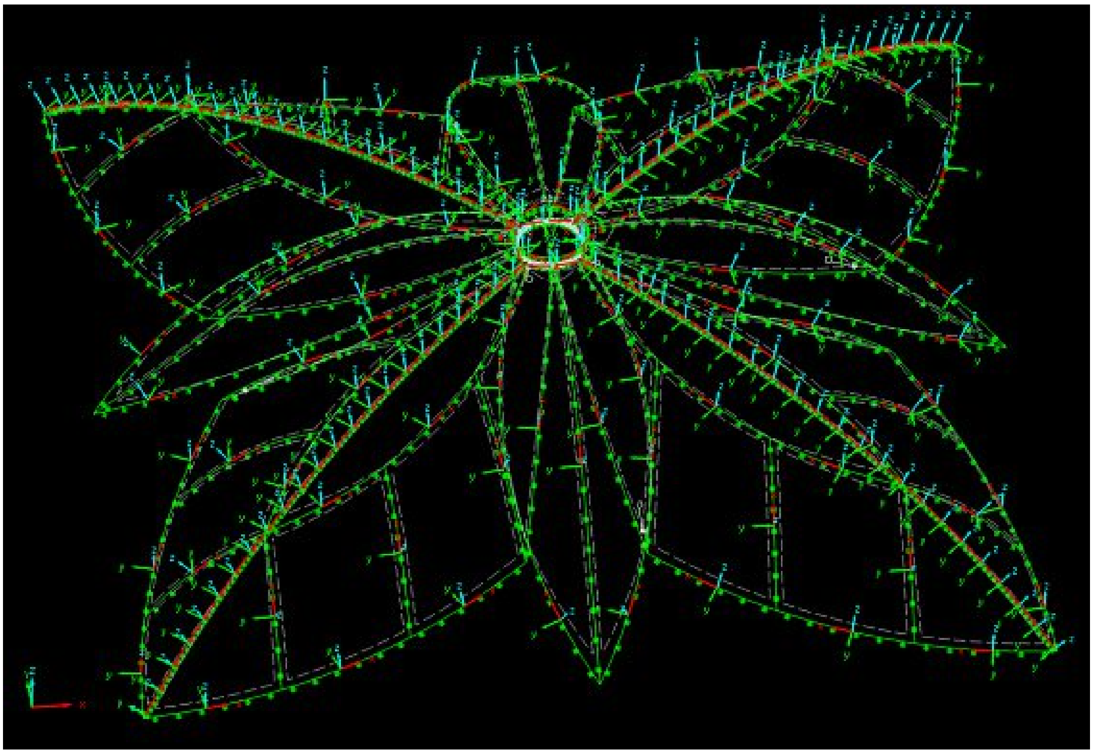

Figure 167: >The Sea Star< MEM – RFEM – Definition of the line supports as local and orientation according to the beam orientation in the STR model for correct load transfer

- ➢ Exemplary support forces, which are then transferred to the structural partial model STR

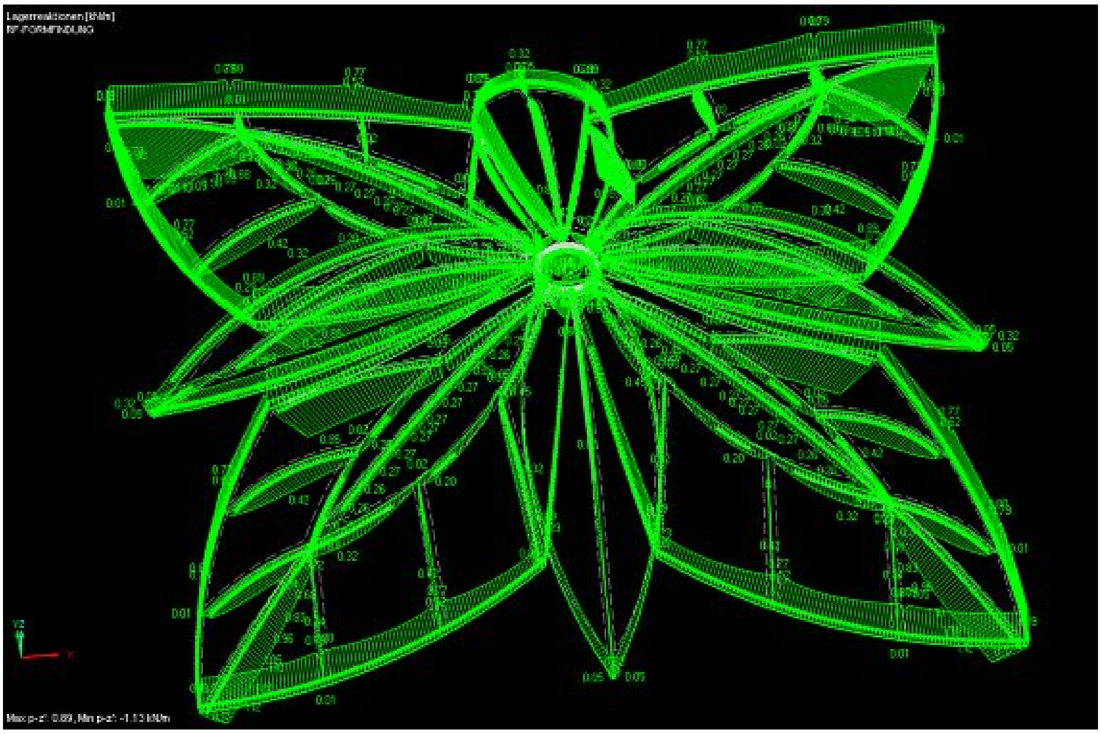

Figure 168: >The Sea Star< MEM – Exemplary support forces pz – LC Form-finding = prestress

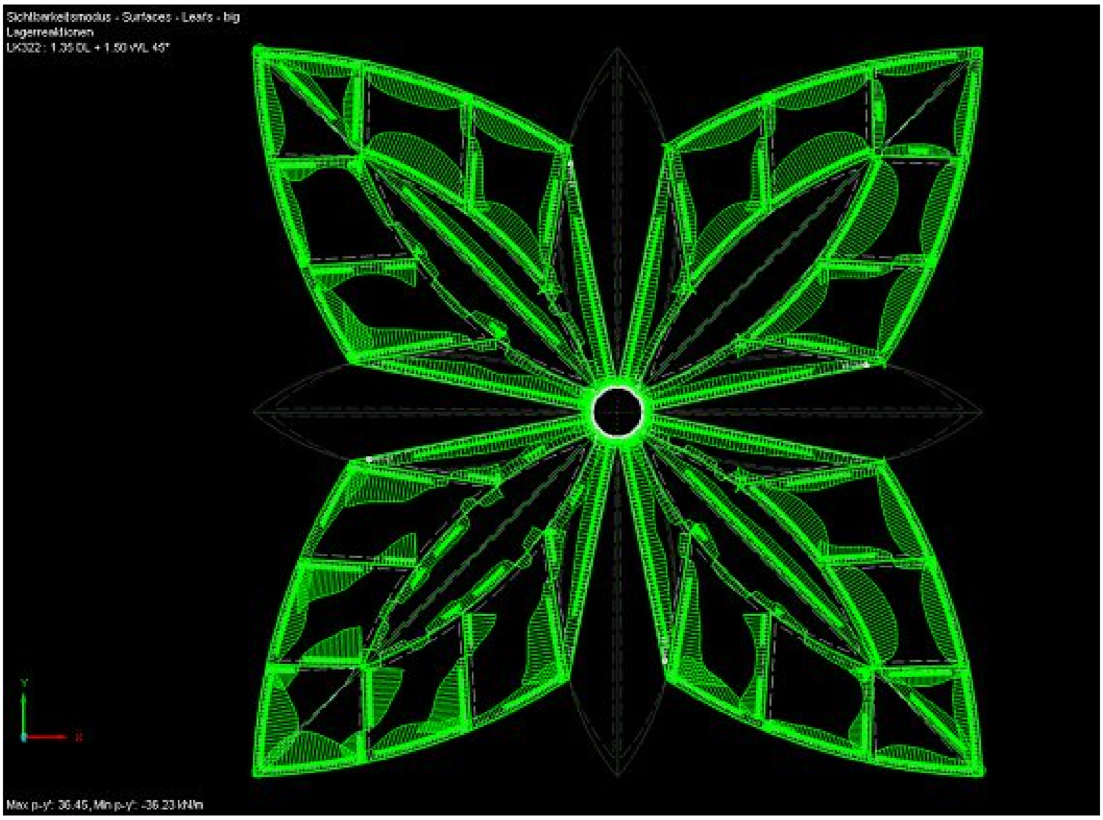

Figure 169: >The Sea Star< MEM – Support forces py – LCC 1.35 DL + 1.50 WL45°

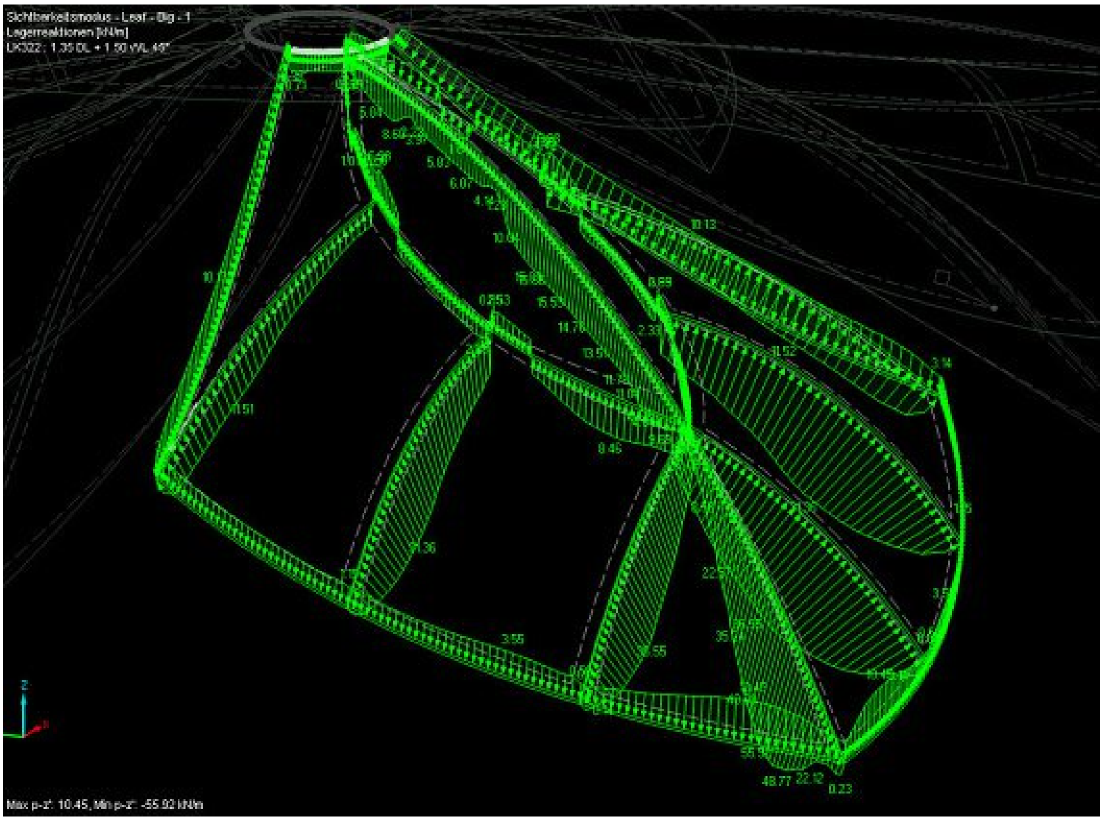

Figure 170: >The Sea Star< MEM – One big leaf – Support forces pz – LCC 1.35 DL + 1.50 WL45°

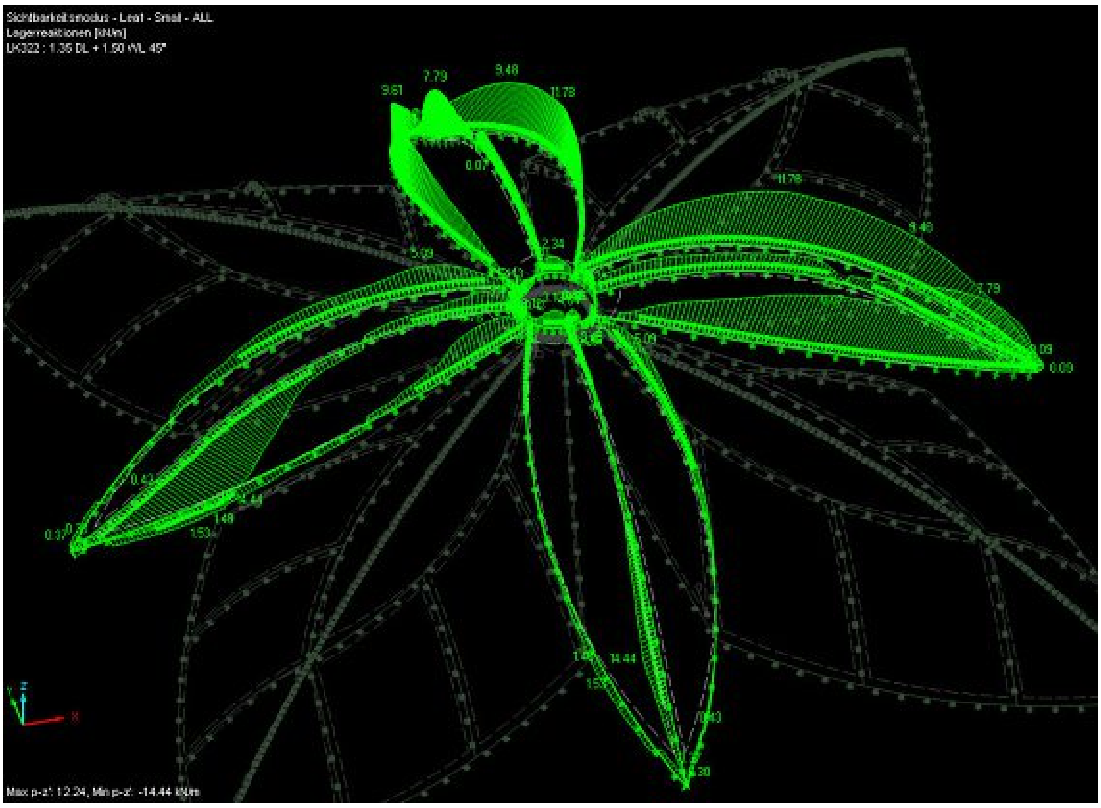

Figure 171: >The Sea Star< MEM – Small leafs – Support forces pz – LCC 1.35 DL + 1.50 WL45°

- STR model: import of the support forces of the MEM model load case combinations

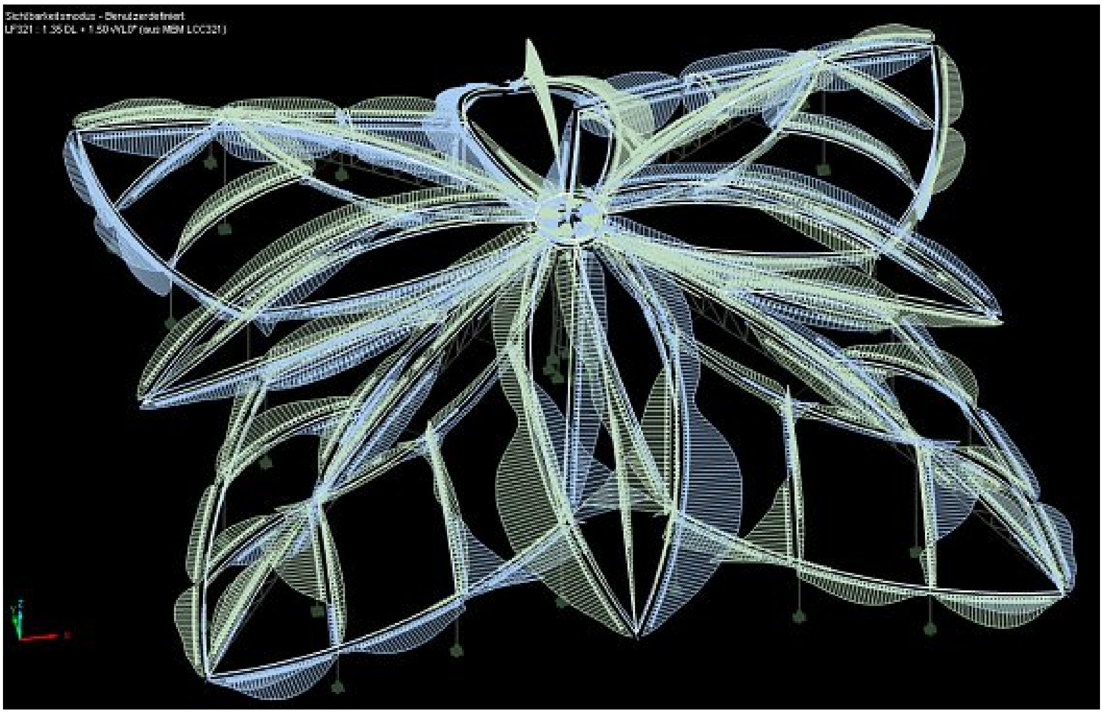

Figure 172: >The Sea Star< STR – Applied member loads – LC 1.35 DL + 1.50 WL0°

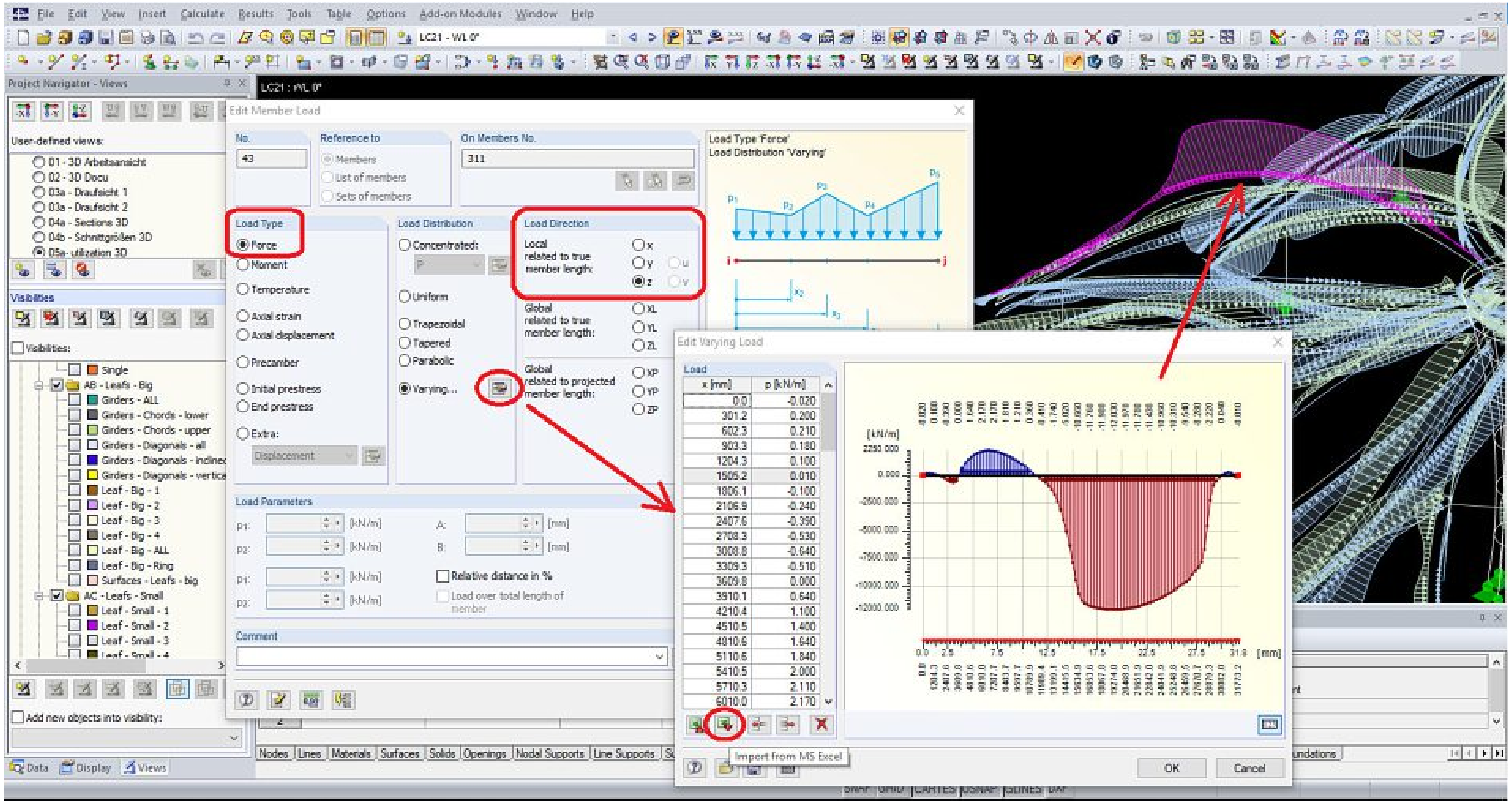

Figure 173: >The Sea Star< RFEM – Procedure of load application of the membrane forces to the STR model

Table 12: >The Sea Star< Load Cases HY and MEM model

LC No	Description	LC Factor	Dead Load	Factor in x	Factor in y	Factor in z	LC-Type	Comment	Abbr.
1	Dead Load struct.	1.00	TRUE	0	0	-1.05	permanent	auto	DLs
11	Live Load roof	1.00	FALSE	0	0	0	variable	0.6 kN/m²	LLrb
21	Wind Load 0°	1.00	FALSE	0	0	0	variable	CFD	WL 0°
22	Wind Load 45°	1.00	FALSE	0	0	0	variable	CFD	WL 45°
23	Wind Load 90°	1.00	FALSE	0	0	0	variable	CFD	WL 90°
24	Wind Load 135°	1.00	FALSE	0	0	0	variable	CFD	WL 135°
25	Wind Load 180°	1.00	FALSE	0	0	0	variable	CFD	WL 180°
26	Wind Load 225°	1.00	FALSE	0	0	0	variable	CFD	WL 225°
27	Wind Load 270°	1.00	FALSE	0	0	0	variable	CFD	WL 270°
28	Wind Load 315°	1.00	FALSE	0	0	0	variable	CFD	WL 315°
31	Temp. increase	1.00	FALSE	0	0	0	variable	+30 K	T+
32	Temp. decrease	1.00	FALSE	0	0	0	variable	-30 K	T-
41	Imperfections	1.00	FALSE	0	0	0	Imp	L/200	Imp

Table 13: >The Sea Star< Load Case Combinations Hybrid Model HY

LCC	LC1	LC11	LC21	LC22	LC23	LC24	LC25	LC26	LC27	LC28	LC31	LC32	LC41
	DLs	LLr	WL 0°	WL 45°	WL 90°	WL 135°	WL 180°	WL 225°	WL 270°	WL 315°	T+	T-	Imp
1	1.35												1.00
2	1.35	1.50											1.00
3	1.35		1.50										1.00
4	1.35			1.50									1.00
5	1.35				1.50								1.00
6	1.35					1.50							1.00
7	1.35						1.50						1.00
8	1.35							1.50					1.00
9	1.35								1.50				1.00
10	1.35									1.50			1.00
11	1.35										1.50		1.00
12	1.35											1.50	1.00
13	1.35	1.50									0.90		1.00
14	1.35	1.50										0.90	1.00
15	1.35		1.50								0.90		1.00
16	1.35		1.50									0.90	1.00
17	1.35			1.50							0.90		1.00
18	1.35			1.50								0.90	1.00
19	1.35				1.50						0.90		1.00
20	1.35				1.50							0.90	1.00
21	1.35					1.50					0.90		1.00

	LC1	LC11	LC21	LC22	LC23	LC24	LC25	LC26	LC27	LC28	LC31	LC32	LC41
LCC	DLs	LLr	WL 0°	WL 45°	WL 90°	WL 135°	WL 180°	WL 225°	WL 270°	WL 315°	T+	T-	Imp
22	1.35					1.50						0.90	1.00
23	1.35						1.50				0.90		1.00
24	1.35						1.50					0.90	1.00
25	1.35							1.50			0.90		1.00
26	1.35							1.50				0.90	1.00
27	1.35								1.50		0.90		1.00
28	1.35								1.50			0.90	1.00
29	1.35									1.50	0.90		1.00
30	1.35									1.50		0.90	1.00
31	1.00	1.50											1.00
32	1.00		1.50										1.00
33	1.00			1.50									1.00
34	1.00				1.50								1.00
35	1.00					1.50							1.00
36	1.00						1.50						1.00
37	1.00							1.50					1.00
38	1.00								1.50				1.00
39	1.00									1.50			1.00
40	1.00	1.50									0.90		1.00
41	1.00	1.50										0.90	1.00
42	1.00		1.50								0.90		1.00
43	1.00		1.50									0.90	1.00
44	1.00			1.50							0.90		1.00
45	1.00			1.50								0.90	1.00
46	1.00				1.50						0.90		1.00
47	1.00				1.50							0.90	1.00
48	1.00					1.50					0.90		1.00
49	1.00					1.50						0.90	1.00
50	1.00						1.50				0.90		1.00
51	1.00						1.50					0.90	1.00
52	1.00							1.50			0.90		1.00
53	1.00							1.50				0.90	1.00
54	1.00								1.50		0.90		1.00
55	1.00								1.50			0.90	1.00
56	1.00									1.50	0.90		1.00
57	1.00									1.50		0.90	1.00

Table 14: >The Sea Star< Load Cases Separate Model STR

LC No	Description	LC Factor	Dead Load	Factor in x	Factor in y	Factor in z	LC-Type	Com-ment	Abbr.
1	Dead Load struct.	1.00	TRUE	0	0	-1.05	permanent	auto	DLs
211	1.0 DLmem + 1.5 LLb	1.00	FALSE	0	0	0	variable	MEM	as descr.
221	1.0 DLmem + 1.5 WL0°	1.00	FALSE	0	0	0	variable	MEM	as descr.
222	1.0 DLmem + 1.5 WL45°	1.00	FALSE	0	0	0	variable	MEM	as descr.
223	1.0 DLmem + 1.5 WL90°	1.00	FALSE	0	0	0	variable	MEM	as descr.
224	1.0 DLmem + 1.5 WL135°	1.00	FALSE	0	0	0	variable	MEM	as descr.
225	1.0 DLmem + 1.5 WL180°	1.00	FALSE	0	0	0	variable	MEM	as descr.
226	1.0 DLmem + 1.5 WL225°	1.00	FALSE	0	0	0	variable	MEM	as descr.
227	1.0 DLmem + 1.5 WL270°	1.00	FALSE	0	0	0	variable	MEM	as descr.
228	1.0 DLmem + 1.5 WL315°	1.00	FALSE	0	0	0	variable	MEM	as descr.
301	1.35 DLmem	1.00	FALSE	0	0	0	permanent	MEM	as descr.
311	1.35 DLmem + 1.5 LLb	1.00	FALSE	0	0	0	variable	MEM	as descr.
321	1.35 DLmem + 1.5 WL0°	1.00	FALSE	0	0	0	variable	MEM	as descr.
322	1.35 DLmem + 1.5 WL45°	1.00	FALSE	0	0	0	variable	MEM	as descr.
323	1.35 DLmem + 1.5 WL90°	1.00	FALSE	0	0	0	variable	MEM	as descr.
324	1.35 DLmem + 1.5 WL135°	1.00	FALSE	0	0	0	variable	MEM	as descr.
325	1.35 DLmem + 1.5 WL180°	1.00	FALSE	0	0	0	variable	MEM	as descr.
326	1.35 DLmem + 1.5 WL225°	1.00	FALSE	0	0	0	variable	MEM	as descr.
327	1.35 DLmem + 1.5 WL270°	1.00	FALSE	0	0	0	variable	MEM	as descr.
328	1.35 DLmem + 1.5 WL315°	1.00	FALSE	0	0	0	variable	MEM	as descr.
31	Temp. increase	1.00	FALSE	0	0	0	variable	+30 K	T+
32	Temp. decrease	1.00	FALSE	0	0	0	variable	-30 K	T-
41	Imperfections	1.00	FALSE	0	0	0	Imp	L/200	Imp

Table 15: >The Sea Star< Load Case Combinations for Steel Design in Separate Model STR

LCC	LC 1 DLs	LC 211 1.0DLm + 1.5 LLb	LC 221 1.0DLm + 1.5 WL0°	LC 222 1.0DLm + 1.5 WL45°	LC 223 1.0DLm + 1.5 WL90°	LC 224 1.0DLm + 1.5 WL135°	LC 225 1.0DLm + 1.5 WL180°	LC 226 1.0DLm + 1.5 WL225°	LC 227 1.0DLm + 1.5 WL270°	LC 228 1.0DLm + 1.5 WL315°	LC 301 1.35DLs	LC 311 1.35DLm + 1.5 LLb	LC 321 1.35DLm + 1.5 WL0°	LC 322 1.35DLm + 1.5 WL45°	LC 323 1.35DLm + 1.5 WL90°	LC 324 1.35DLm + 1.5 WL135°	LC 325 1.35DLm + 1.5 WL180°	LC 326 1.35DLm + 1.5 WL225°	LC 327 1.35DLm + 1.5 WL270°	LC 328 1.35DLm + 1.5 WL315°	LC 31 T+	LC 32 T-
1	1.35										1.00											
2	1.35											1.00										
3	1.35												1.00									
4	1.35													1.00								
5	1.35														1.00							
6	1.35															1.00						
7	1.35																1.00					
8	1.35																	1.00				
9	1.35																		1.00			
10	1.35																			1.00		
11	1.35										1.00										1.50	
12	1.35										1.00											1.50
13	1.35											1.00									0.90	
14	1.35											1.00										0.90
15	1.35												1.00								0.90	
16	1.35												1.00									0.90
17	1.35													1.00							0.90	
18	1.35													1.00								0.90

LCC	LC 1 DLs	LC 211 1.0DLm + 1.5 LLb	LC 221 1.0DLm + 1.5 WL0°	LC 222 1.0DLm + 1.5 WL45°	LC 223 1.0DLm + 1.5 WL90°	LC 224 1.0DLm + 1.5 WL135°	LC 225 1.0DLm + 1.5 WL180°	LC 226 1.0DLm + 1.5 WL225°	LC 227 1.0DLm + 1.5 WL270°	LC 228 1.0DLm + 1.5 WL315°	LC 301 1.35DLs	LC 311 1.35DLm + 1.5 LLb	LC 321 1.35DLm + 1.5 WL0°	LC 322 1.35DLm + 1.5 WL45°	LC 323 1.35DLm + 1.5 WL90°	LC 324 1.35DLm + 1.5 WL135°	LC 325 1.35DLm + 1.5 WL180°	LC 326 1.35DLm + 1.5 WL225°	LC 327 1.35DLm + 1.5 WL270°	LC 328 1.35DLm + 1.5 WL315°	LC 31 T+	LC 32 T-
19	1.35														1.00						0.90	
20	1.35														1.00							0.90
21	1.35															1.00					0.90	
22	1.35															1.00						0.90
23	1.35																1.00				0.90	
24	1.35																1.00					0.90
25	1.35																	1.00			0.90	
26	1.35																	1.00				0.90
27	1.35																		1.00		0.90	
28	1.35																		1.00			0.90
29	1.35																			1.00	0.90	
30	1.35																			1.00		0.90
31	1.00	1.00																				
32	1.00		1.00																			
33	1.00			1.00																		
34	1.00				1.00																	
35	1.00					1.00																
36	1.00						1.00															
37	1.00							1.00														
38	1.00								1.00													
39	1.00									1.00												

LCC	LC 1	LC 211	LC 221	LC 222	LC 223	LC 224	LC 225	LC 226	LC 227	LC 228	LC 301	LC 311	LC 321	LC 322	LC 323	LC 324	LC 325	LC 326	LC 327	LC 328	LC 31	LC 32
	DLs	1.0DLm + 1.5 LLb	1.0DLm + 1.5 WL0°	1.0DLm + 1.5 WL45°	1.0DLm + 1.5 WL90°	1.0DLm + 1.5 WL135°	1.0DLm + 1.5 WL180°	1.0DLm + 1.5 WL225°	1.0DLm + 1.5 WL270°	1.0DLm + 1.5 WL315°	1.35DLs	1.35DLm + 1.5 LLb	1.35DLm + 1.5 WL0°	1.35DLm + 1.5 WL45°	1.35DLm + 1.5 WL90°	1.35DLm + 1.5 WL135°	1.35DLm + 1.5 WL180°	1.35DLm + 1.5 WL225°	1.35DLm + 1.5 WL270°	1.35DLm + 1.5 WL315°	T+	T-
40	1.00	1.00																			0.90	
41	1.00	1.00																				0.90
42	1.00		1.00																		0.90	
43	1.00		1.00																			0.90
44	1.00			1.00																	0.90	
45	1.00			1.00																		0.90
46	1.00				1.00																0.90	
47	1.00				1.00																	0.90
48	1.00					1.00															0.90	
49	1.00					1.00																0.90
50	1.00						1.00														0.90	
51	1.00						1.00															0.90
52	1.00							1.00													0.90	
53	1.00							1.00														0.90
54	1.00								1.00												0.90	
55	1.00								1.00													0.90
56	1.00									1.00											0.90	
57	1.00									1.00												0.90

E.2 Results

Following results are based on dimensioned cross-sections. Only where indicated >HYBRID – sections as separate< the cross-sections are not the dimensioned ones for the respective model but the same for all models. In some comparative colour plots the same sections are used because otherwise the comparison would be useless.

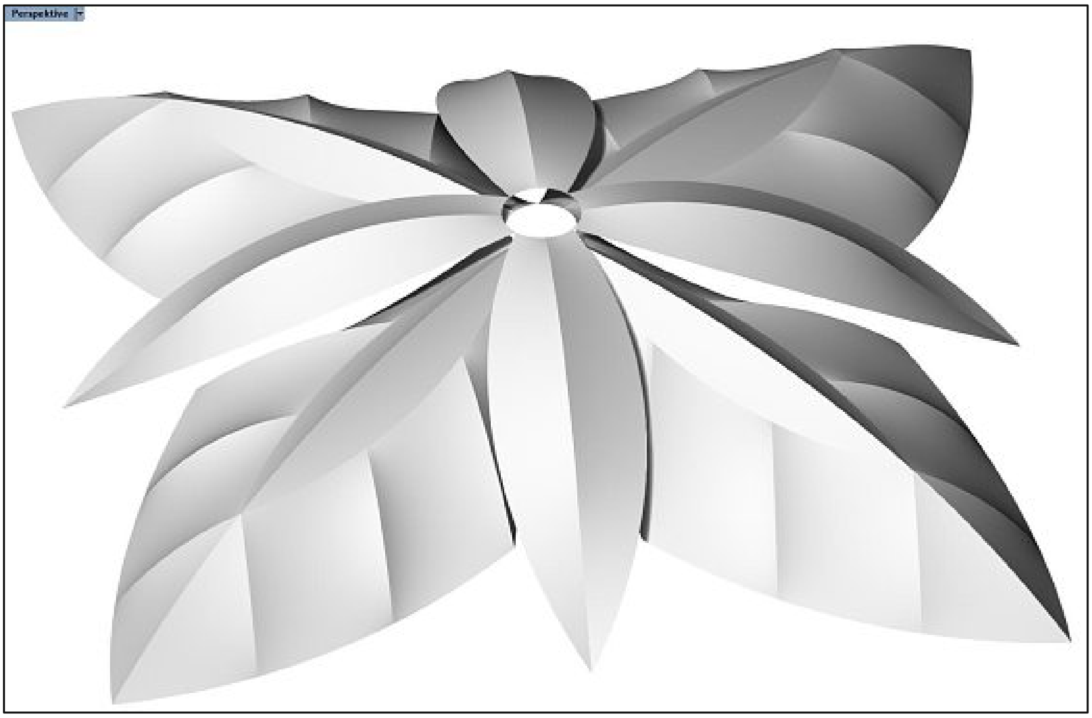

Figure 174: >The Sea Star< Membrane shapes after final form-finding – Exported to Rhino

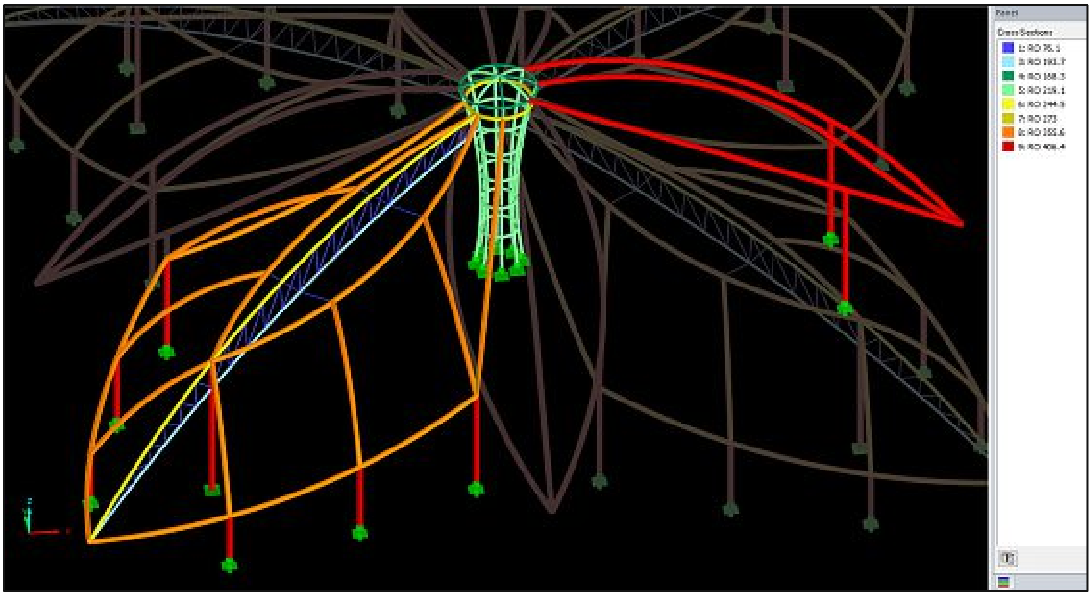

Figure 175: >The Sea Star< HY – Outer diameter sections by colours

On the following pages, comparative colour plots of the stress utilisations are shown to illustrate the differences in the results of hybrid versus separate. The cross-sections are identical in both models since such a comparison would not have any meaningful significance for both calculations with the dimensioned sections. The sections used are the ones needed in separate dimensioning. Clearly visible is how much lower the utilisation is in most cases in the hybrid calculation. In all other result illustrations the sections correspond to the required dimensioning. The results are arranged as follows: First two pages compare the perspective full-model overviews. Then top views of members membranes are attached to. Afterwards, results of a separate calculation without values and below those with values, always arranged on one page. On the following page the same procedure for hybrid. Scrolling can thus achieve a very good comparative impression. The legend for all following result plots showing utilisations is identical. In each illustration the colours indicate the identical utilisation.

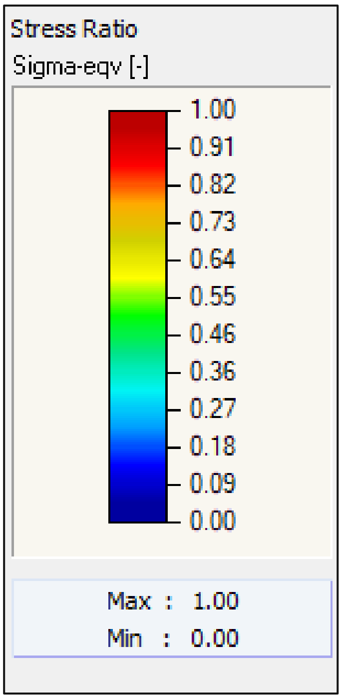

Figure 176: >The Sea Star< – Legend utilisation for following colour plots

In the membrane deformation and internal forces graphs, the colour scale is always set manually and identical so that the same colour stands for the same result. This enables a better visual comparative impression. The membrane deformation diagrams always show the local z-deformation of the membranes, which is perpendicular to its surface. In these membrane deformation plots, it should be noted that in the hybrid calculations the edges also deform, whereas this does not happen in separate calculations since they are fix supported. Nevertheless, the differences can clearly be identified.

E.2.1 Stress Utilisation Separate/Hybrid (identical sections)

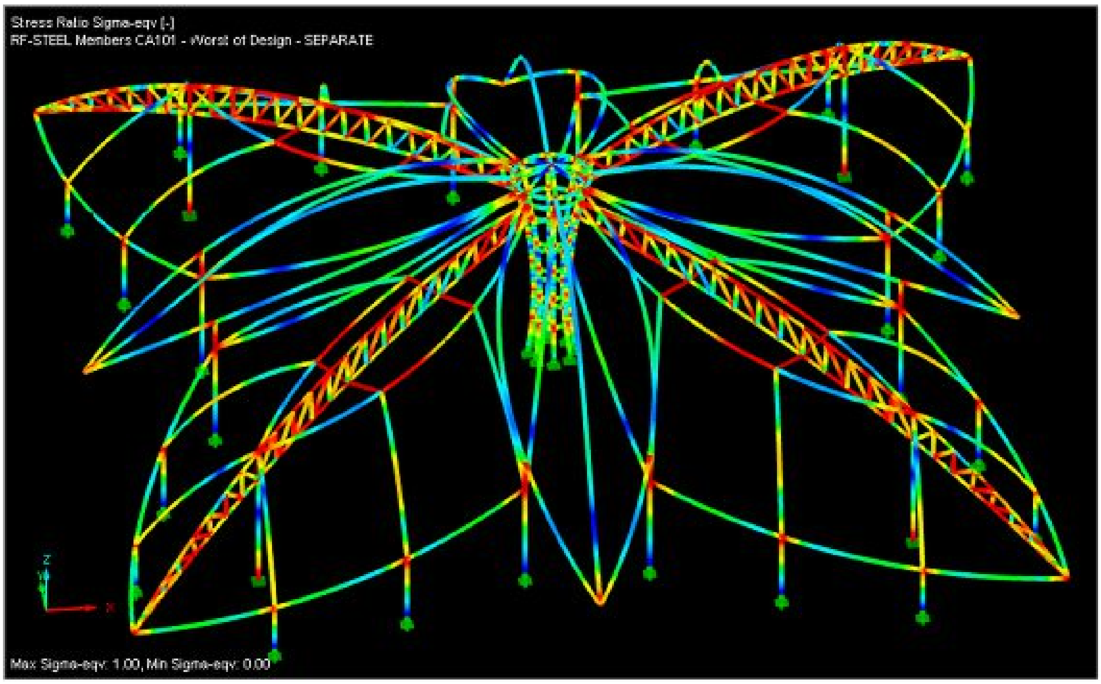

Figure 177: >The Sea Star< SEPARATE –
Utilisation all members

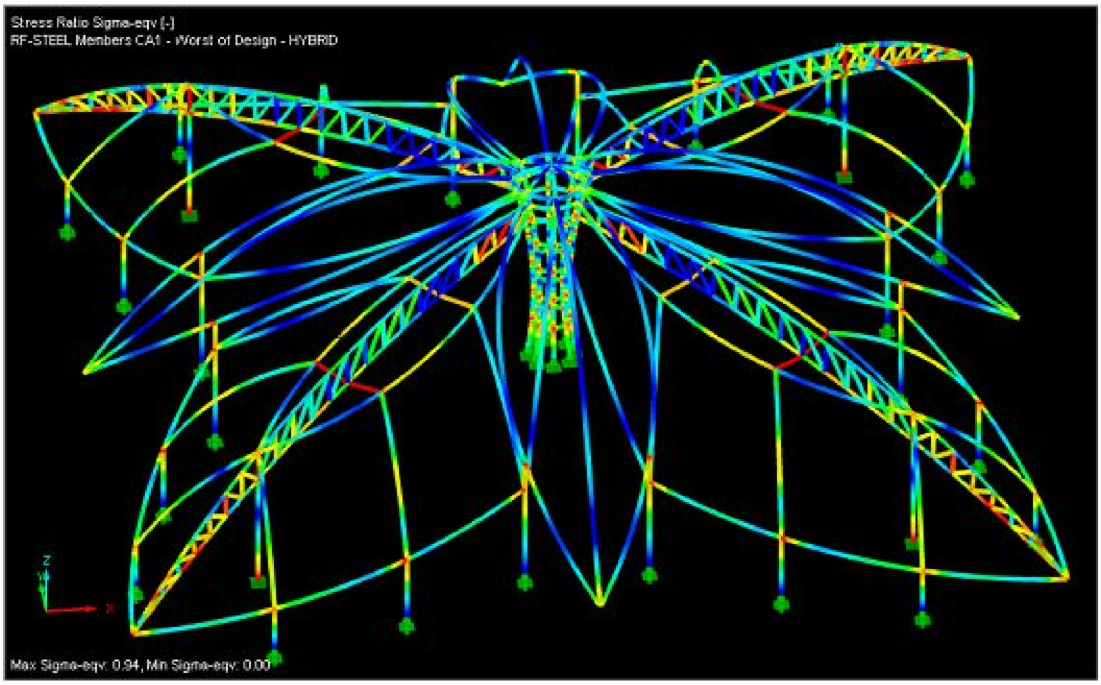

Figure 178: >The Sea Star< HYBRID – Sections as separate –
Utilisation all members

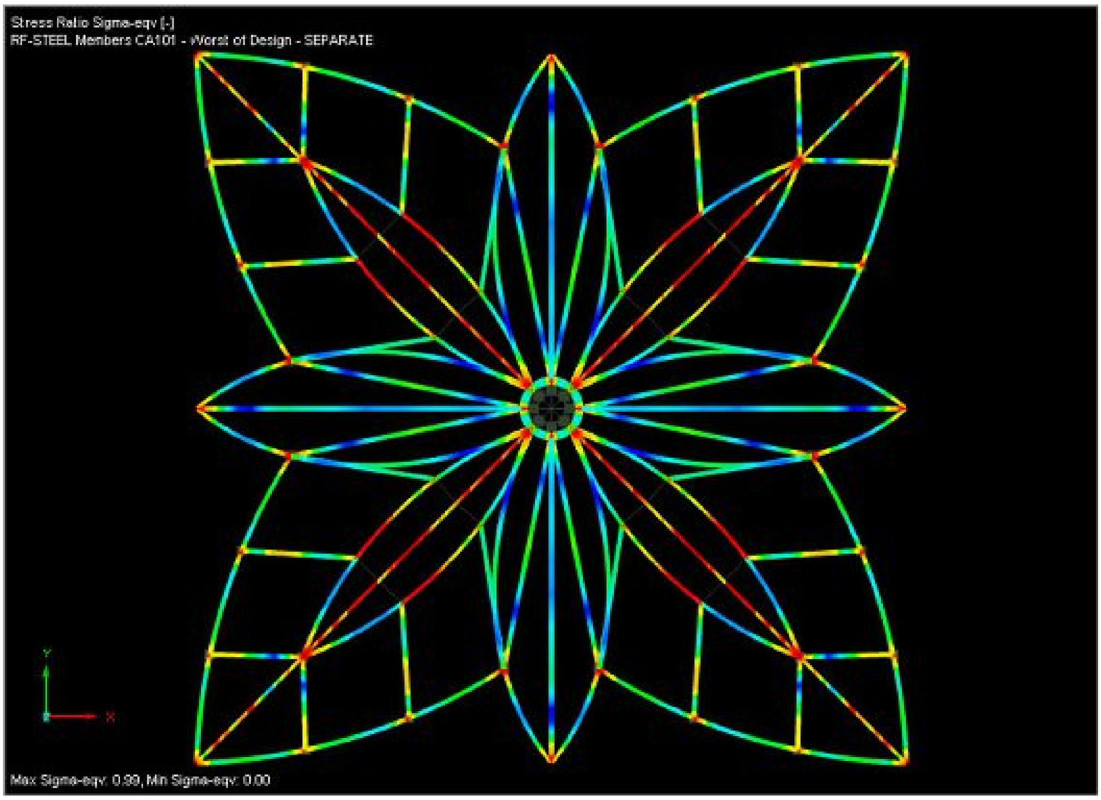

Figure 179: >The Sea Star< SEPARATE –
Utilisation all membrane attached members

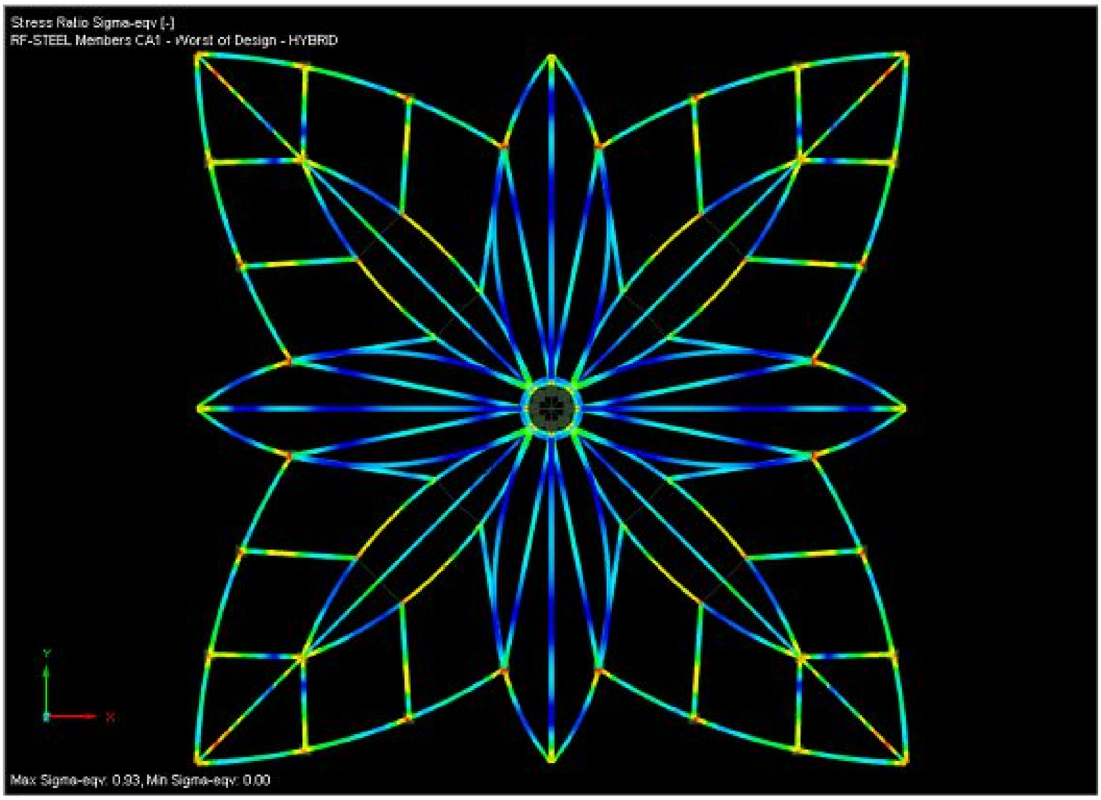

Figure 180: >The Sea Star< HYBRID – Sections as separate –
Utilisation all membrane attached members

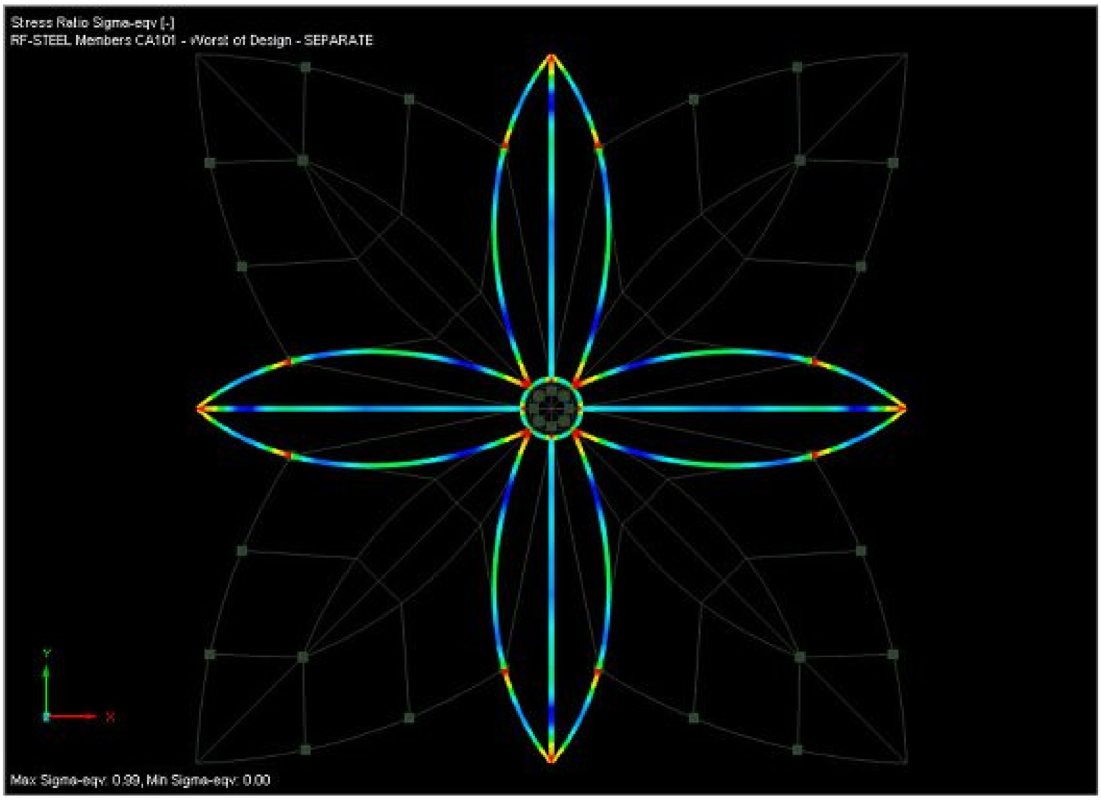

Figure 181: >The Sea Star< SEPARATE –
Utilisation membrane attached members small leaves

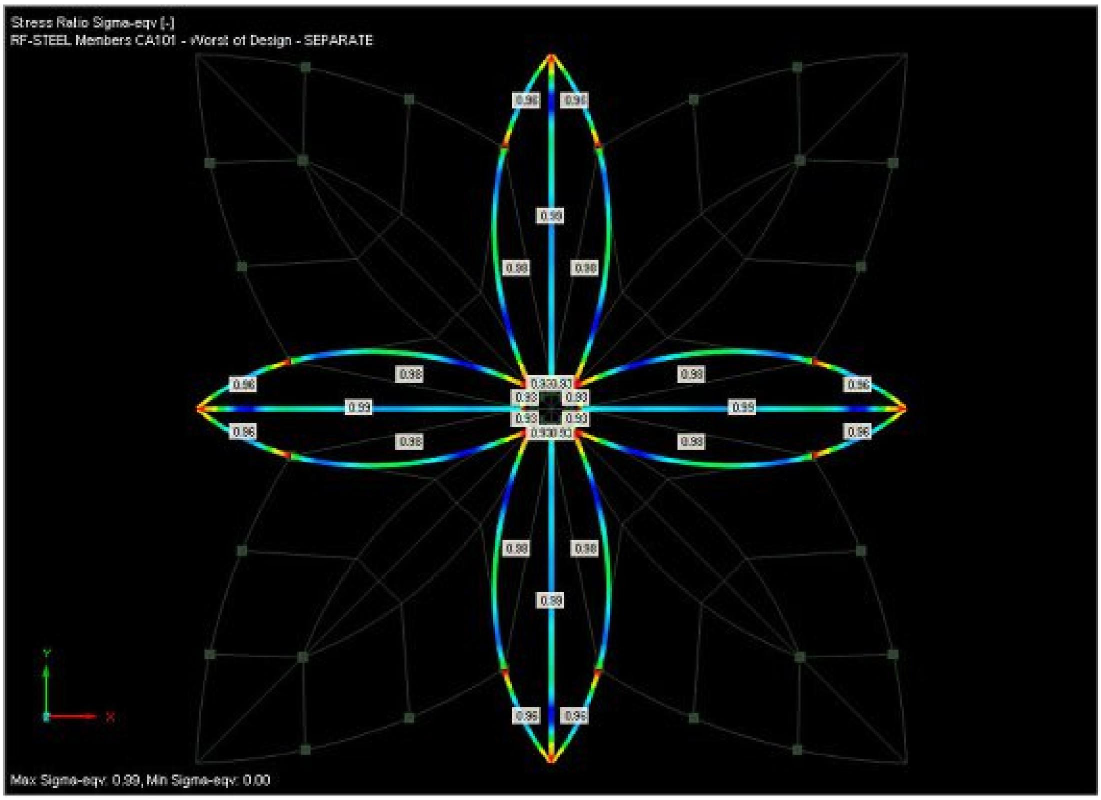

Figure 182: >The Sea Star< SEPARATE –
Utilisation membrane attached members small leaves – With values

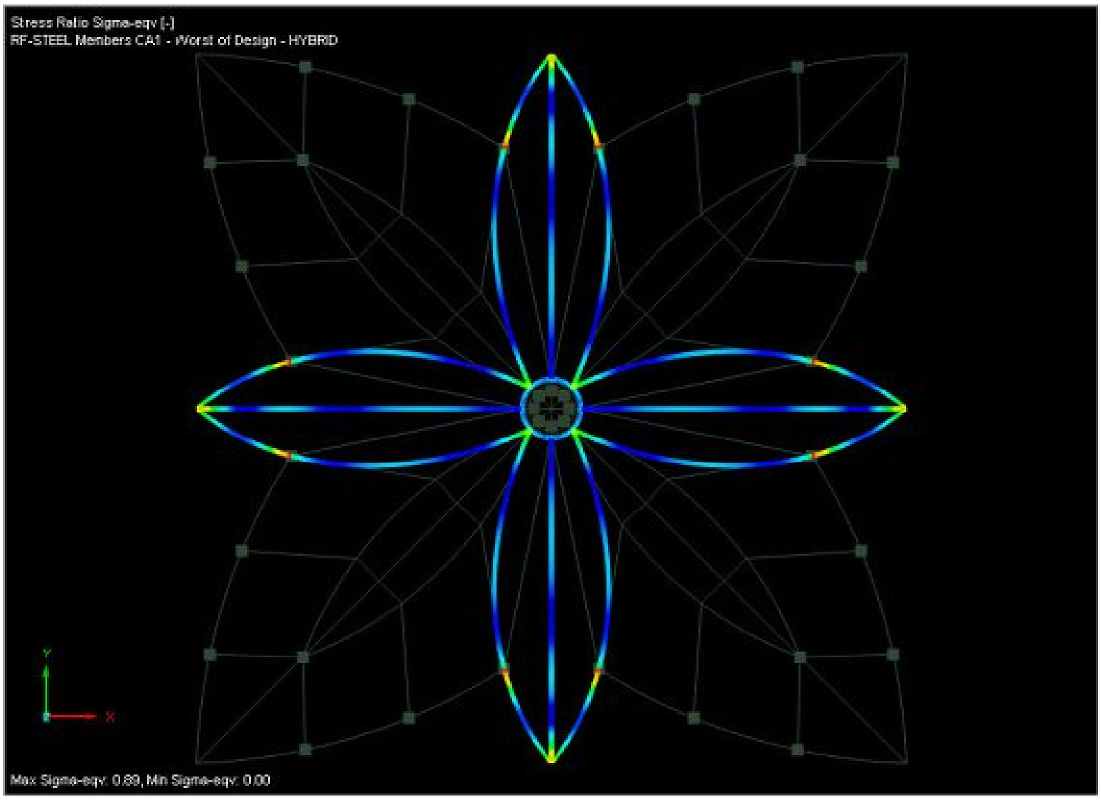

Figure 183: >The Sea Star< HYBRID – Sections as separate –
Utilisation membrane attached members small leaves

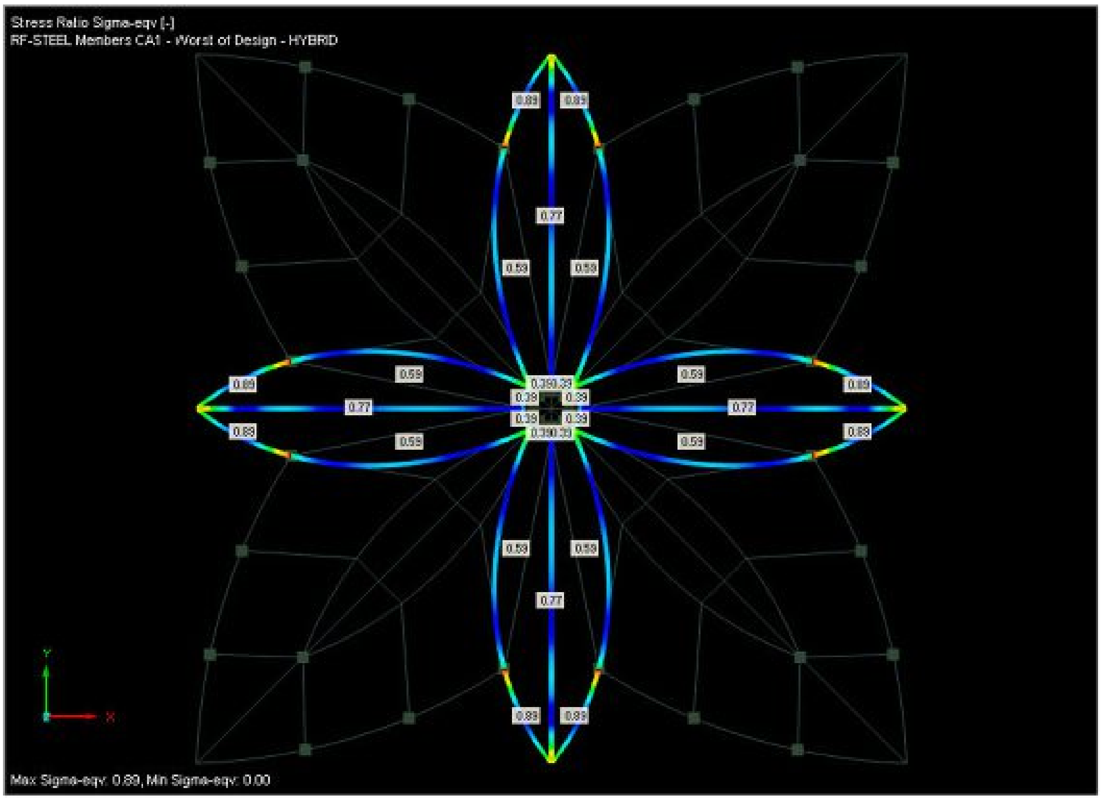

Figure 184: >The Sea Star< HYBRID – Sections as separate –
Utilisation membrane attached members small leaves – With values

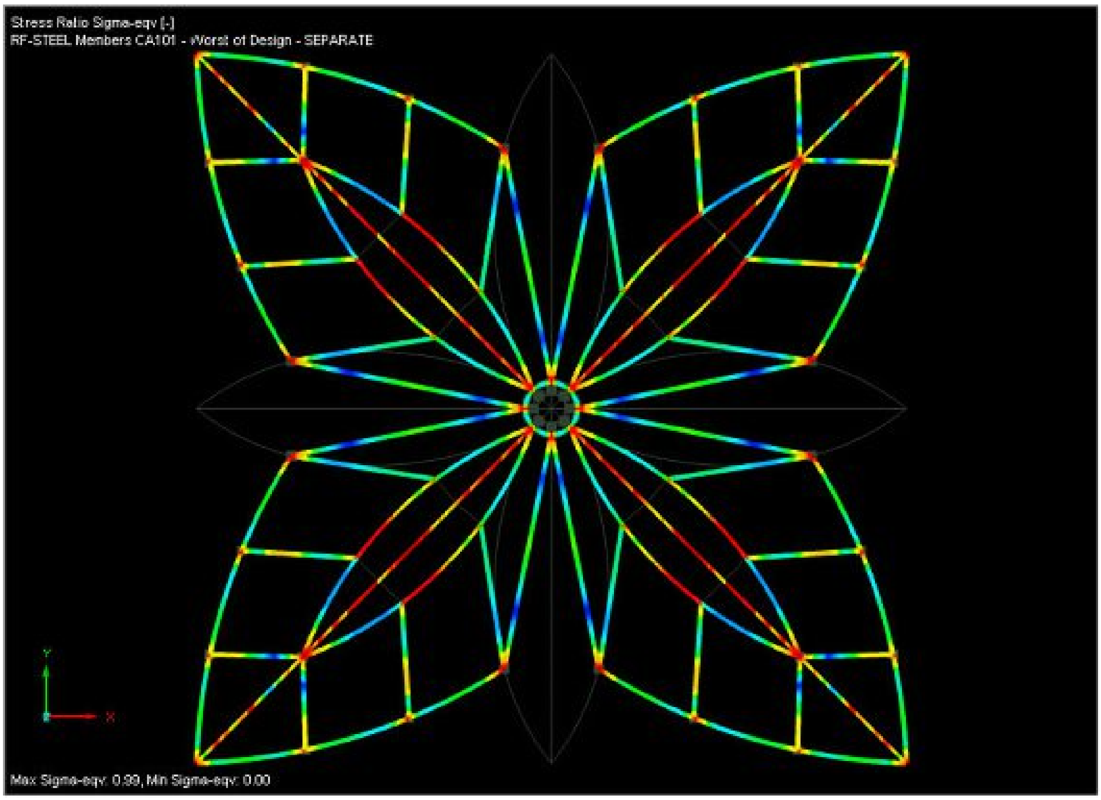

Figure 185: >The Sea Star< SEPARATE –
Utilisation membrane attached members big leaves

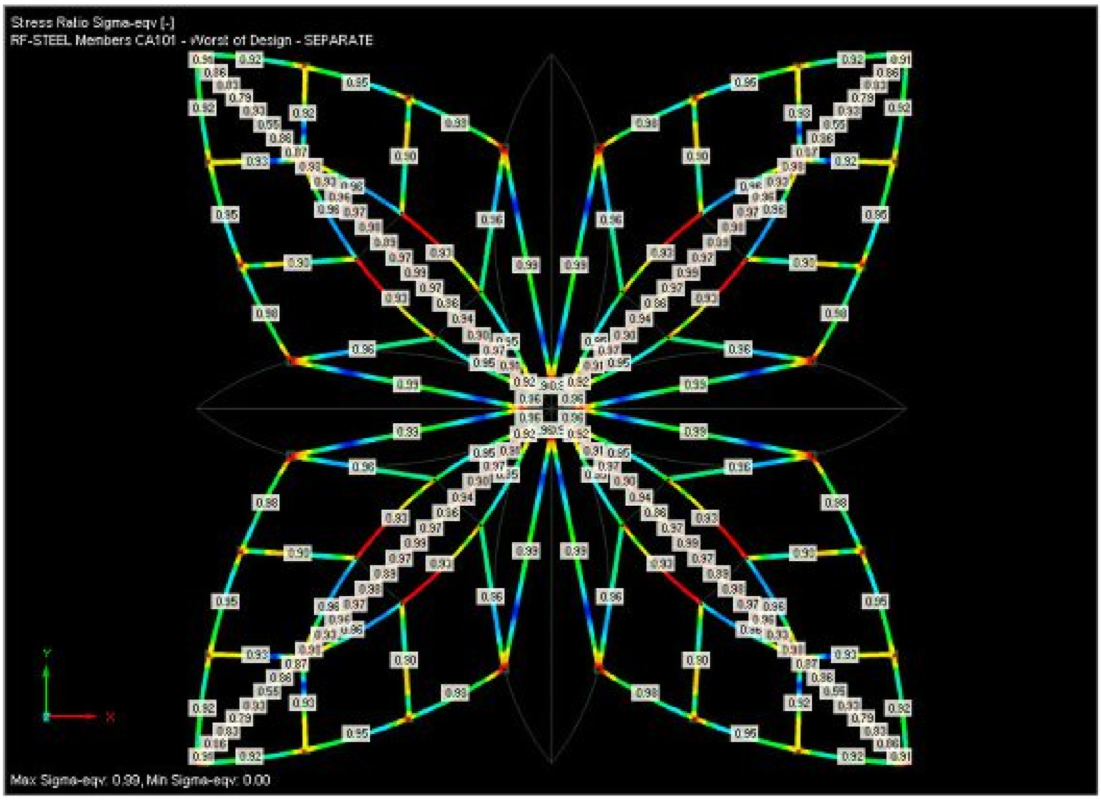

Figure 186: >The Sea Star< SEPARATE –
Utilisation membrane attached members big leaves – With values

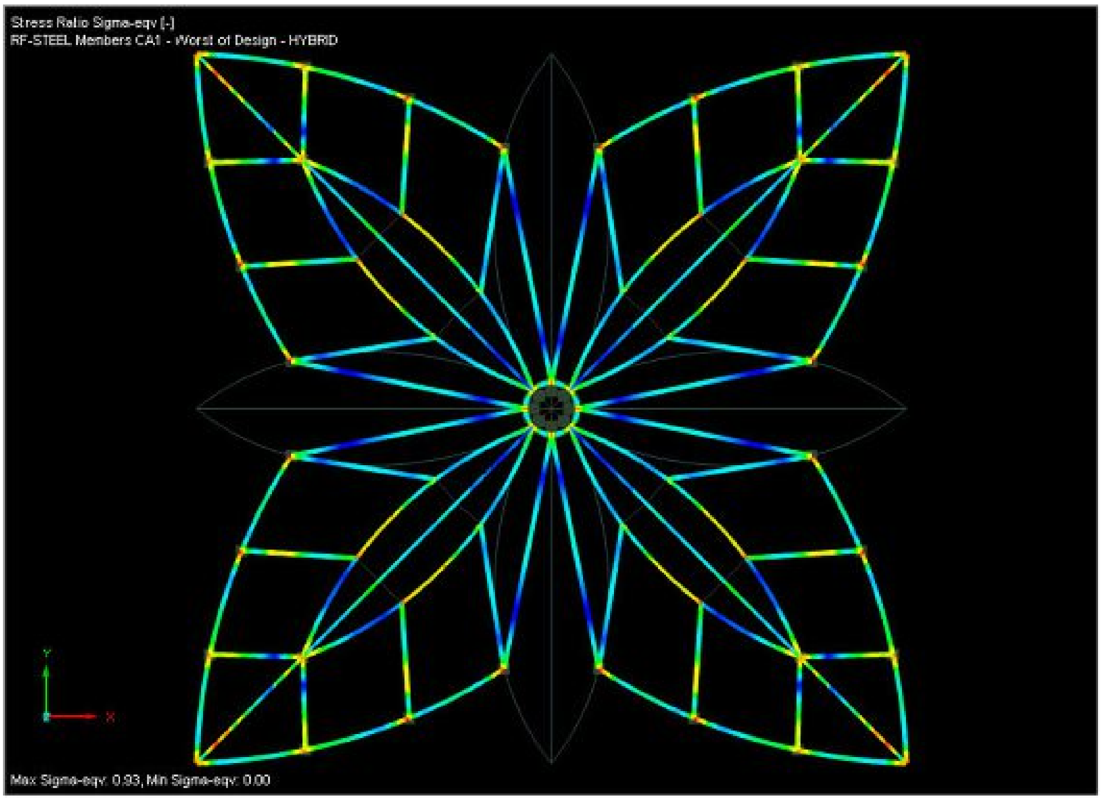

Figure 187: >The Sea Star< HYBRID – Sections as separate – Utilisation membrane attached members big leaves

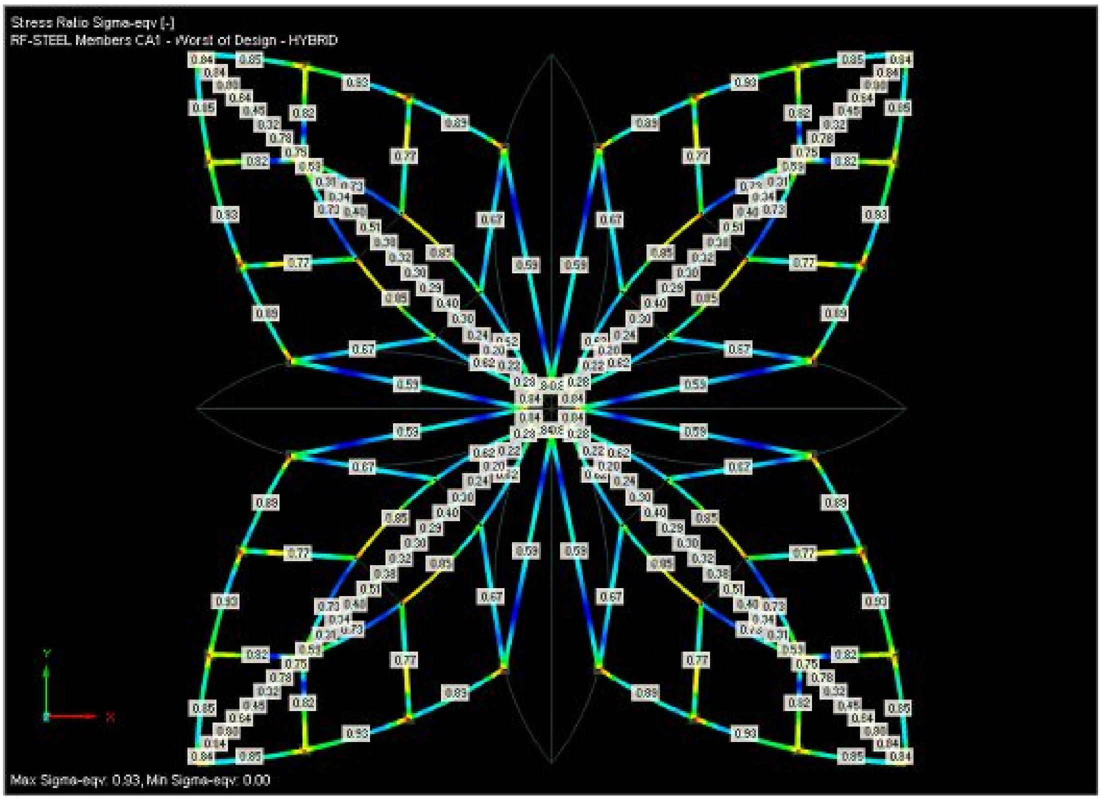

Figure 188: >The Sea Star< HYBRID – Sections as separate – Utilisation membrane attached members big leaves – With values

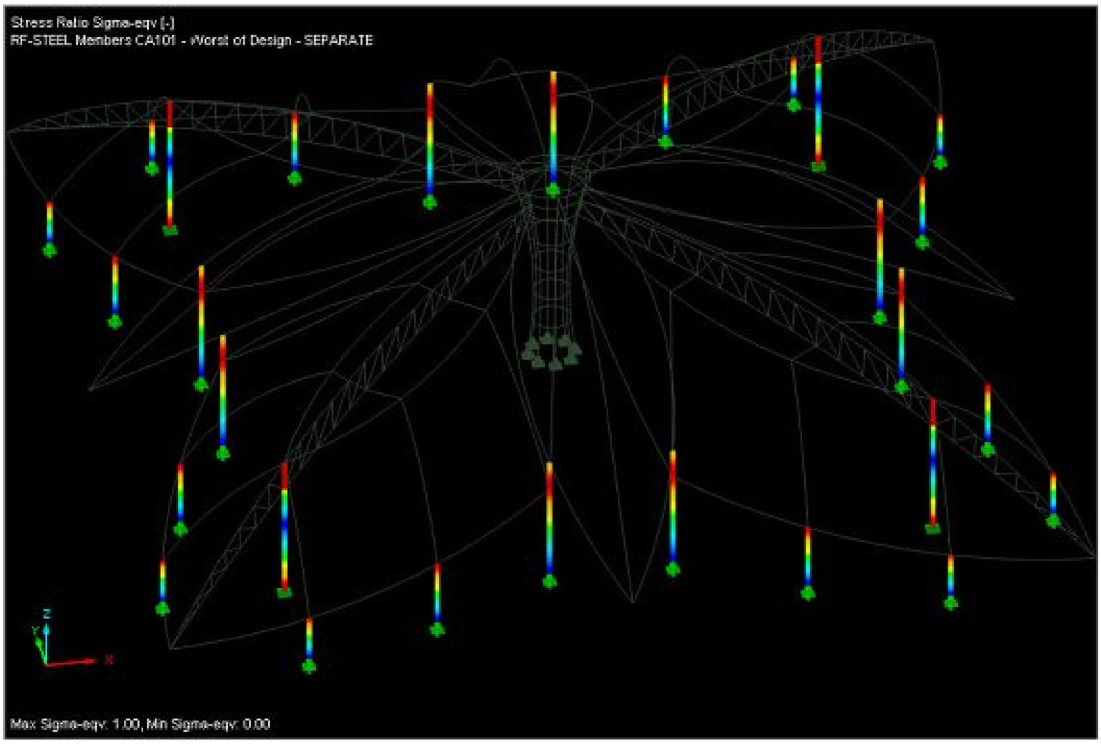

Figure 189: >The Sea Star< SEPARATE –
Utilisation columns

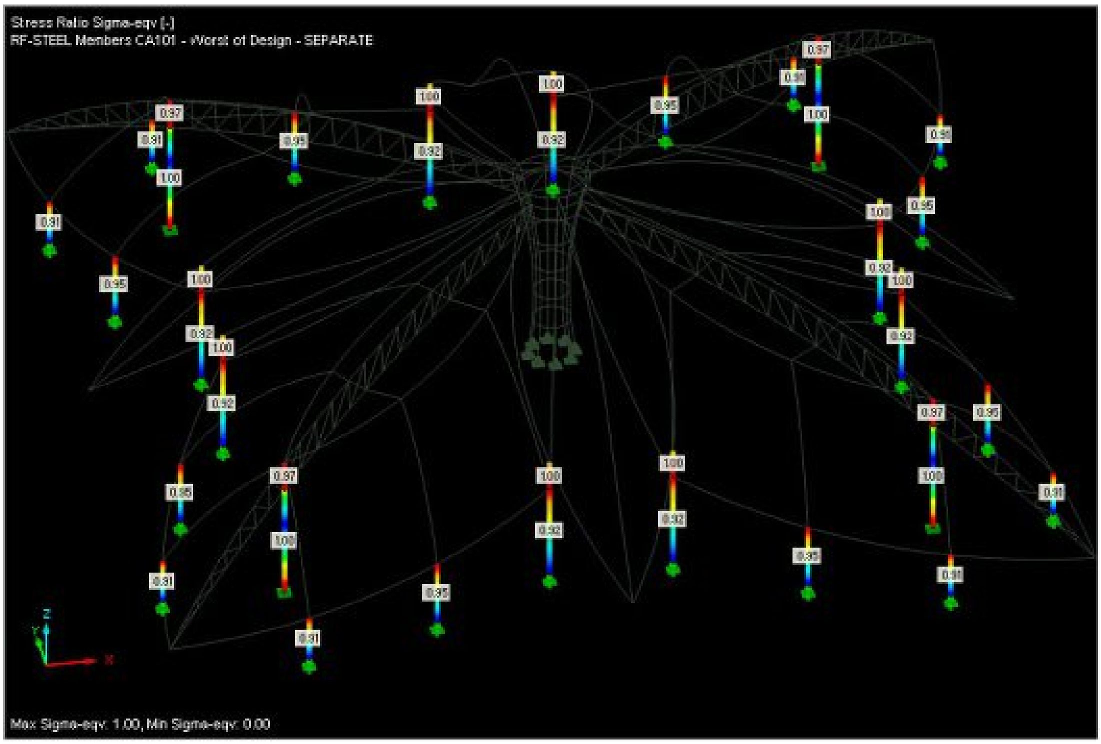

Figure 190: >The Sea Star< SEPARATE –
Utilisation columns – With values

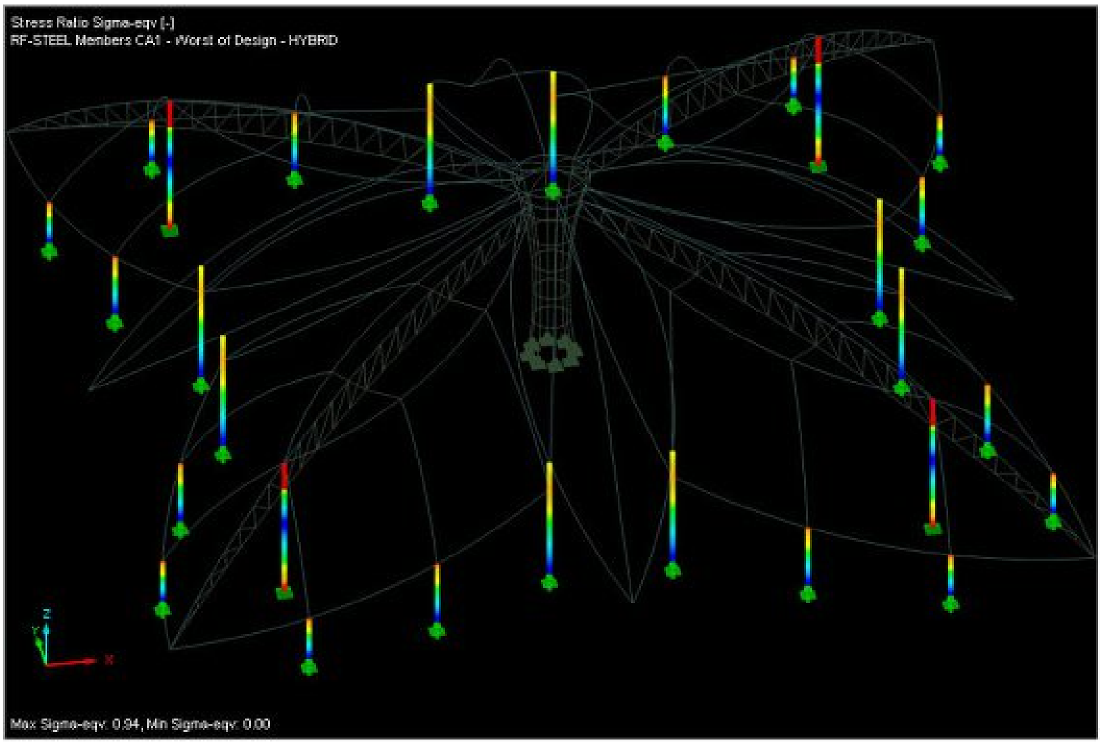

Figure 191: >The Sea Star< HYBRID – Sections as separate – Utilisation columns

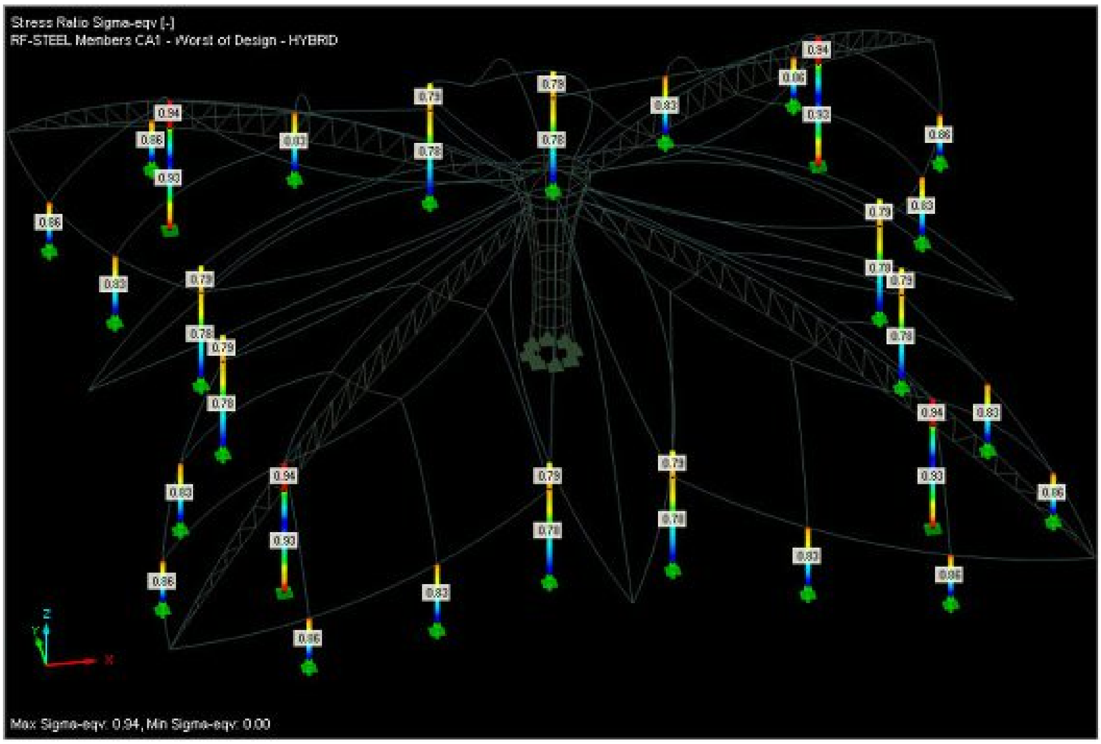

Figure 192: >The Sea Star< HYBRID – Sections as separate – Utilisation columns – With values

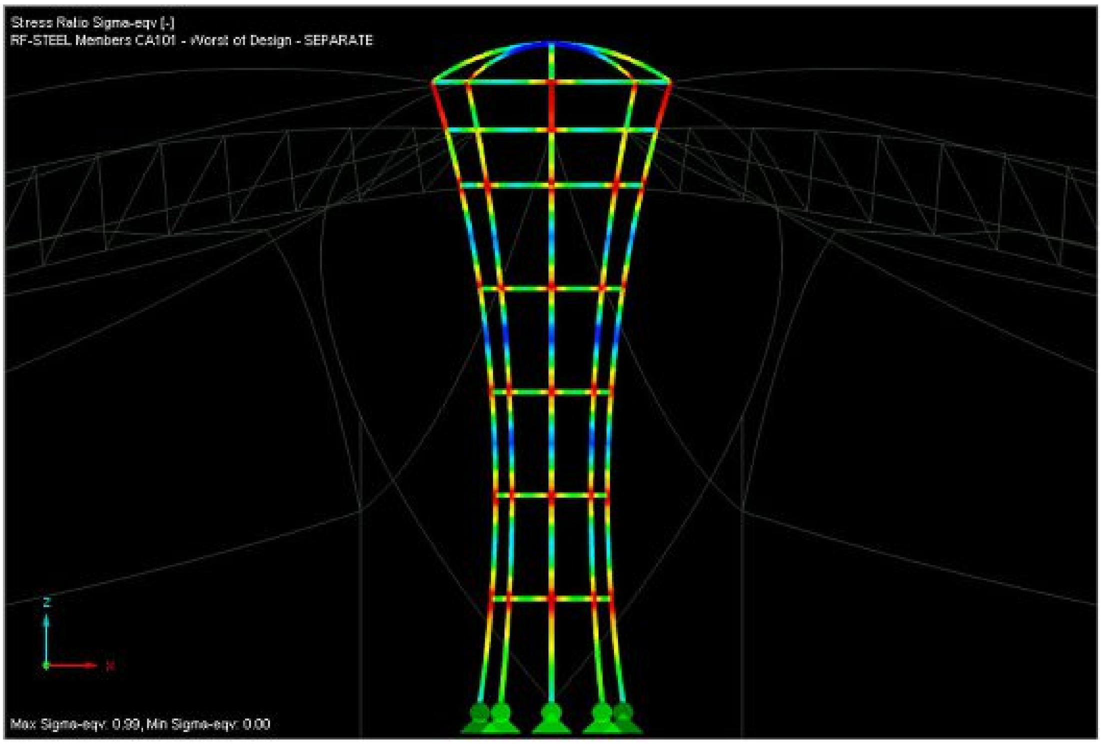

Figure 193: >The Sea Star< SEPARATE –
Utilisation central funnel

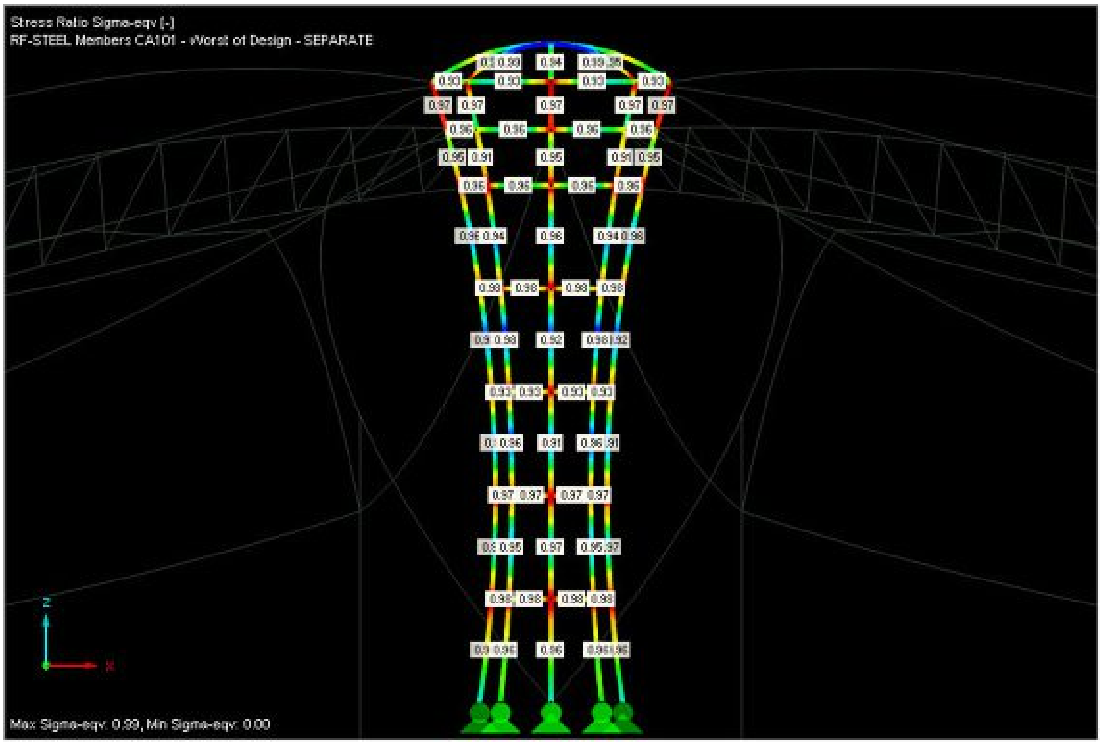

Figure 194: >The Sea Star< SEPARATE –
Utilisation central funnel – With values

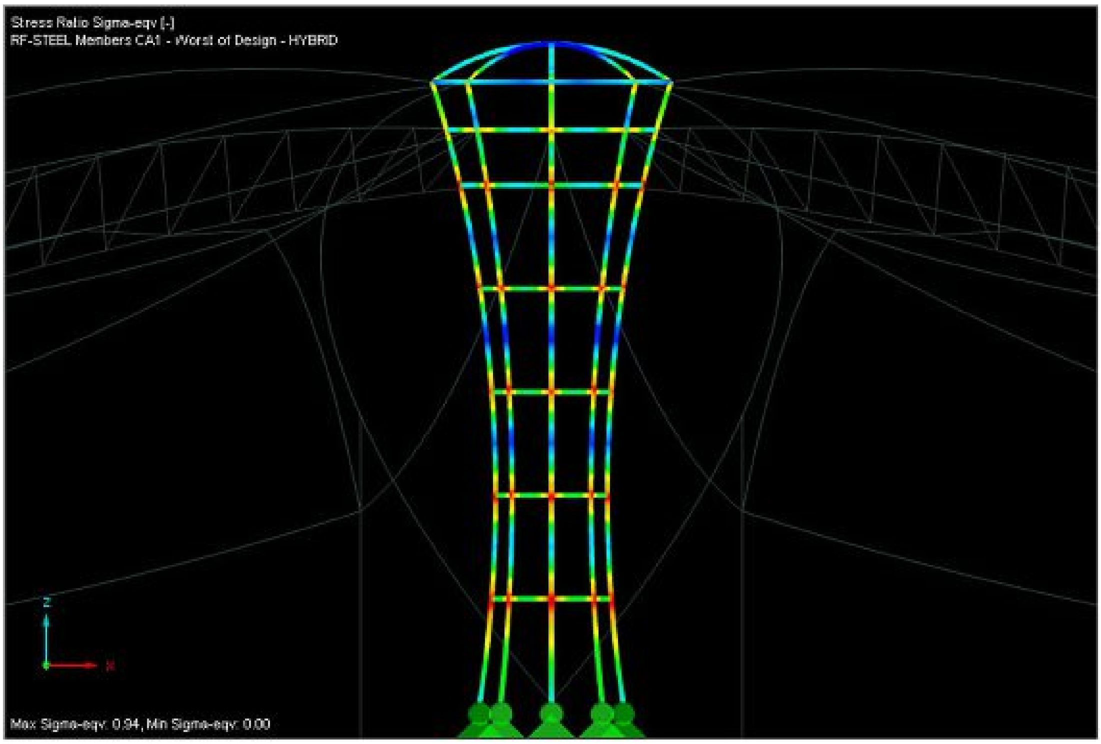

Figure 195: >The Sea Star< HYBRID – Sections as separate –
Utilisation central funnel

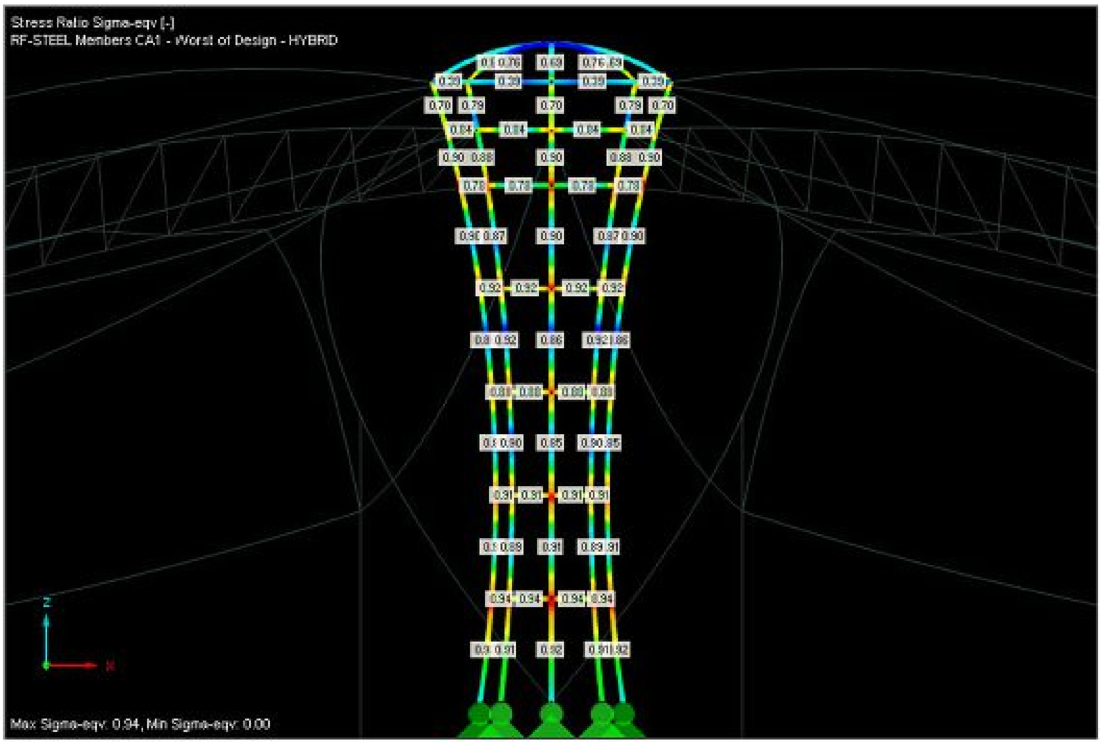

Figure 196: >The Sea Star< HYBRID – Sections as separate –
Utilisation central funnel – With values

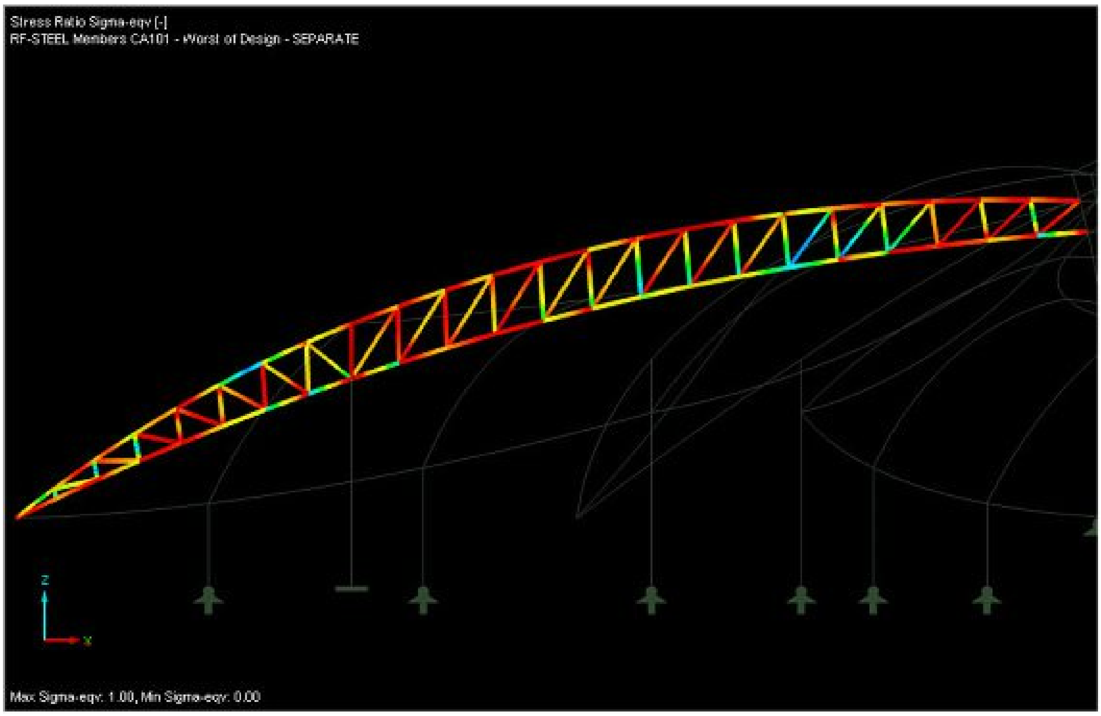

Figure 197: >The Sea Star< SEPARATE –
Utilisation trusses

Figure 198: >The Sea Star< SEPARATE –
Utilisation trusses – With values

Figure 199: >The Sea Star< HYBRID – Sections as separate – Utilisation trusses

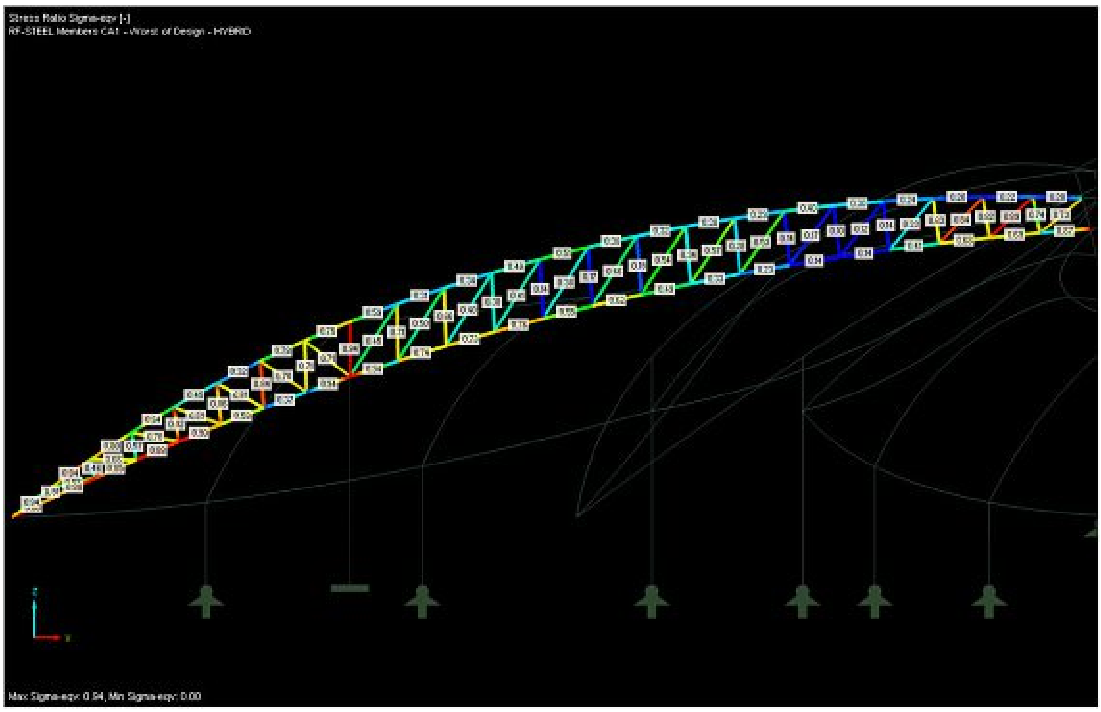

Figure 200: >The Sea Star< HYBRID – Sections as separate – Utilisation trusses – With values

E.2.2 Max. Internal Forces Separate/Hybrid

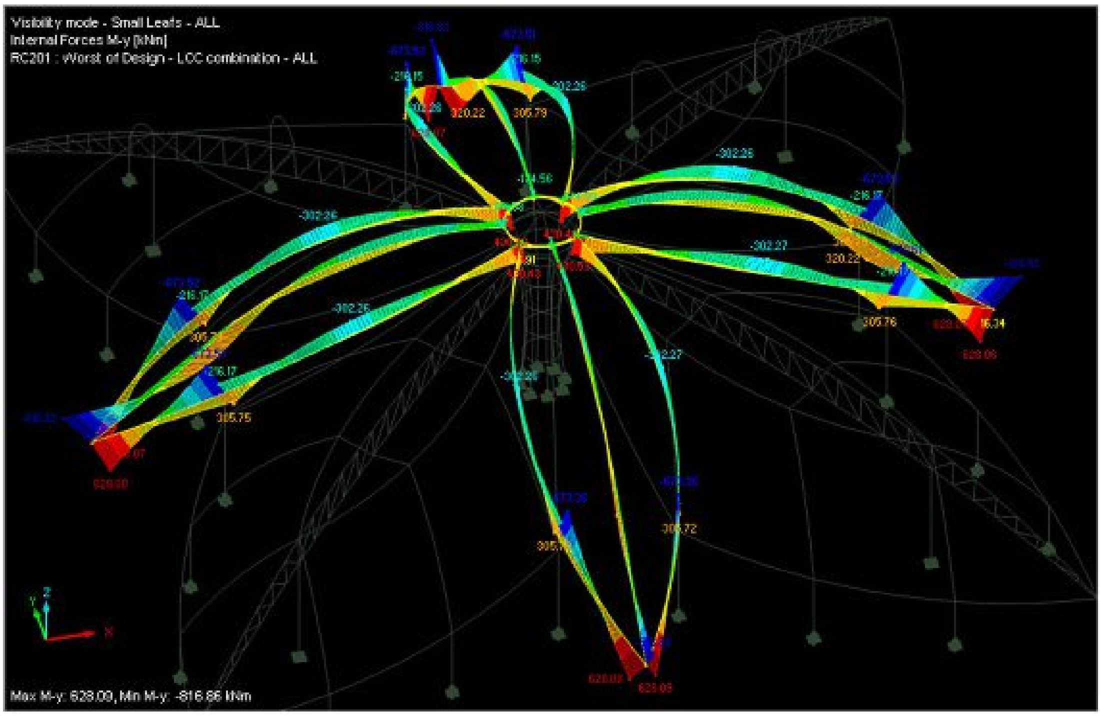

Figure 201: >The Sea Star< SEPARATE – Max. bending moment M_{yd}

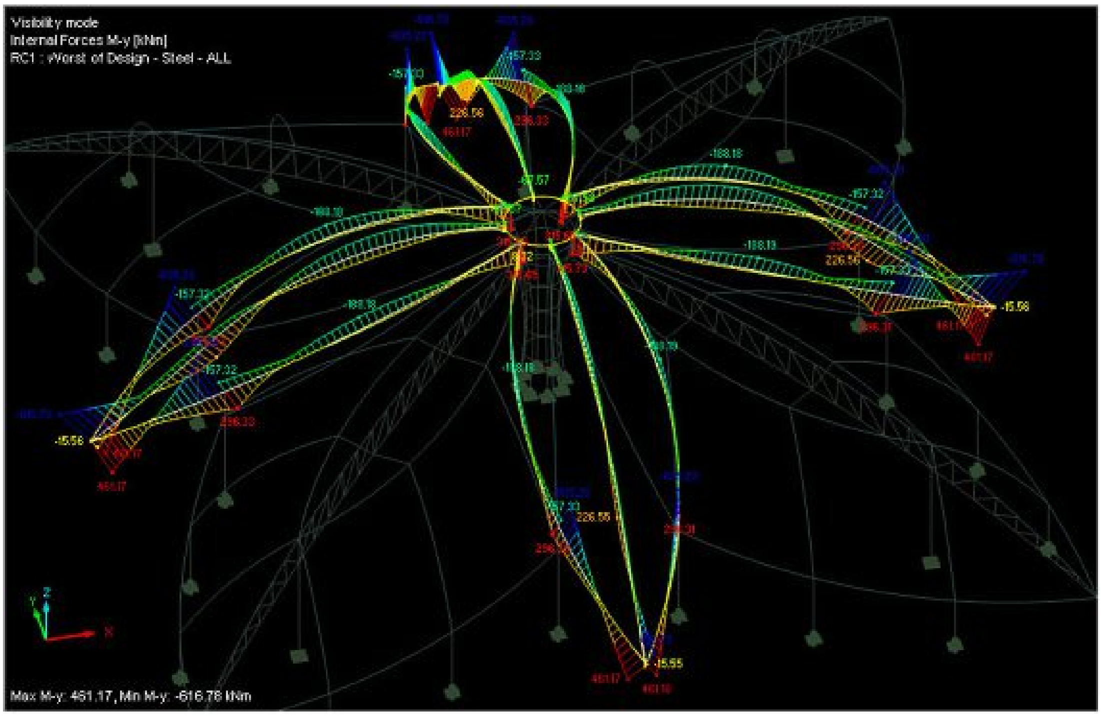

Figure 202: >The Sea Star< HYBRID – Max. bending moment M_{yd}

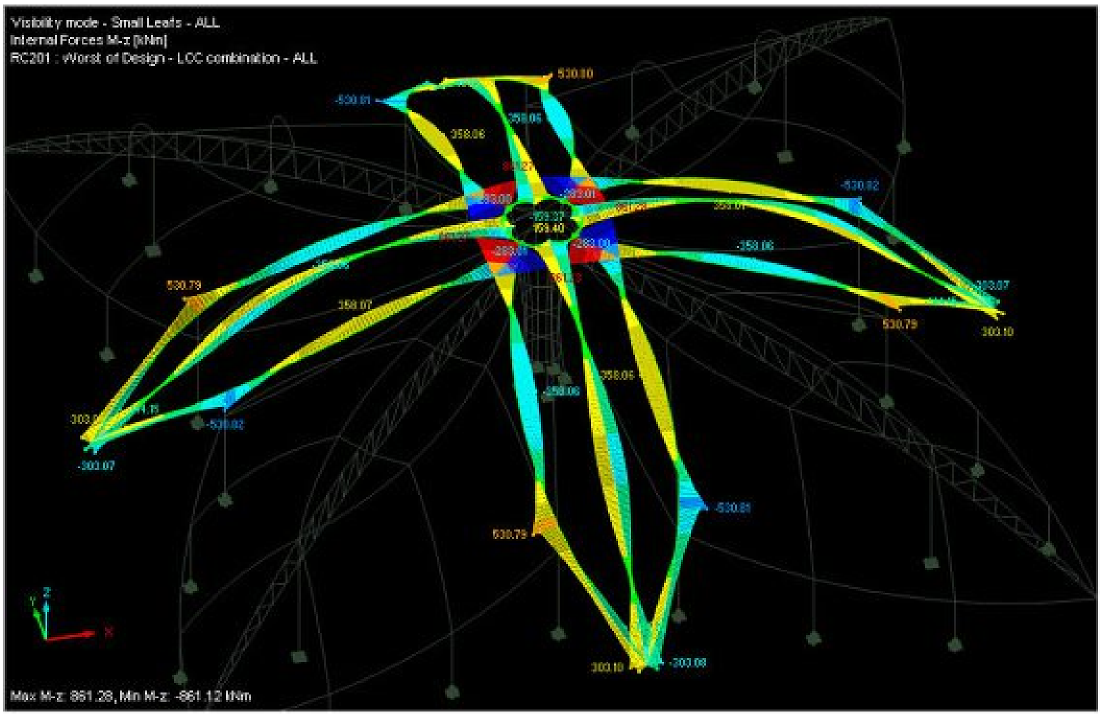

Figure 203: >The Sea Star< SEPARATE – Max. bending moment M_{zd}

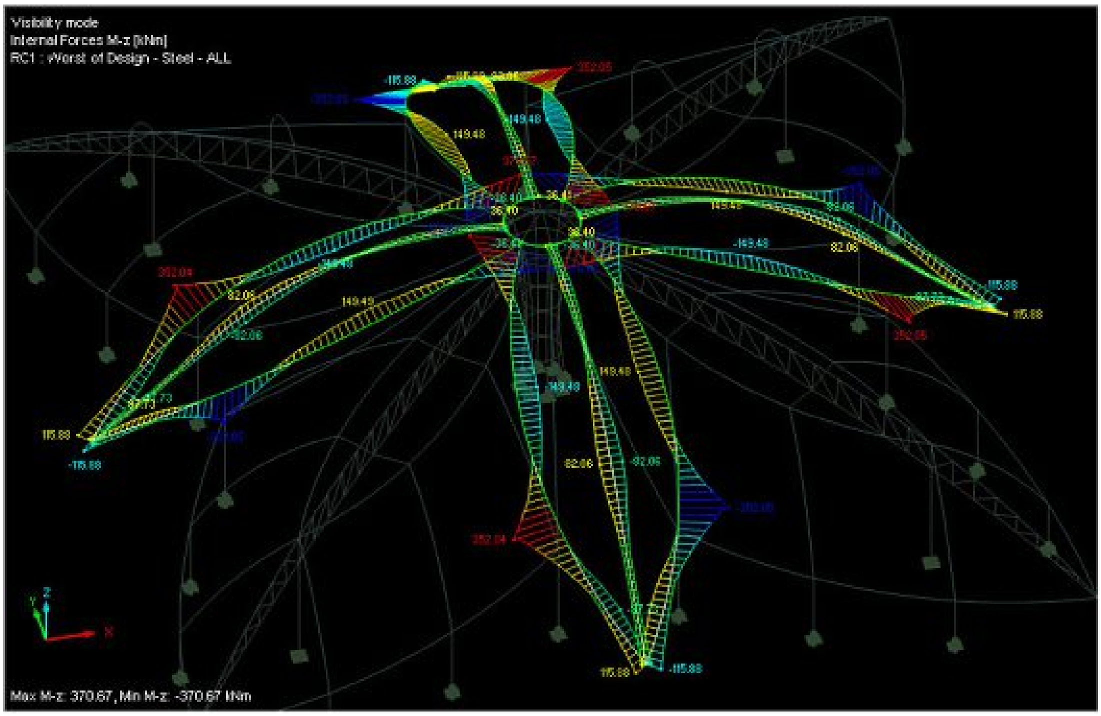

Figure 204: >The Sea Star< HYBRID – Max. bending moment M_{zd}

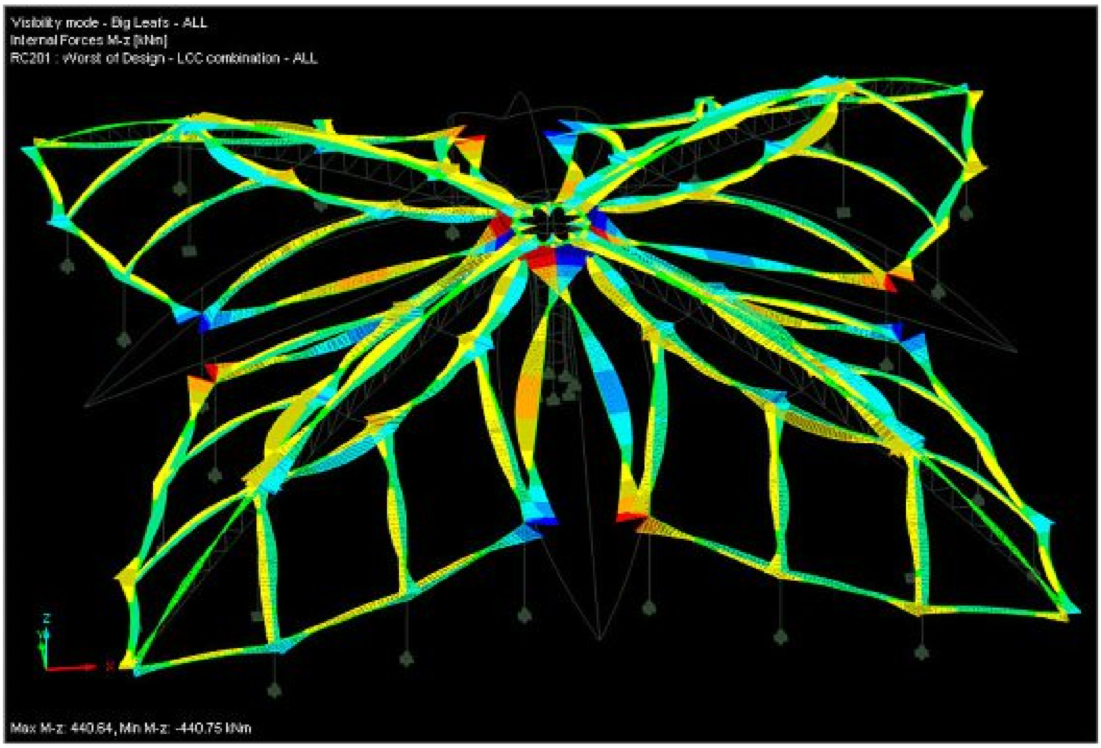

Figure 205: >The Sea Star< SEPARATE – Big leaves – Max. bending moment M_{zd}

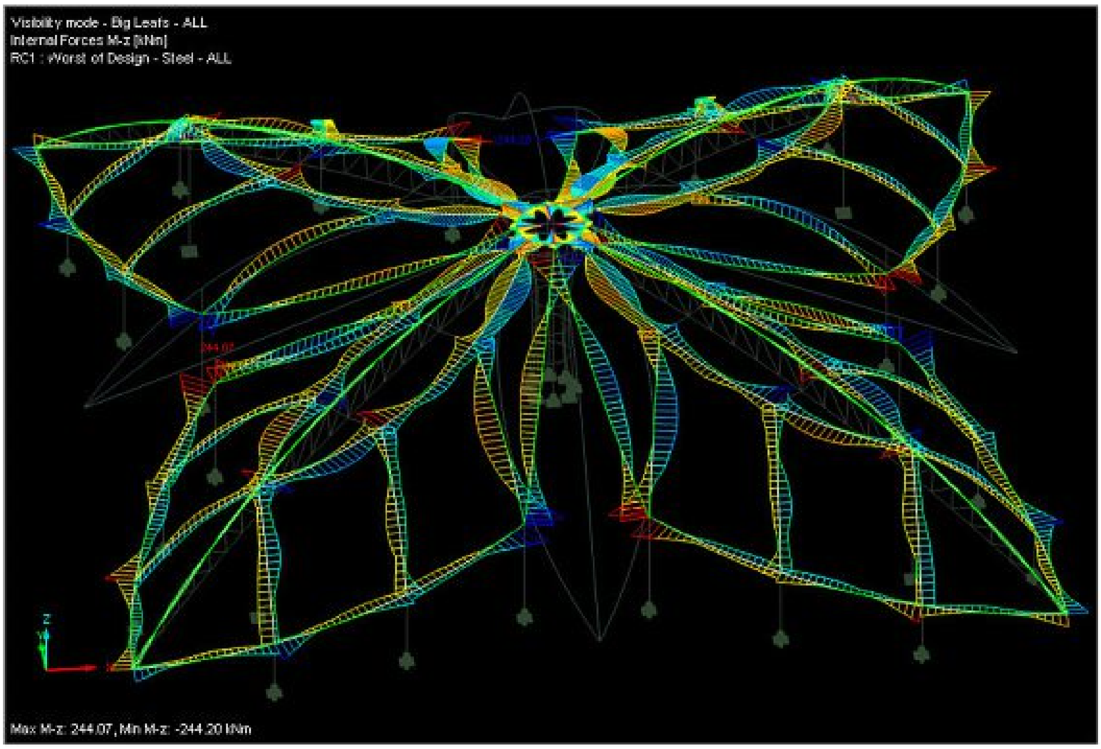

Figure 206: >The Sea Star< HYBRID – Big leaves – Max. bending moment M_{zd}

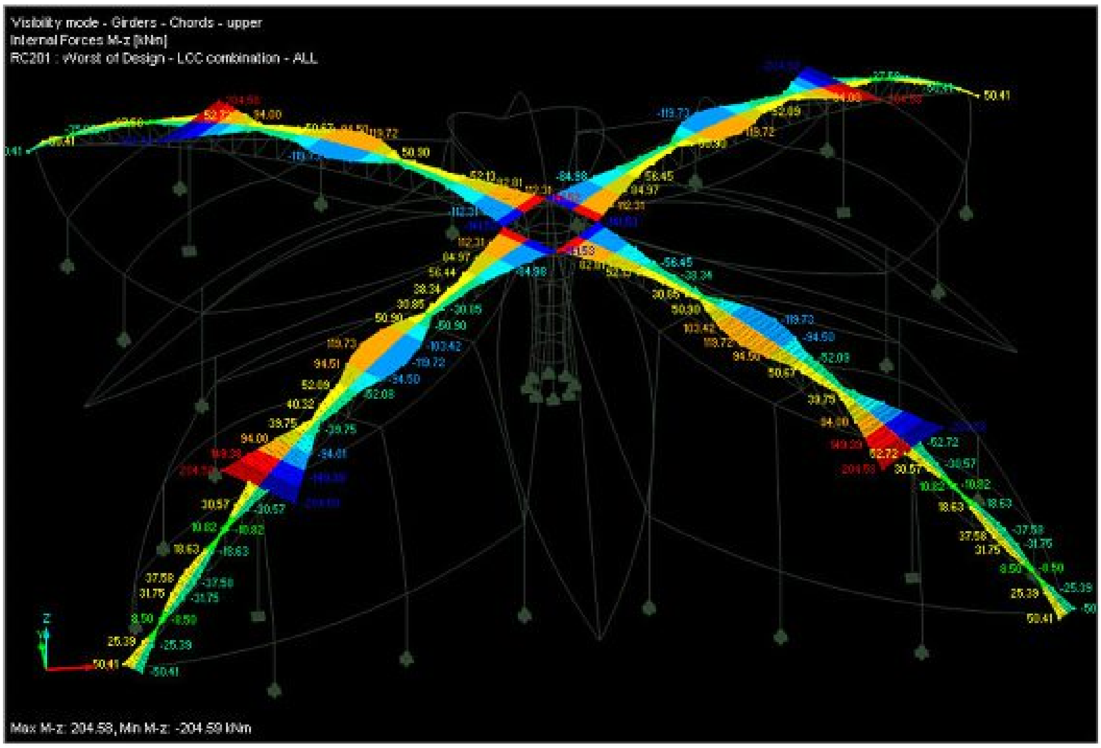

Figure 207: >The Sea Star< SEPARATE – Top chords trusses – Max. bending moment M_{zd}

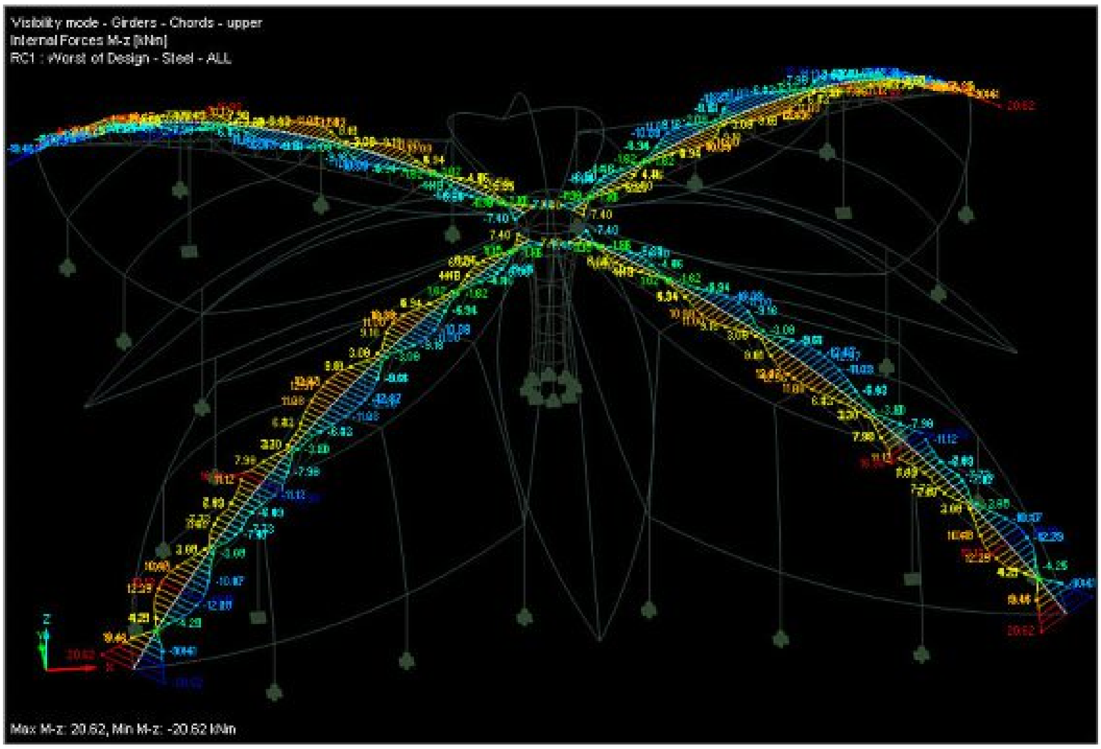

Figure 208: >The Sea Star< HYBRID – Top chords trusses – Max. bending moment M_{zd}

E.2.3 Deflections Structure Separate/Hybrid

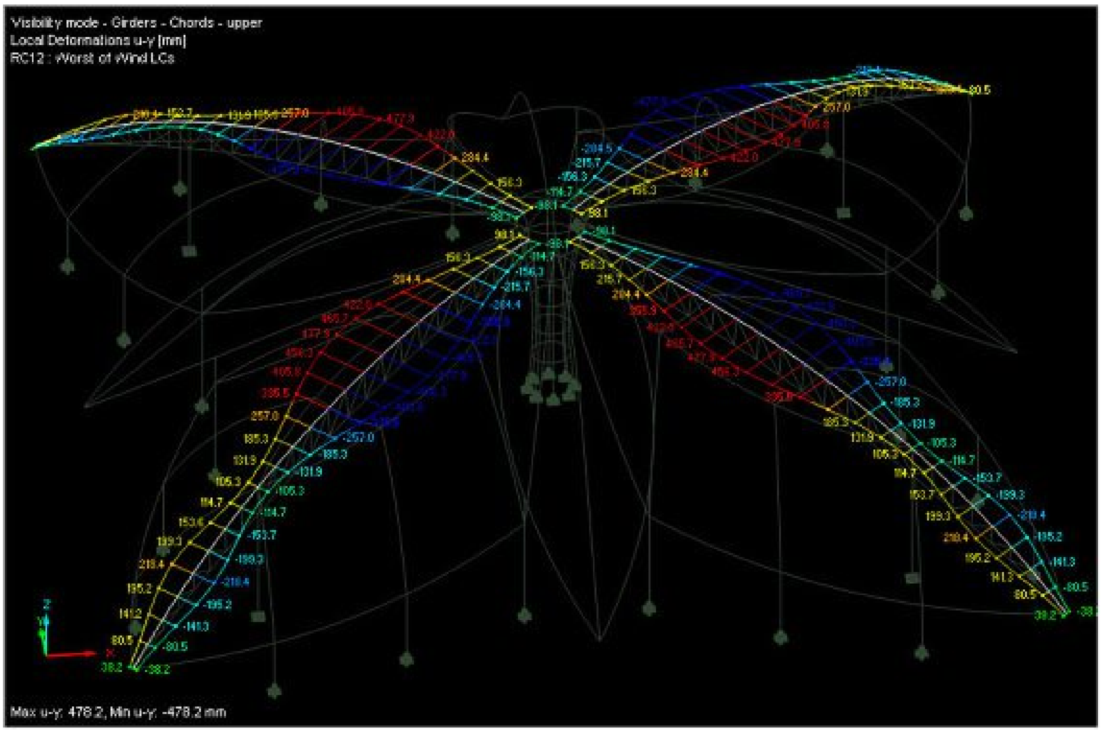

Figure 209: >The Sea Star< SEPARATE – Local deflection trusses top chord – Wind LCs

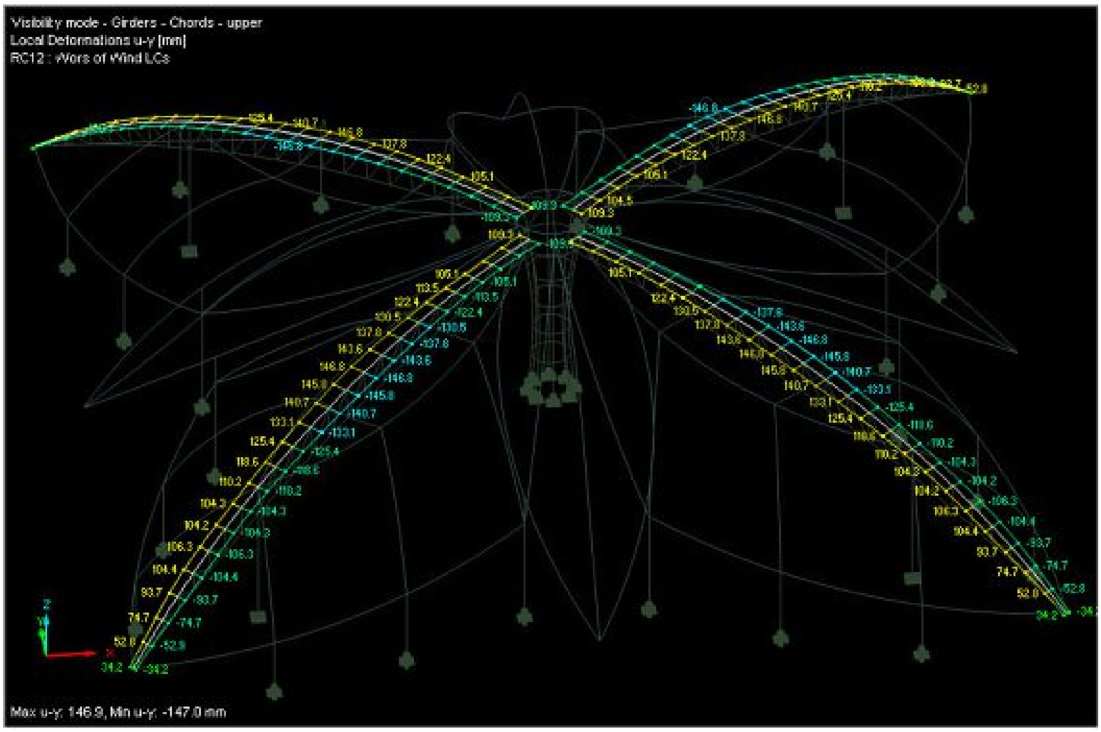

Figure 210: >The Sea Star< HYBRID – Local deflection trusses top chord – Wind LCs

E.2.4 Membrane Deflections Separate/Hybrid

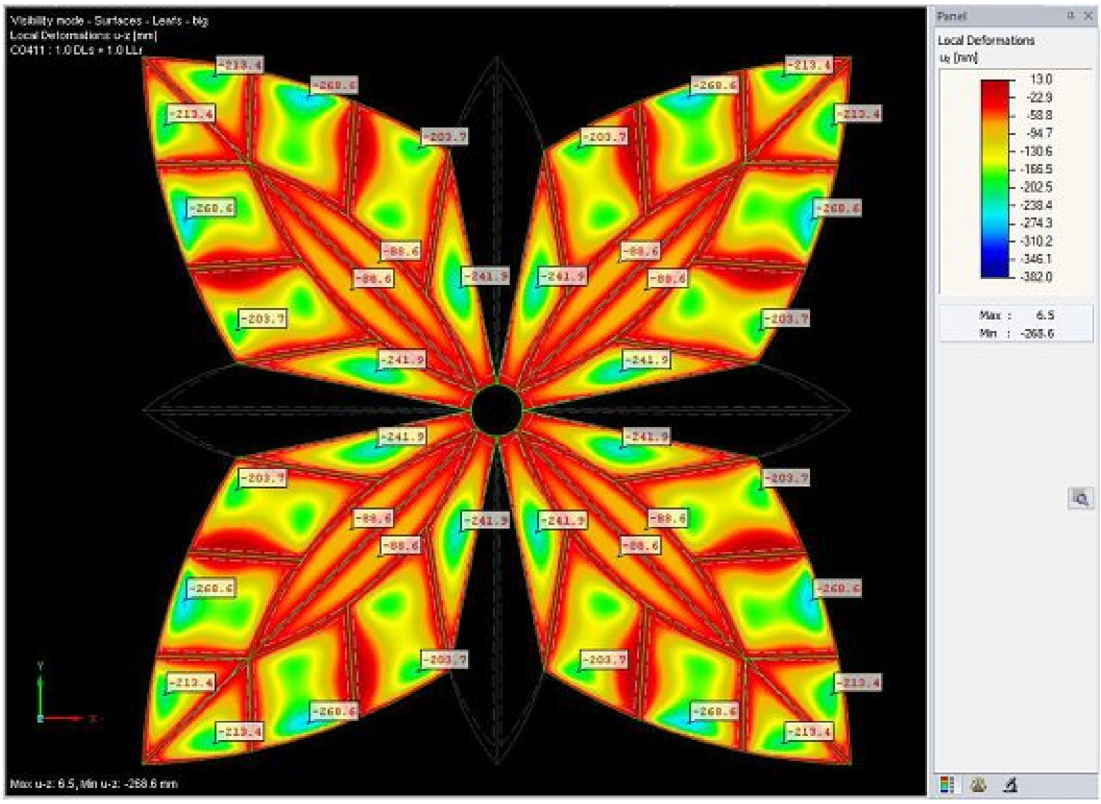

Figure 211: >The Sea Star< SEPARATE – Local deflections u_z' – LCC 411 DL+LL – Big leaves

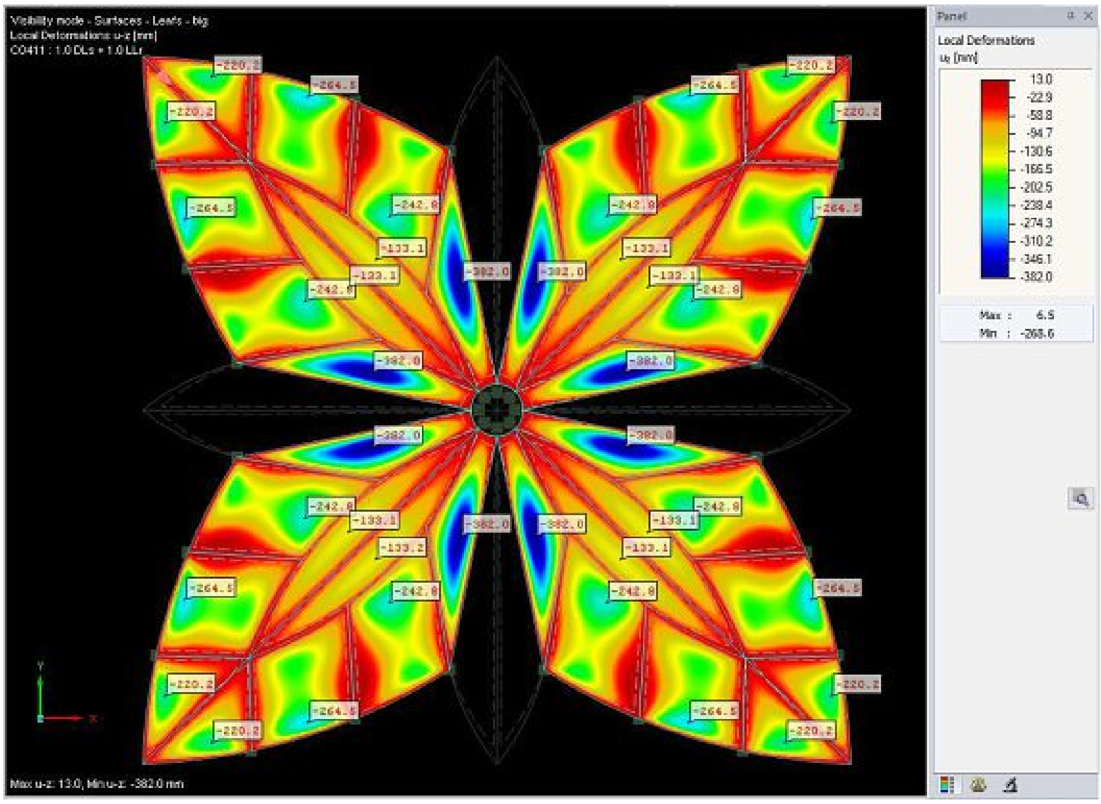

Figure 212: >The Sea Star< HYBRID – Local deflections u_z' – LCC 411 DL+LL – Big leaves

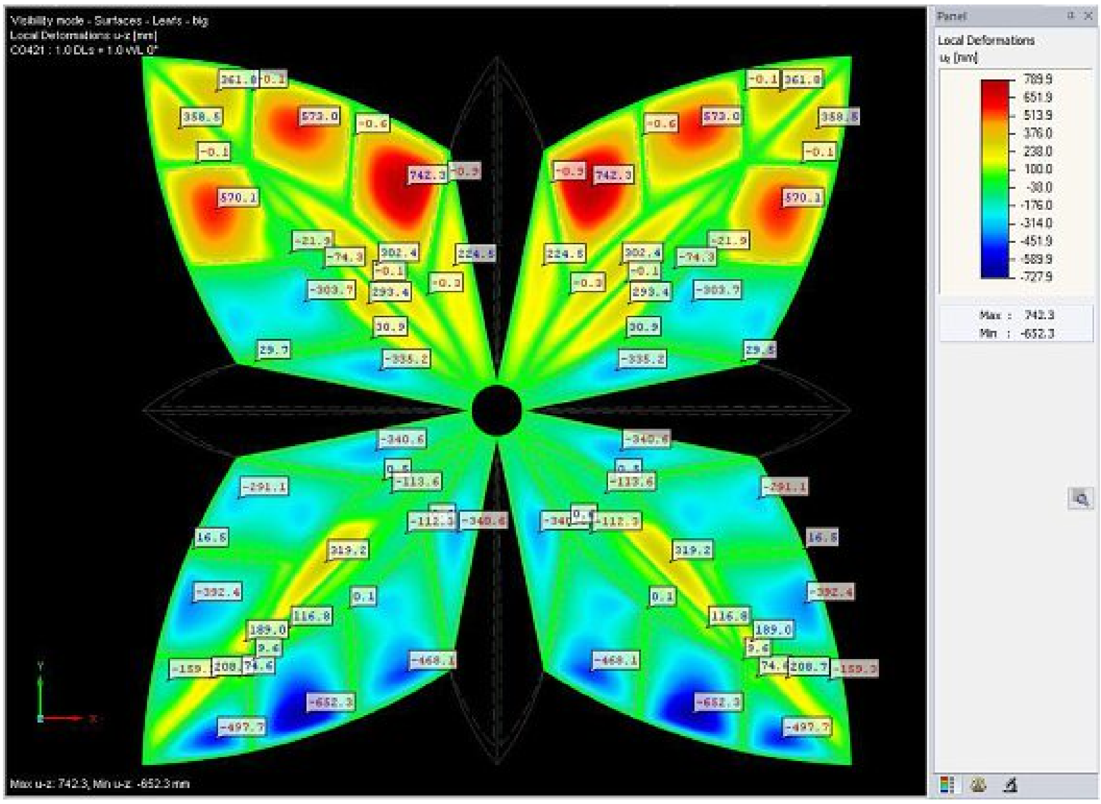

Figure 213: >The Sea Star< SEPARATE – Local deflections u_z' – LCC 421 DL+WL0° – Big leaves

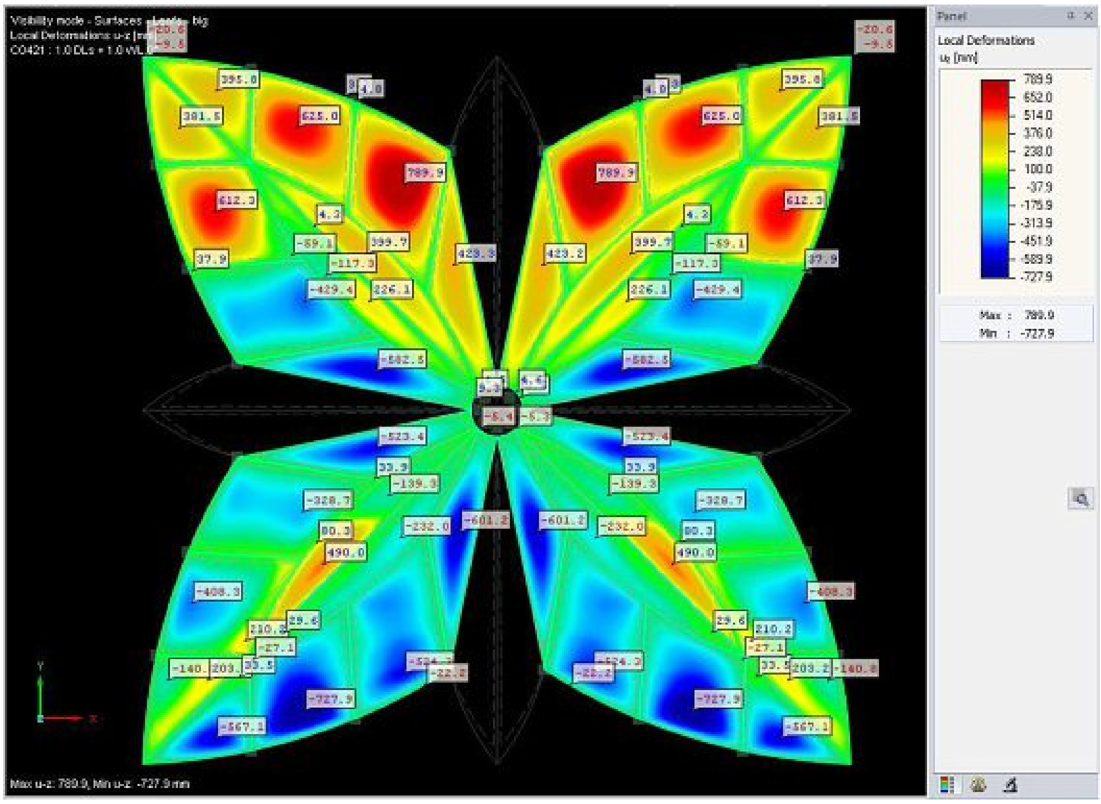

Figure 214: >The Sea Star< HYBRID – Local deflections u_z' – LCC 421 DL+WL0° – Big leaves

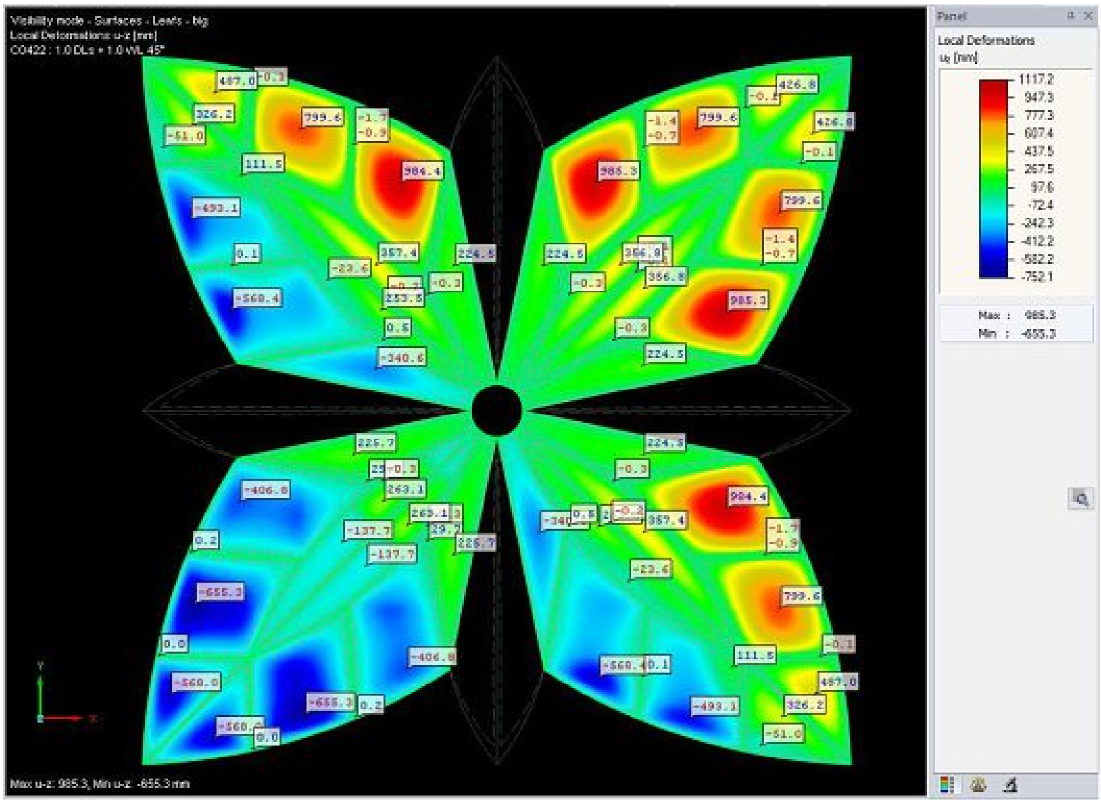

Figure 215: >The Sea Star< SEPARATE – Local deflections u_z' – LCC 422 DL+WL45° – Big leaves

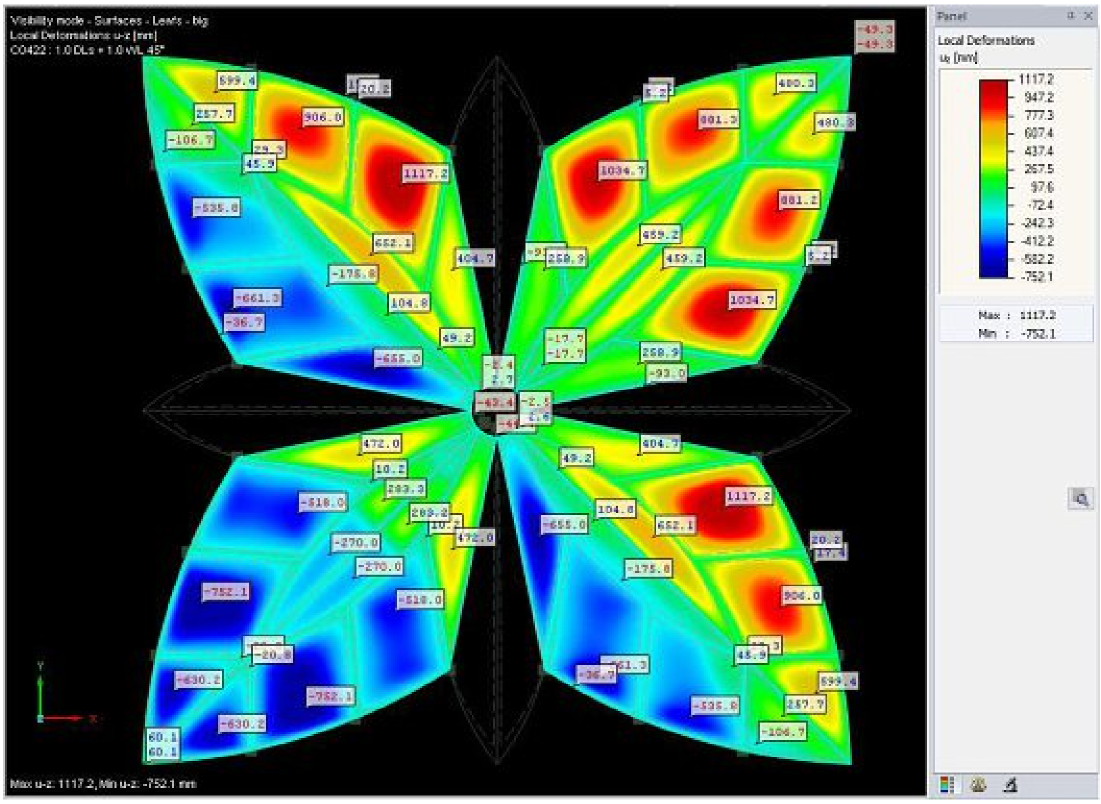

Figure 216: >The Sea Star< HYBRID – Local deflections u_z' – LCC 422 DL+WL45° – Big leaves

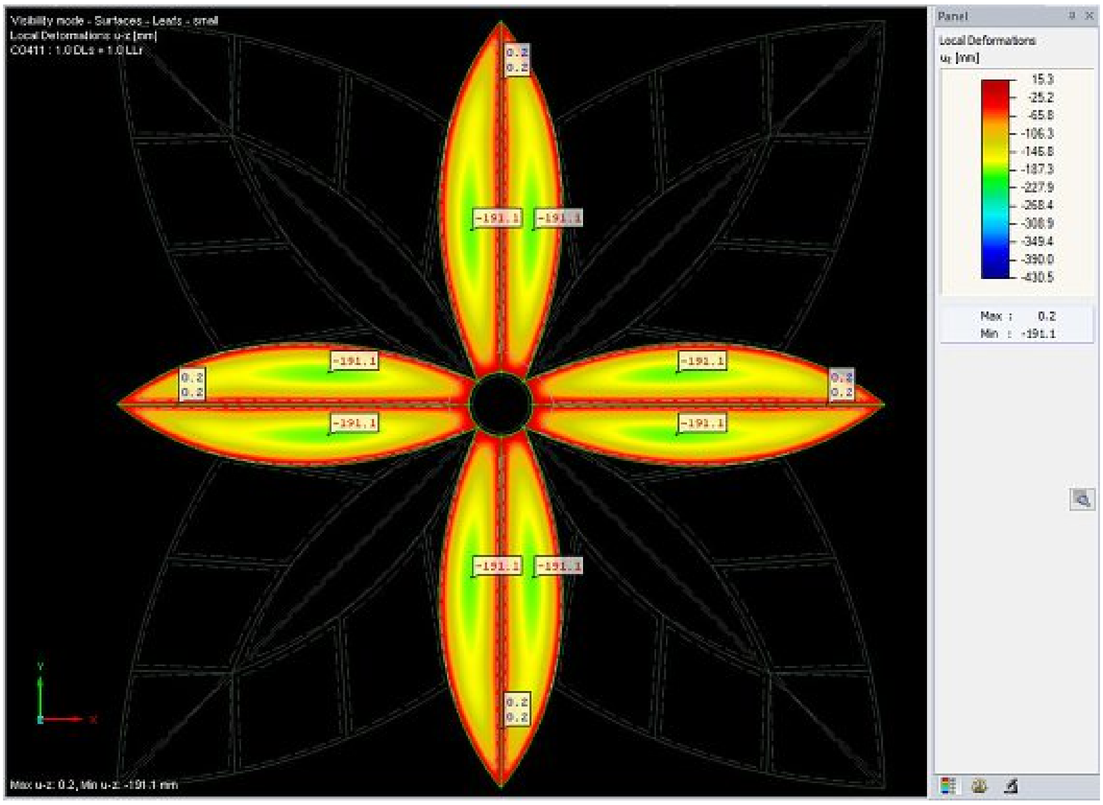

Figure 217: >The Sea Star< SEPARATE – Local deflections u_z' – LCC 411 DL+LL – Small leaves

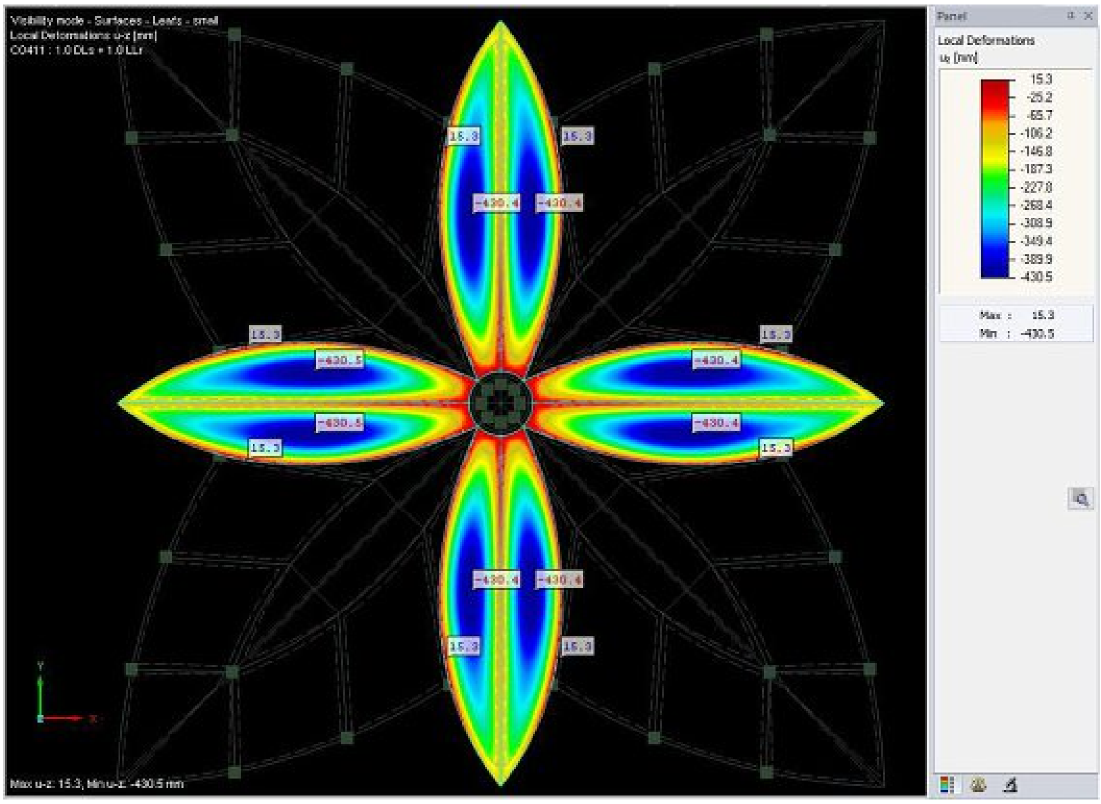

Figure 218: >The Sea Star< HYBRID – Local deflections u_z' – LCC 411 DL+LL – Small leaves

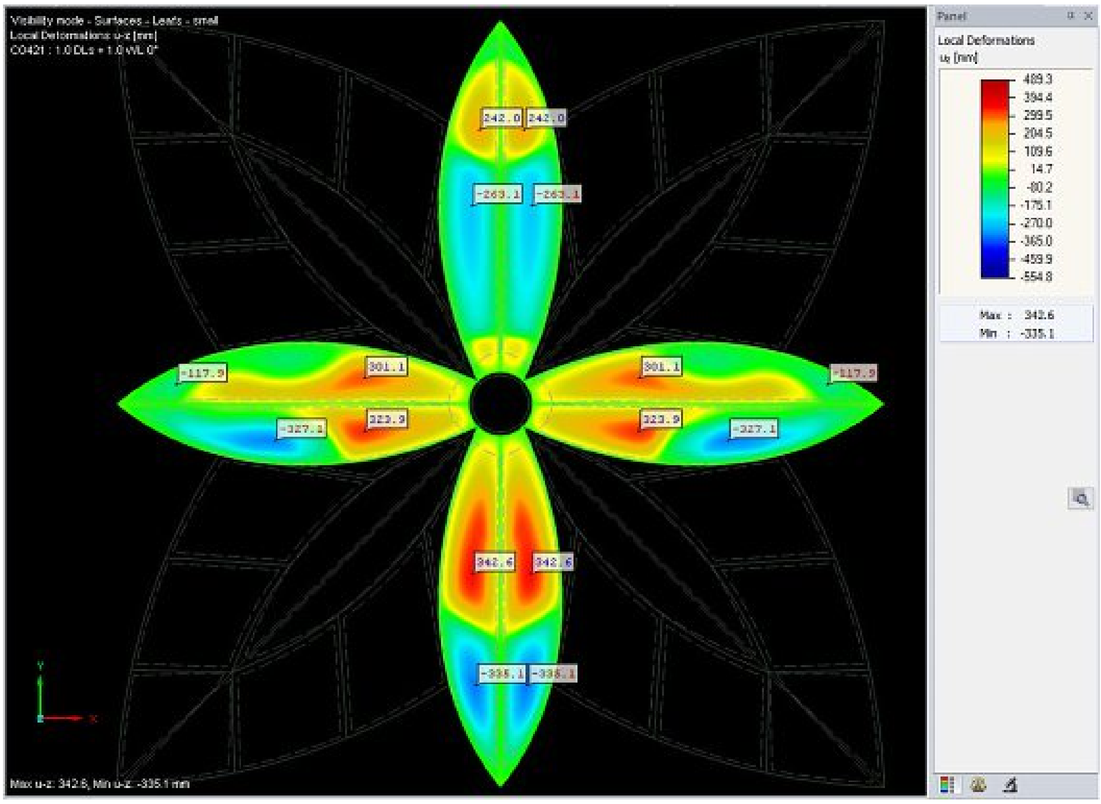

Figure 219: >The Sea Star< SEPARATE – Local deflections u_z' – LCC 421 DL+WL0° – Small leaves

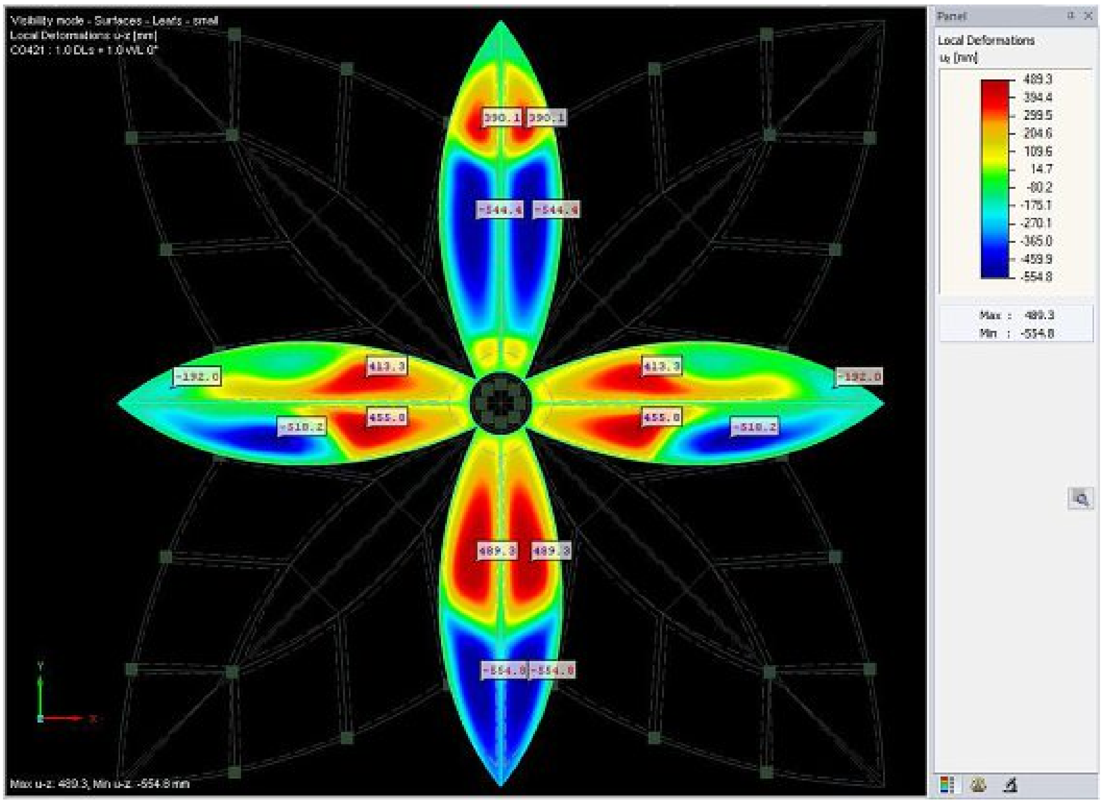

Figure 220: >The Sea Star< HYBRID – Local deflections u_z' – LCC 421 DL+WL0° – Small leaves

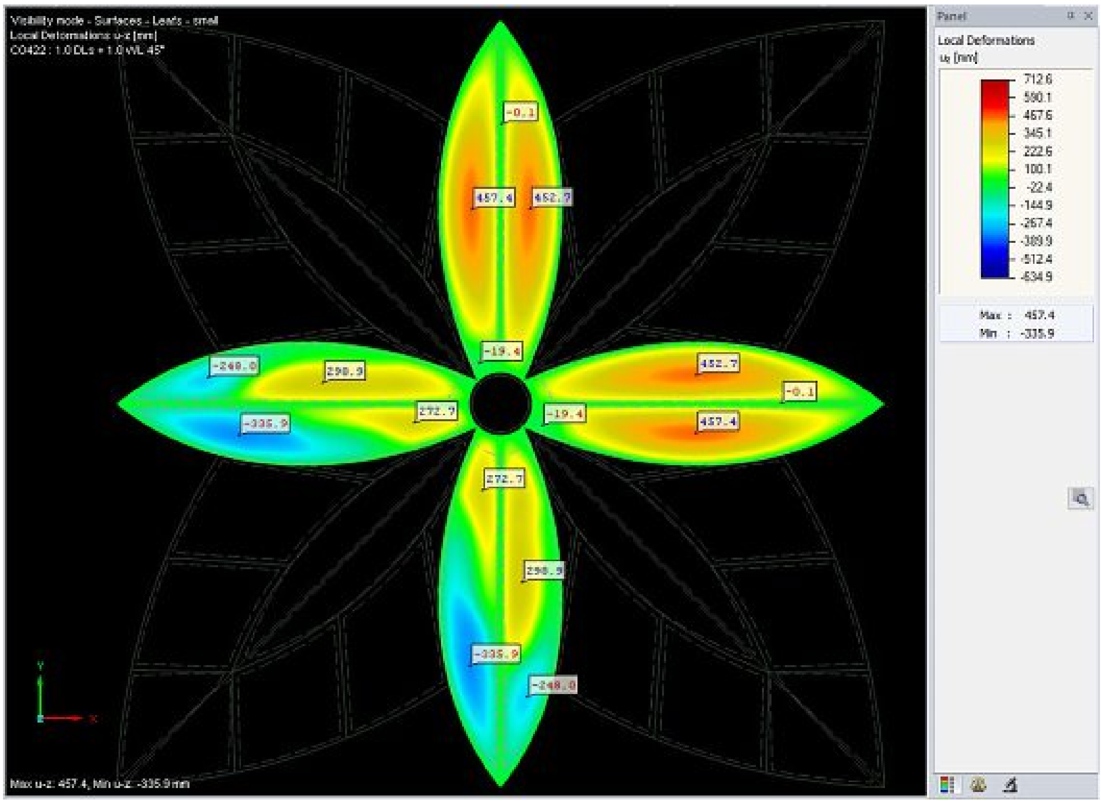

Figure 221: >The Sea Star< SEPARATE – Local deflections u_z' – LCC 422 DL+WL45° – Small leaves

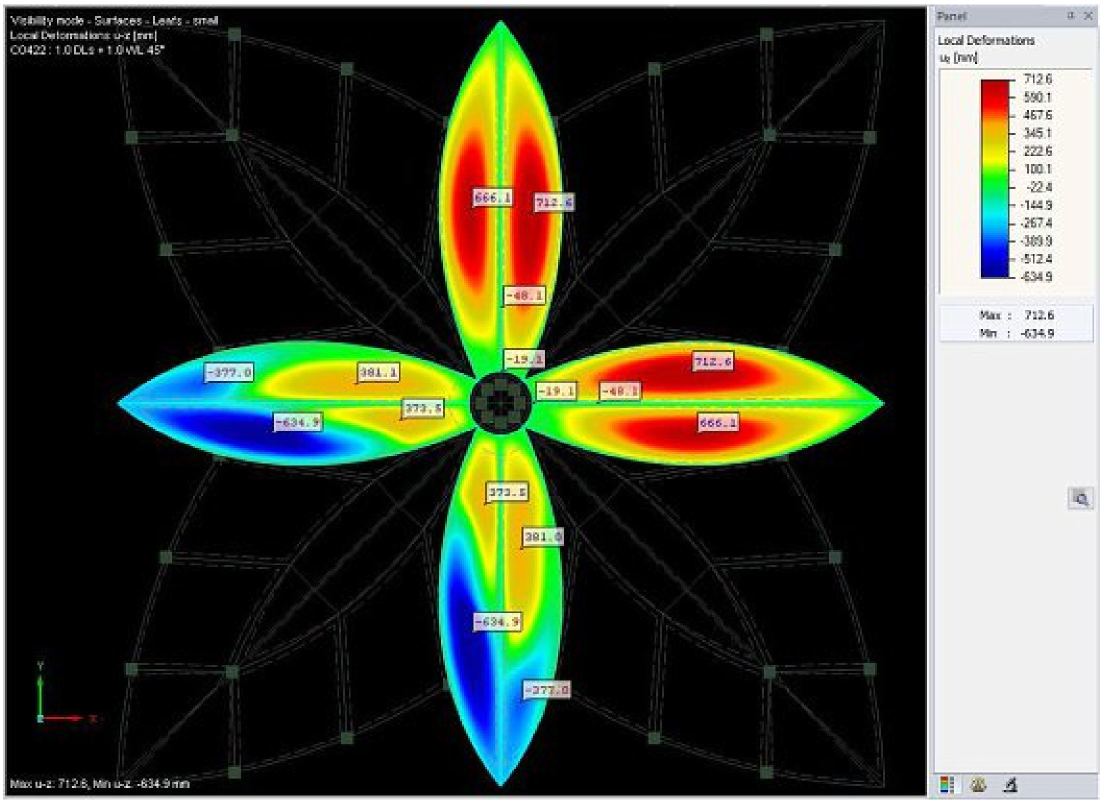

Figure 222: >The Sea Star< HYBRID – Local deflections u_z' – LCC 422 DL+WL45° – Small leaves

E.2.5 Membrane Forces Separate/Hybrid

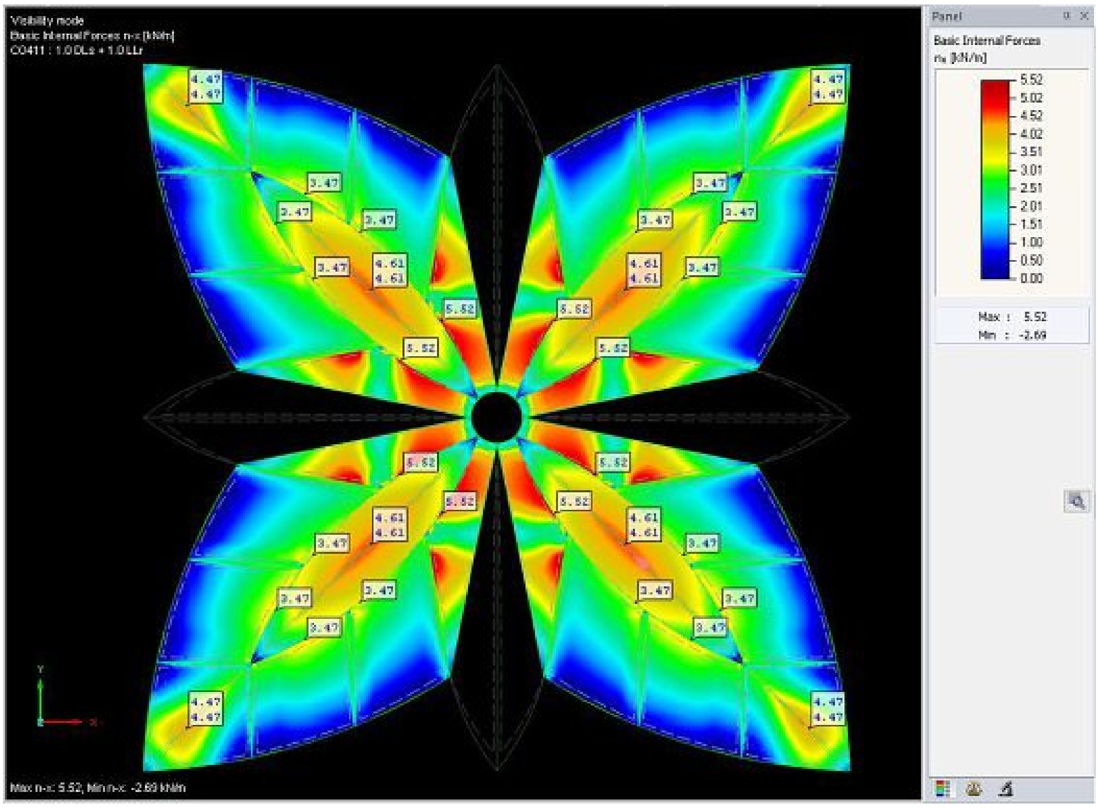

Figure 223: >The Sea Star< SEPARATE – Membrane forces n_x – LCC 411 DL+LL – Small leaves

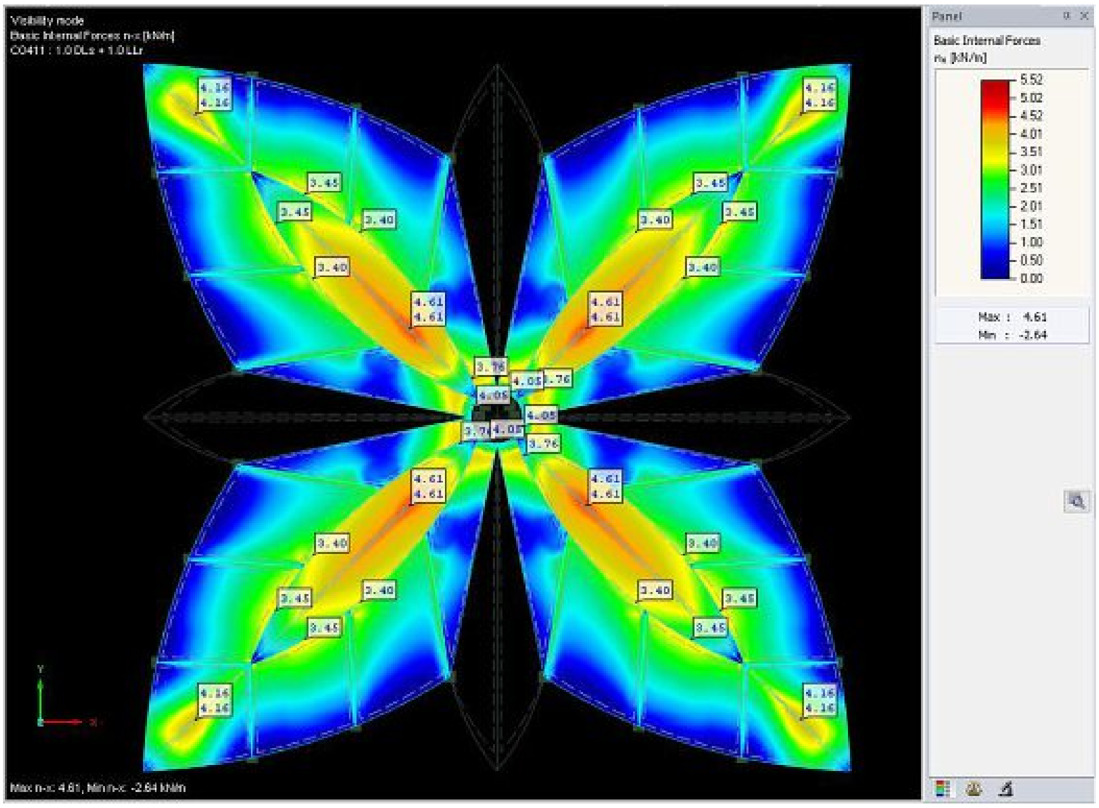

Figure 224: >The Sea Star< HYBRID – Membrane forces n_x – LCC 411 DL+LL – Small leaves

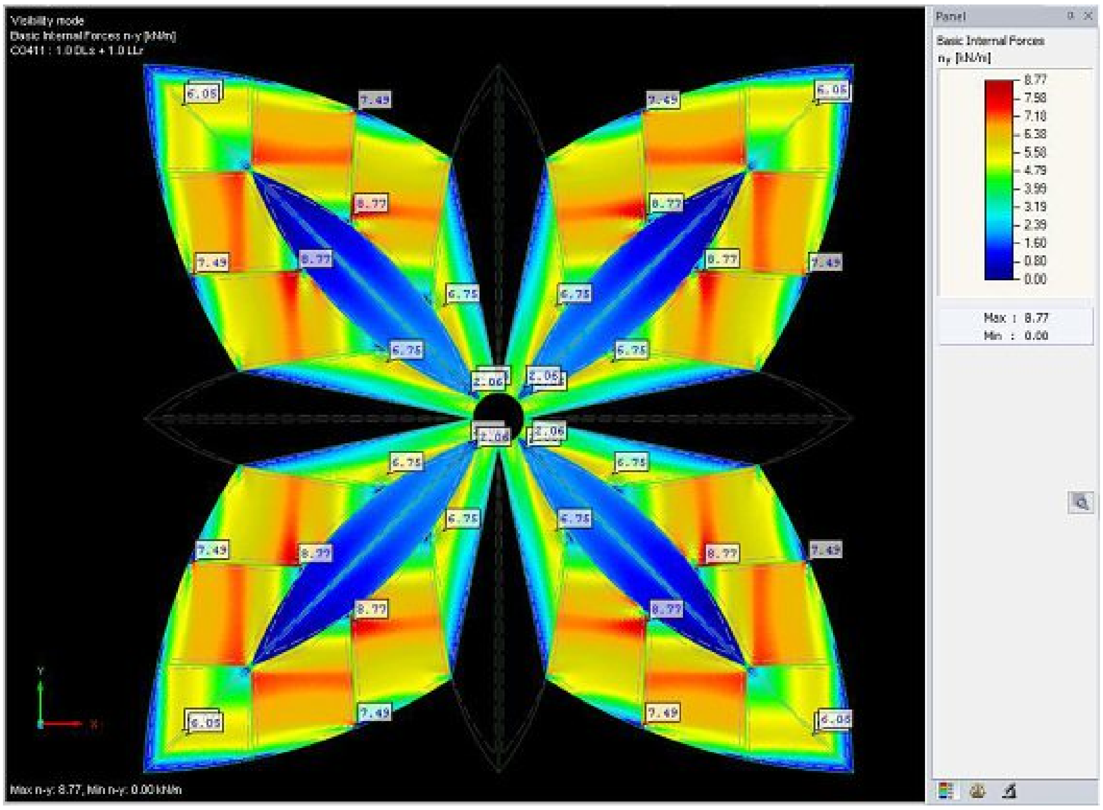

Figure 225: >The Sea Star< SEPARATE – Membrane forces n_y – LCC 411 DL+LL – Big leaves

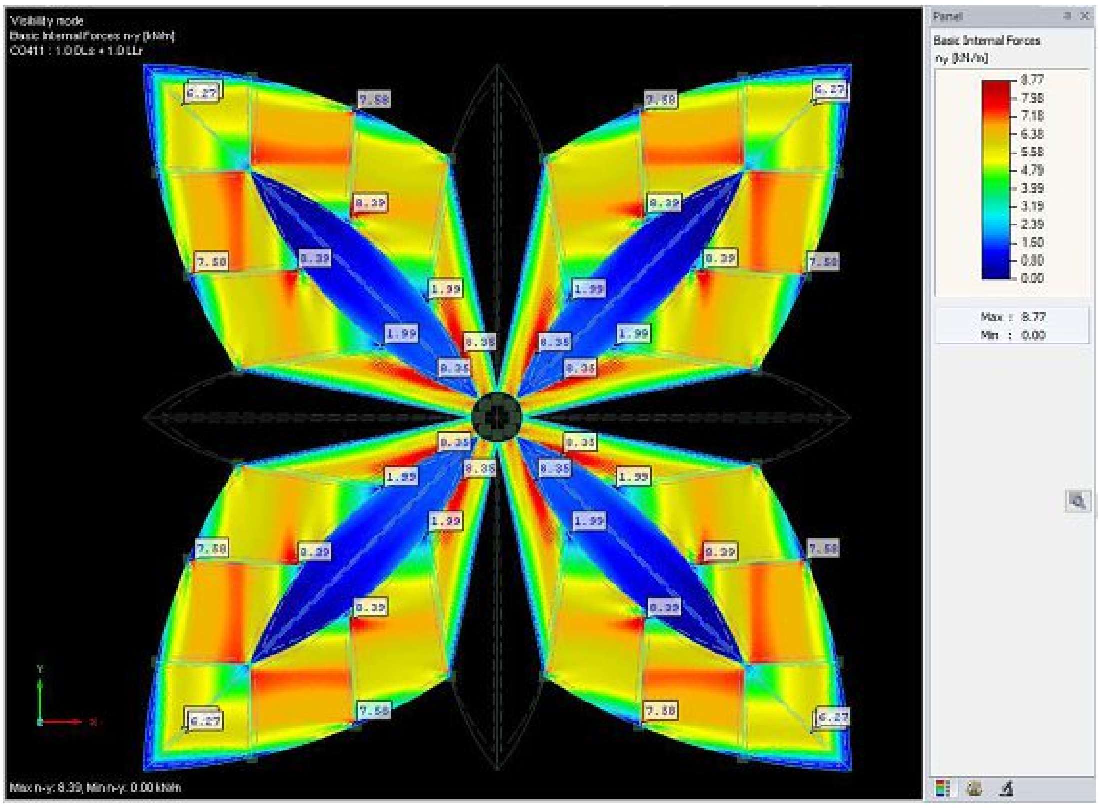

Figure 226: >The Sea Star< HYBRID – Membrane forces n_y – LCC 411 DL+LL – Big leaves

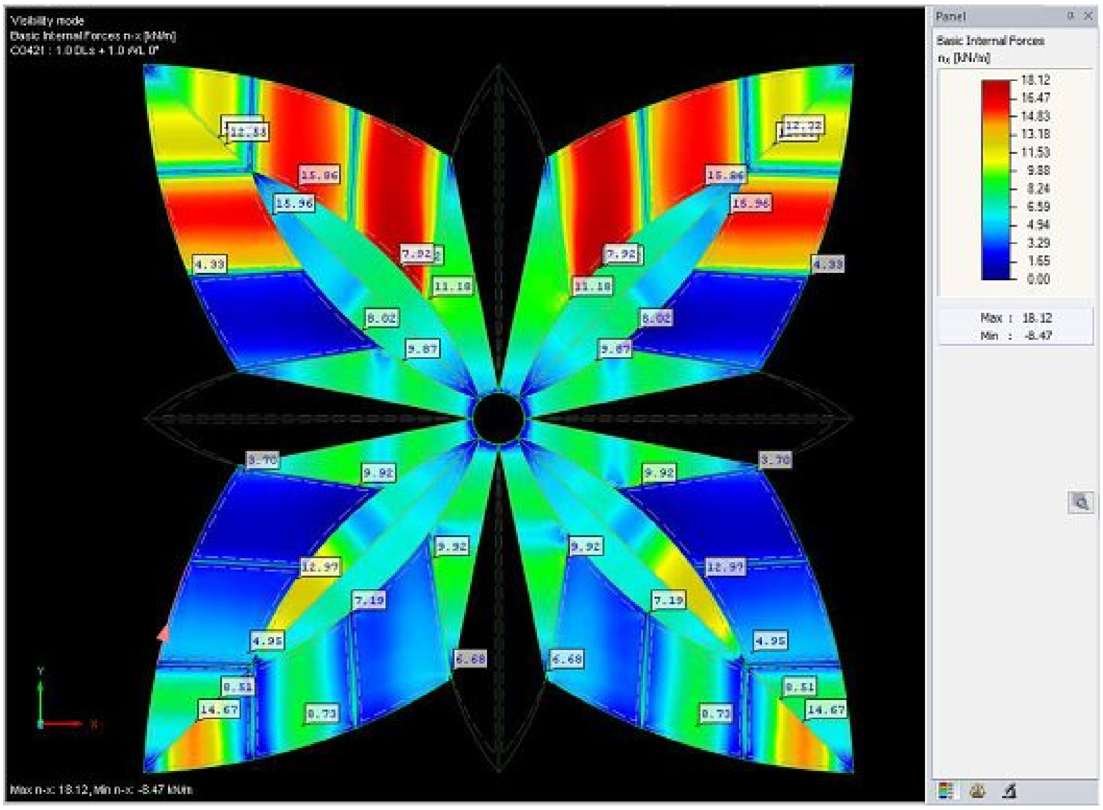

Figure 227: >The Sea Star< SEPARATE – Membrane forces n_x – LCC 421 DL+WL0° – Big leaves

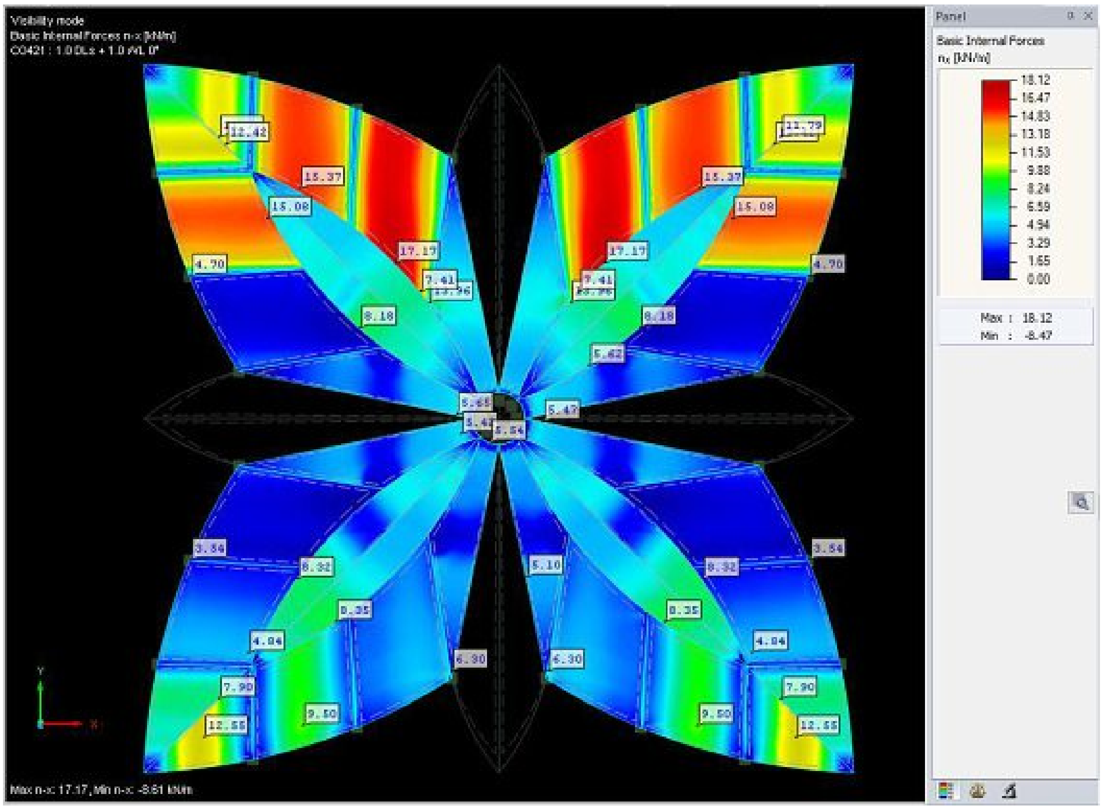

Figure 228: >The Sea Star< HYBRID – Membrane forces n_x – LCC 421 DL+WL0° – Big leaves

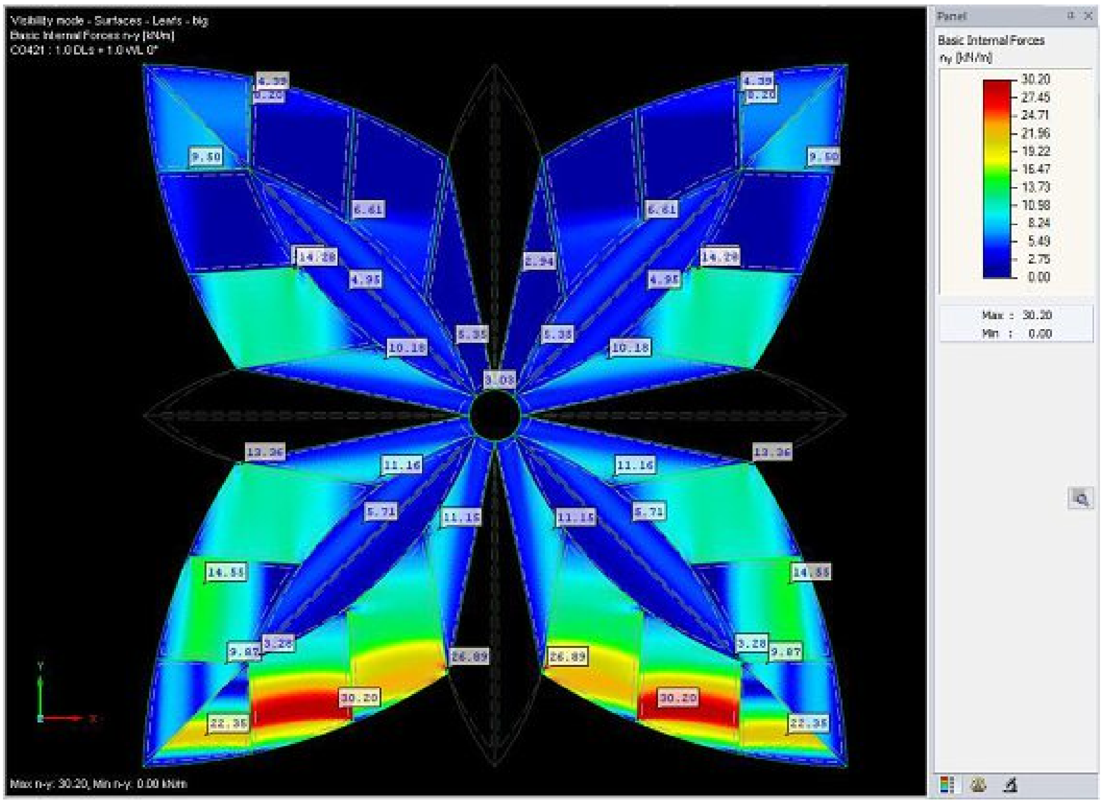

Figure 229: >The Sea Star< SEPARATE – Membrane forces n_y – LCC 421 DL+WL0° – Big leaves

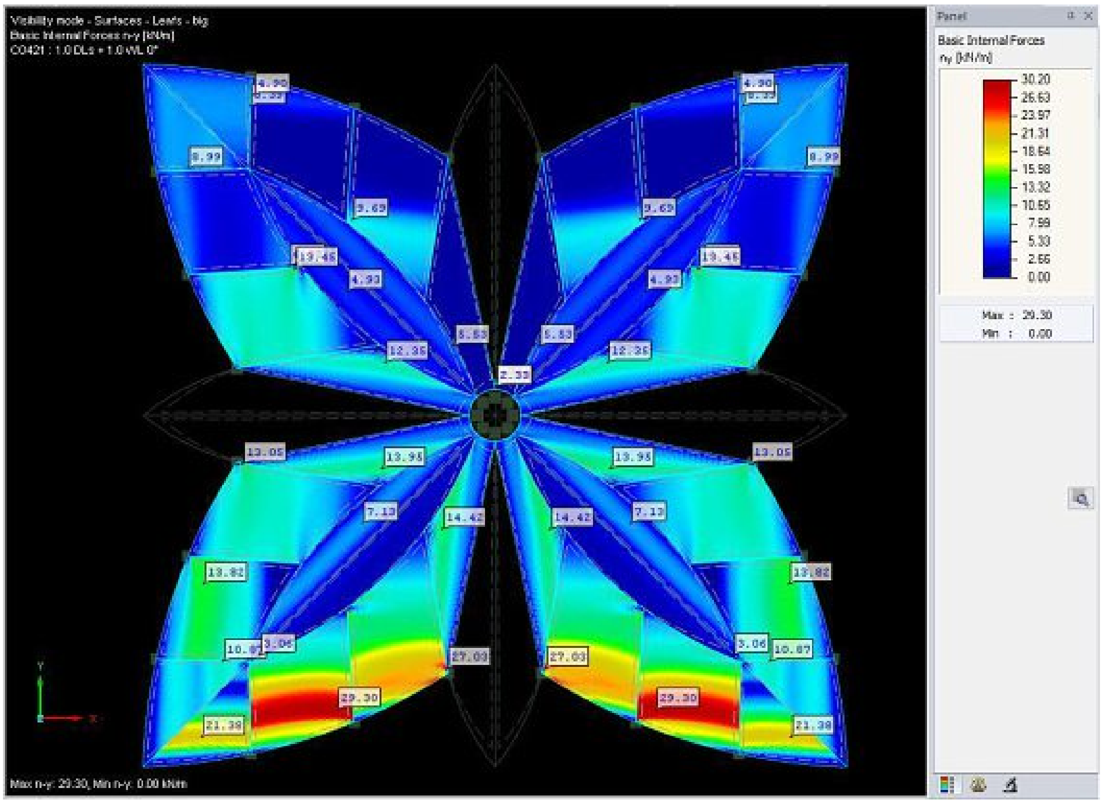

Figure 230: >The Sea Star< HYBRID – Membrane forces n_y – LCC 421 DL+WL0° – Big leaves

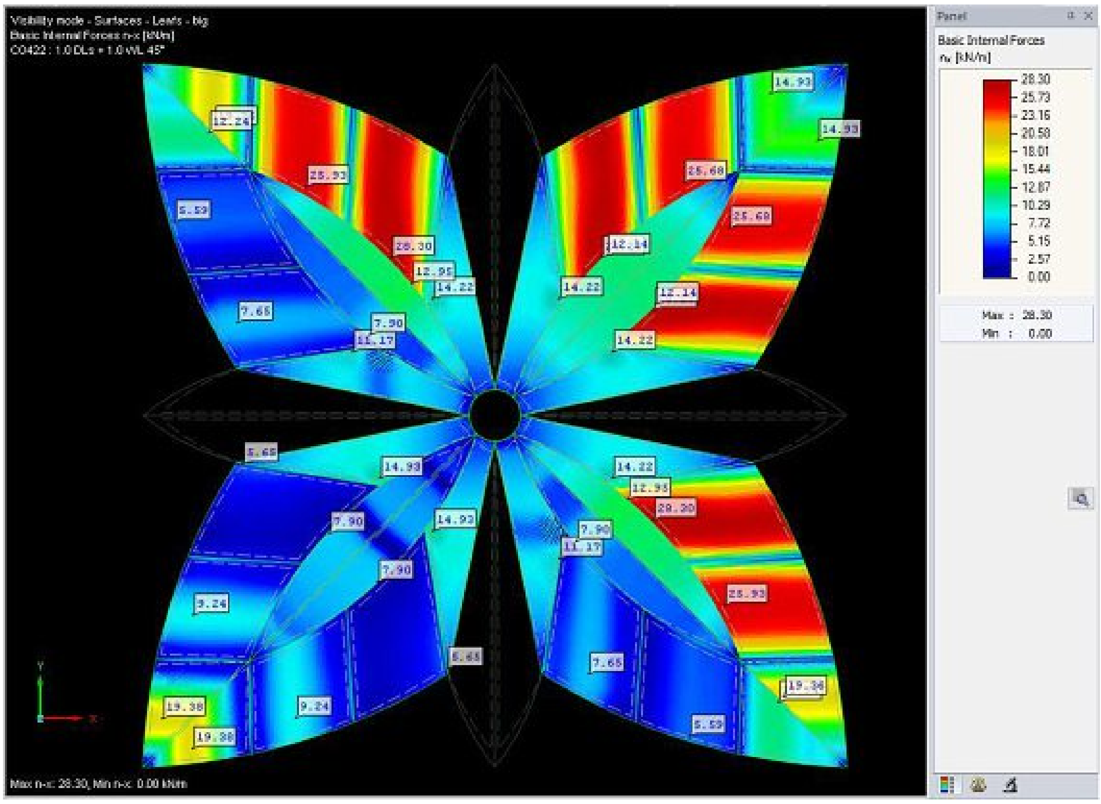

Figure 231: >The Sea Star< SEPARATE – Membrane forces n_x – LCC 422 DL+WL45° – Big leaves

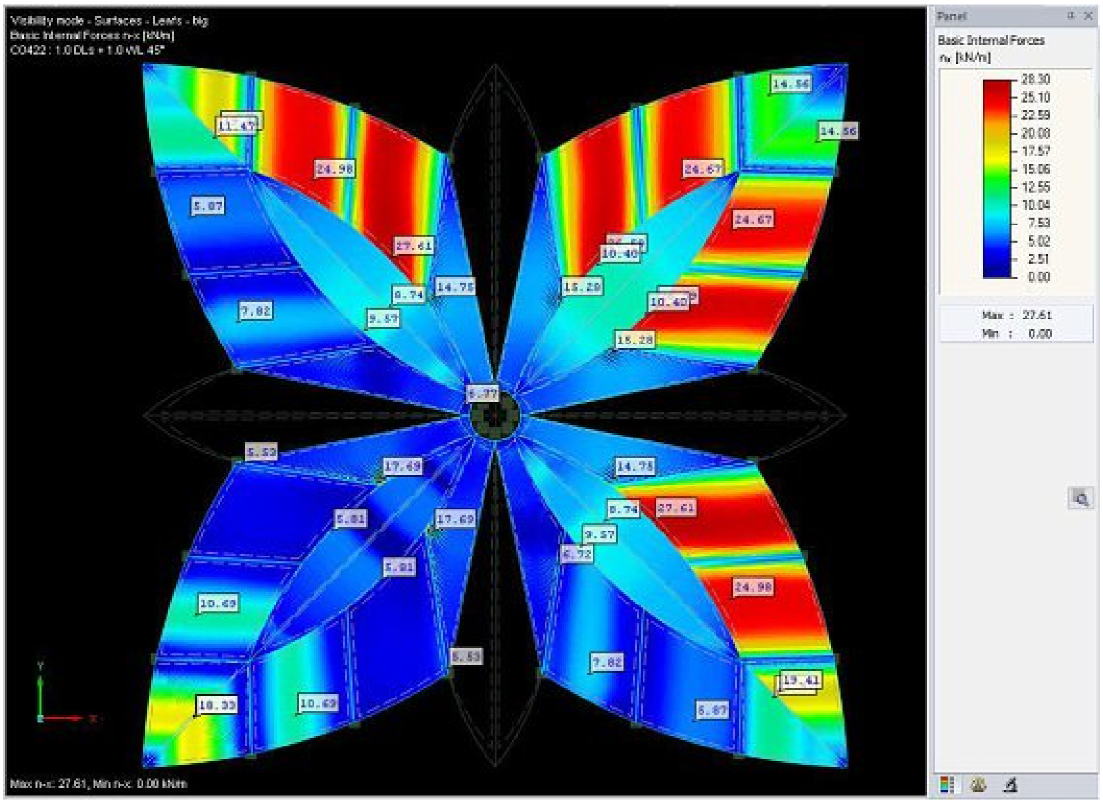

Figure 232: >The Sea Star< HYBRID – Membrane forces n_x – LCC 422 DL+WL45° – Big leaves

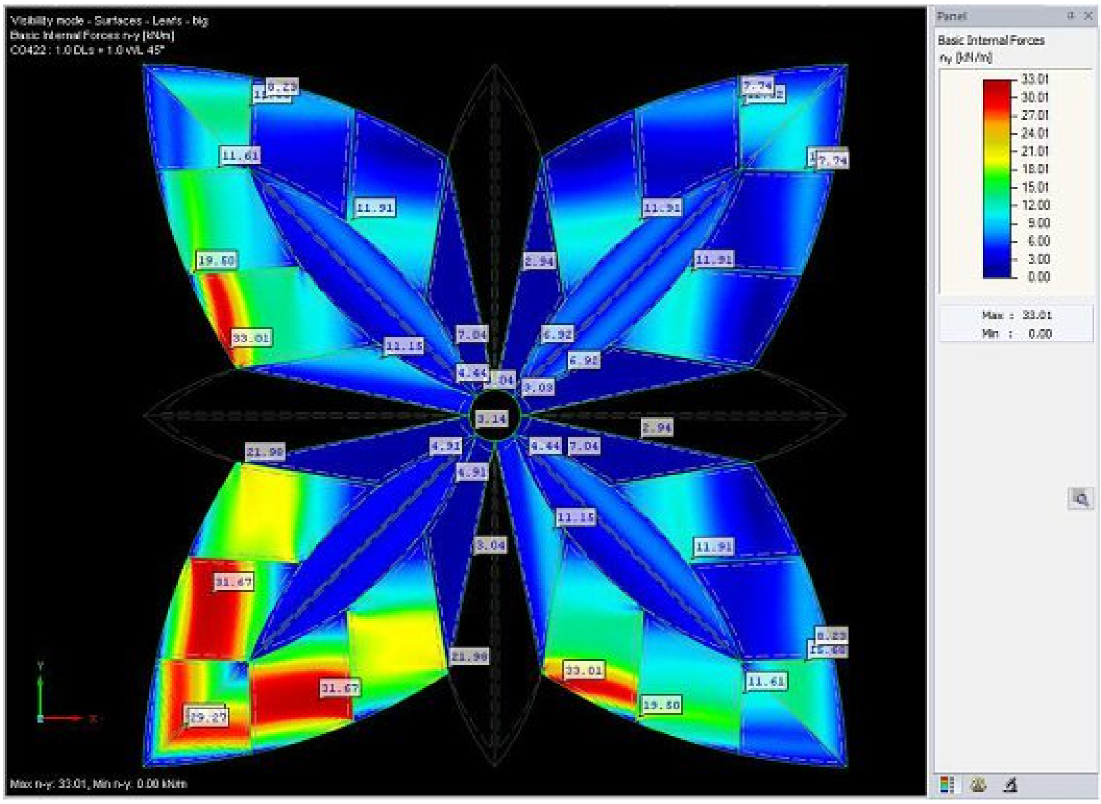

Figure 233: >The Sea Star< SEPARATE – Membrane forces n_y – LCC 422 DL+WL45° – Big leaves

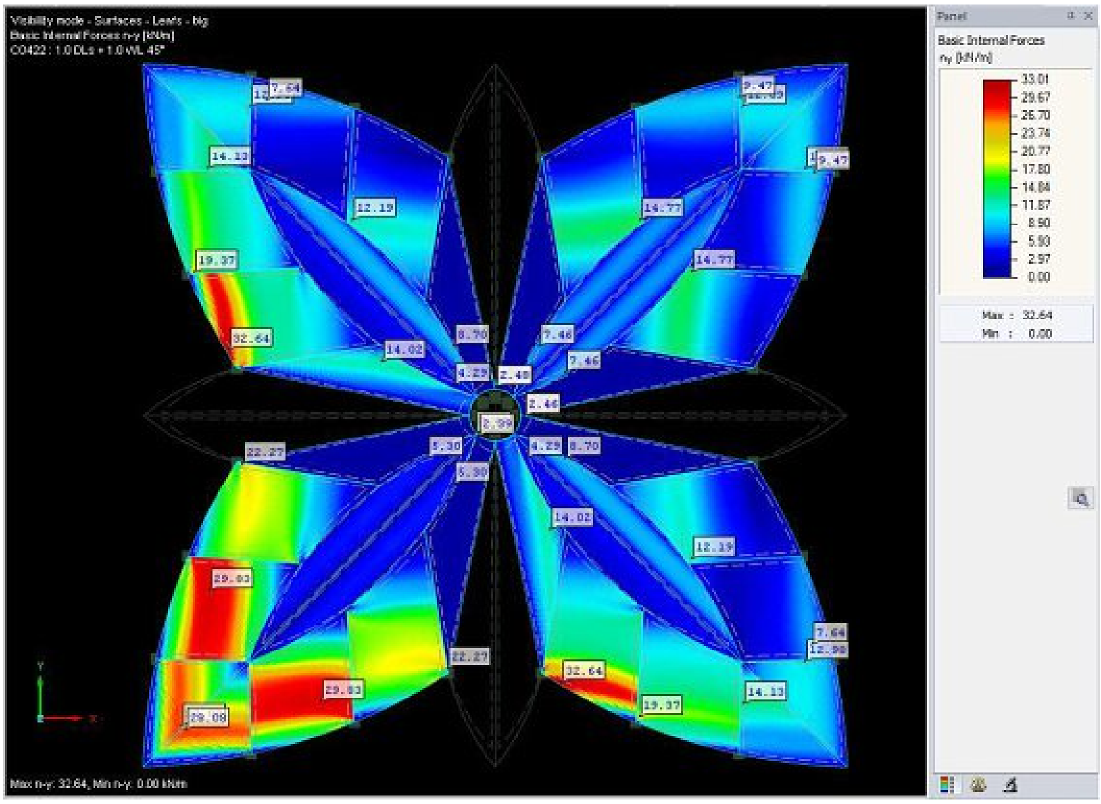

Figure 234: >The Sea Star< HYBRID – Membrane forces n_y – LCC 422 DL+WL45° – Big leaves

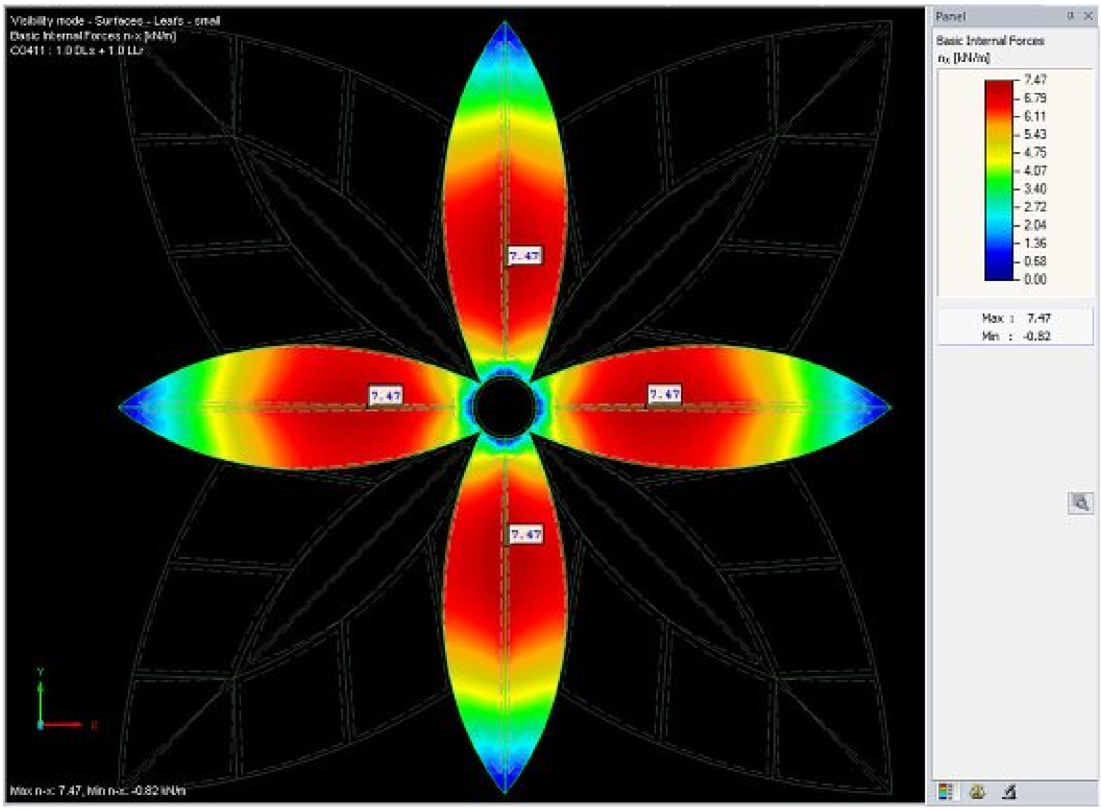

Figure 235: >The Sea Star< SEPARATE – Membrane forces n_x – LCC 411 DL+LL – Small leaves

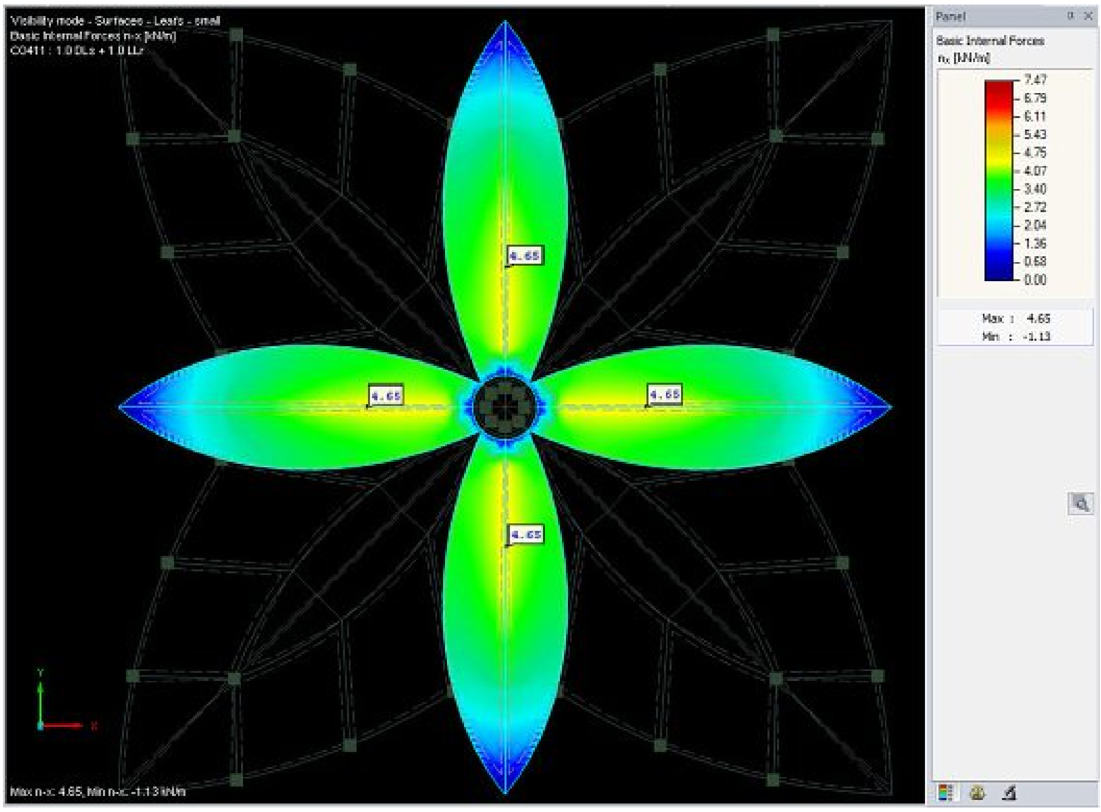

Figure 236: >The Sea Star< HYBRID – Membrane forces n_x – LCC 411 DL+LL – Small leaves

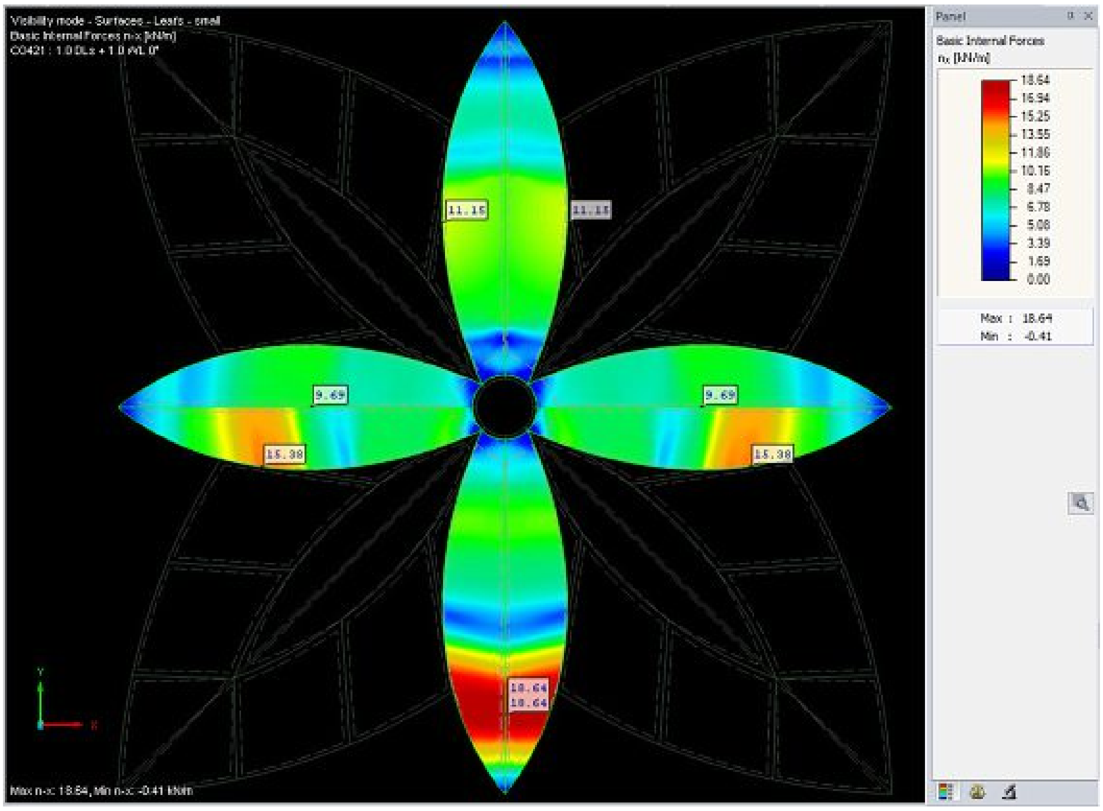

Figure 237: >The Sea Star< SEPARATE – Membrane forces n_x – LCC 421 DL+WL0° – Small leaves

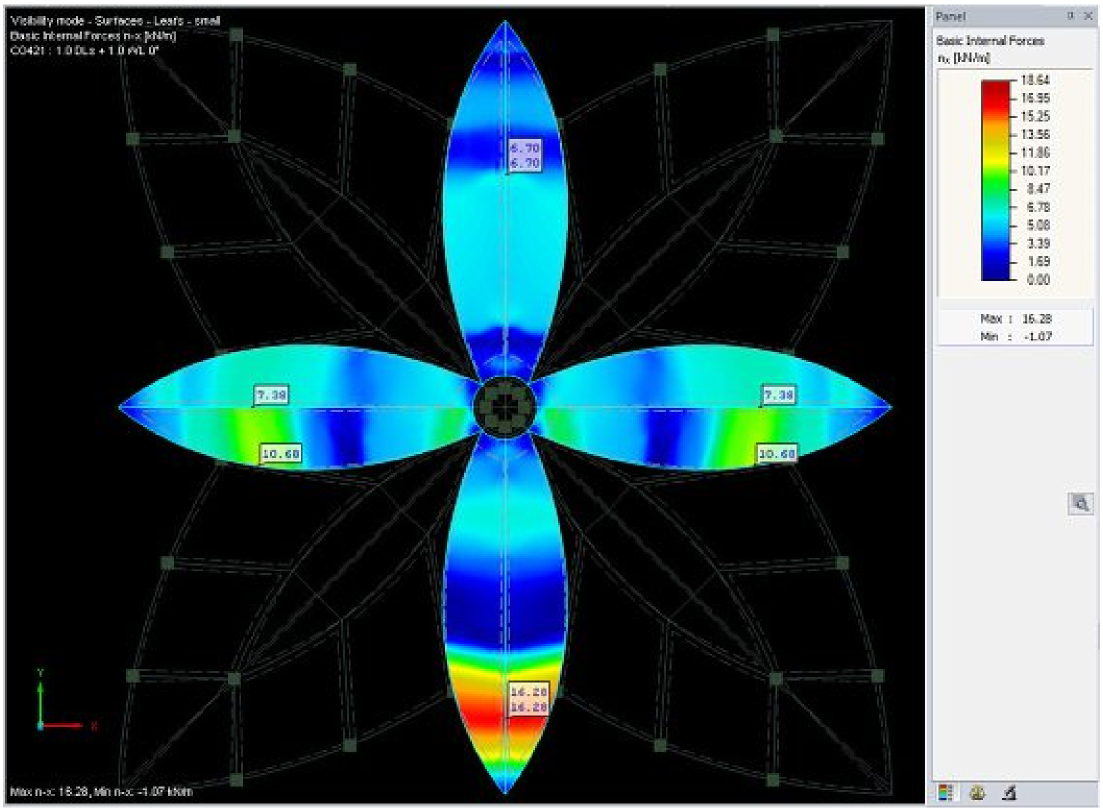

Figure 238: >The Sea Star< HYBRID – Membrane forces n_x – LCC 421 DL+WL0° – Small leaves

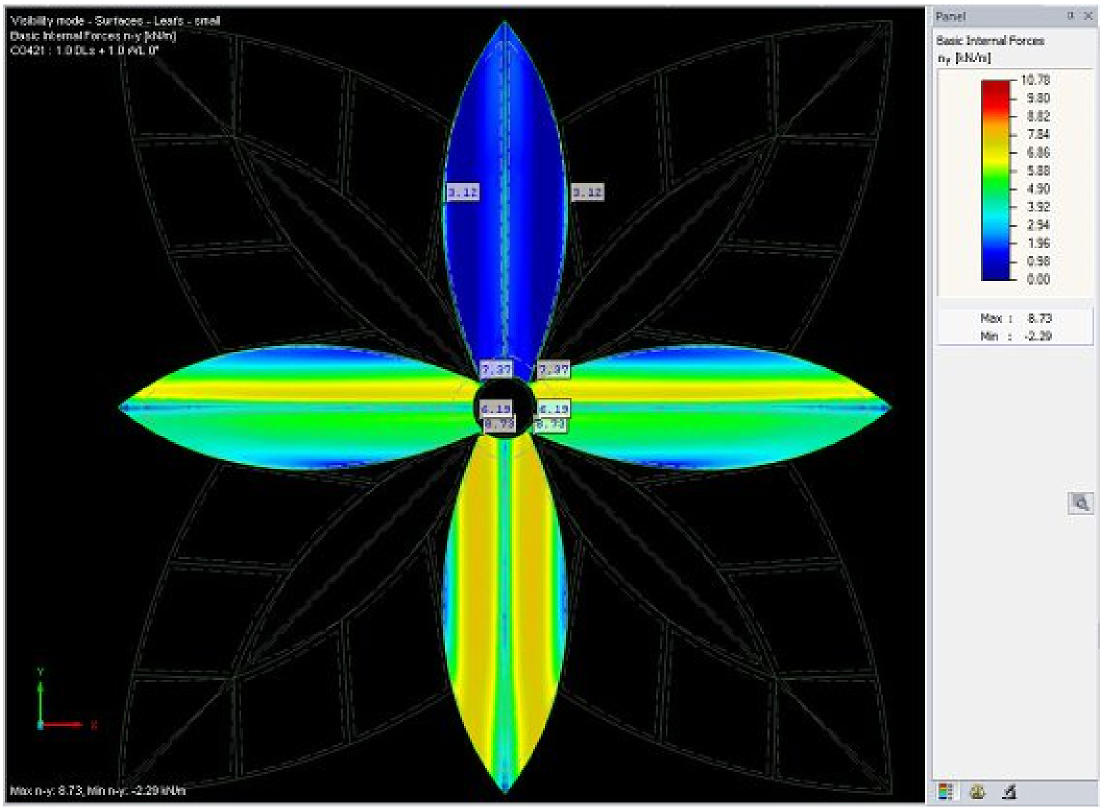

Figure 239: >The Sea Star< SEPARATE – Membrane forces n_y – LCC 421 DL+WL0° – Small leaves

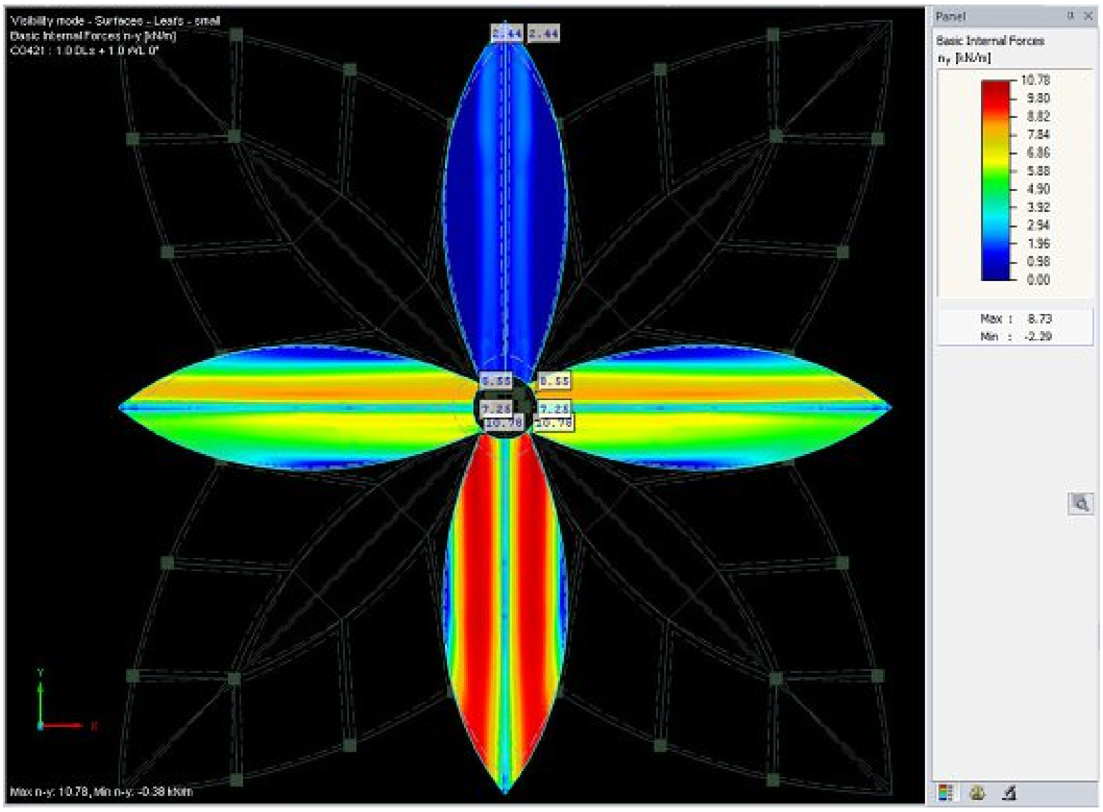

Figure 240: >The Sea Star< HYBRID – Membrane forces n_y – LCC 421 DL+WL0° – Small leaves

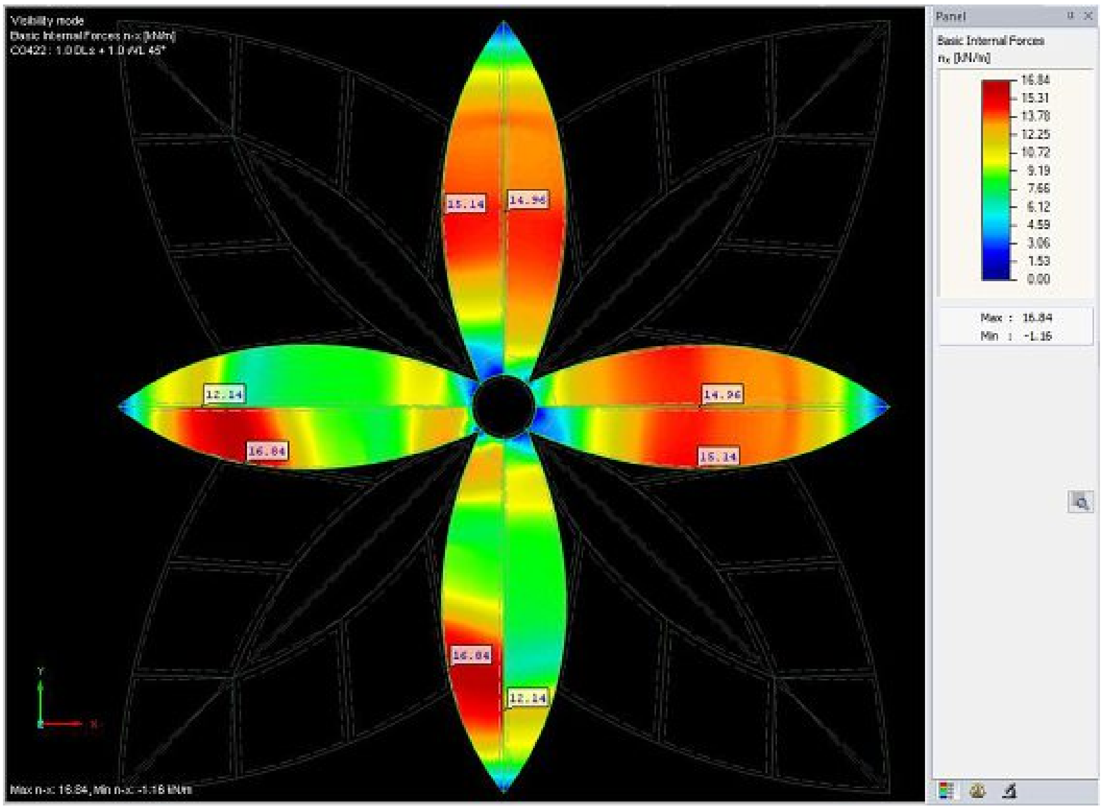

Figure 241: >The Sea Star< SEPARATE – Membrane forces n_x – LCC 422 DL+WL45° – Small leaves

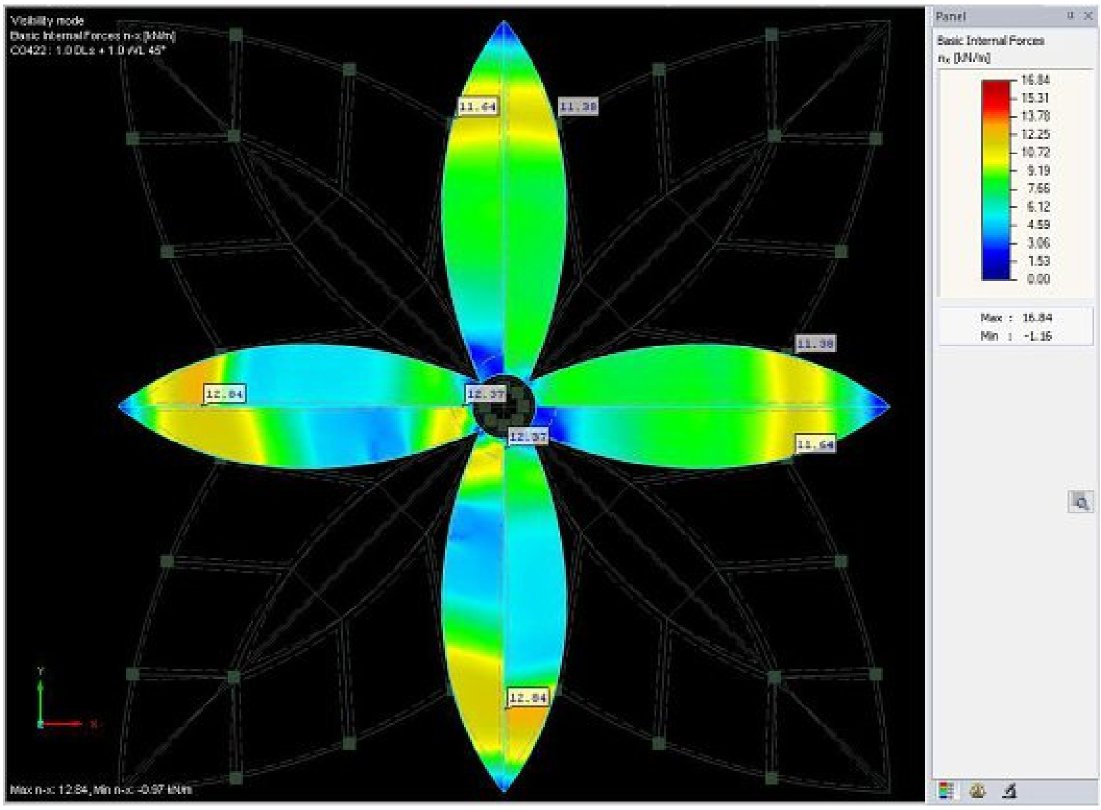

Figure 242: >The Sea Star< HYBRID – Membrane forces n_x – LCC 422 DL+WL45° – Small leaves

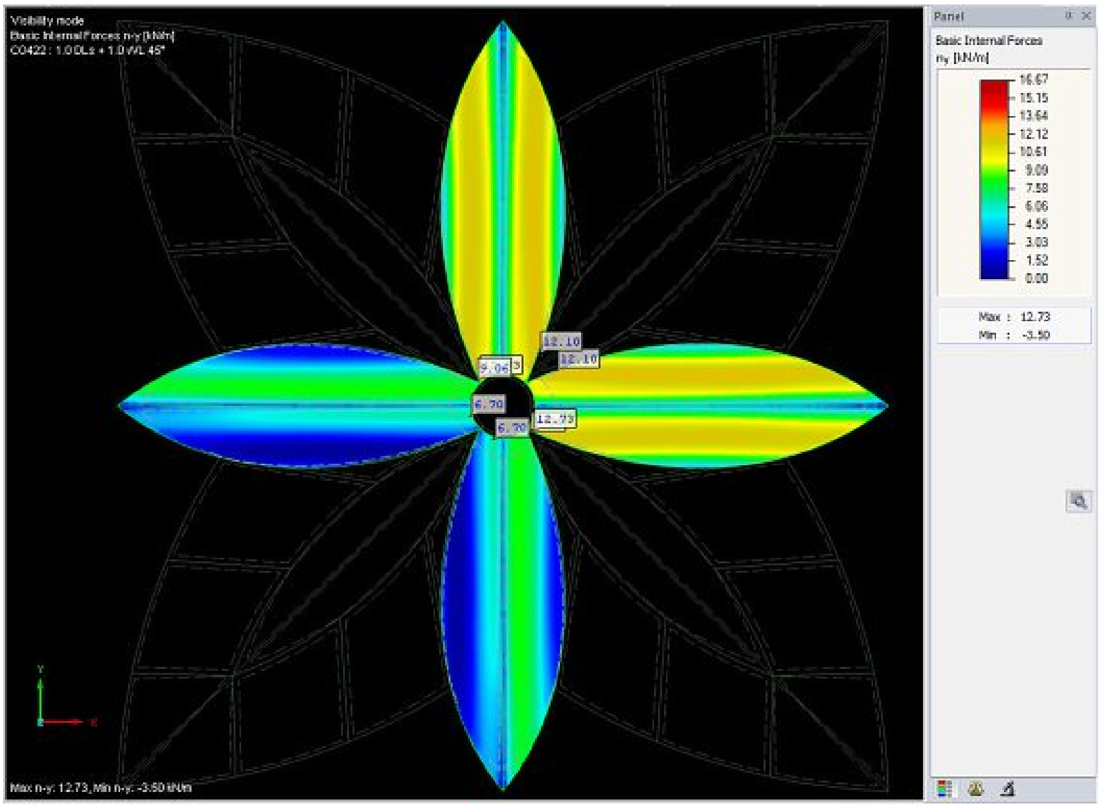

Figure 243: >The Sea Star< SEPARATE – Membrane forces n_y – LCC 422 DL+WL45° – Small leaves

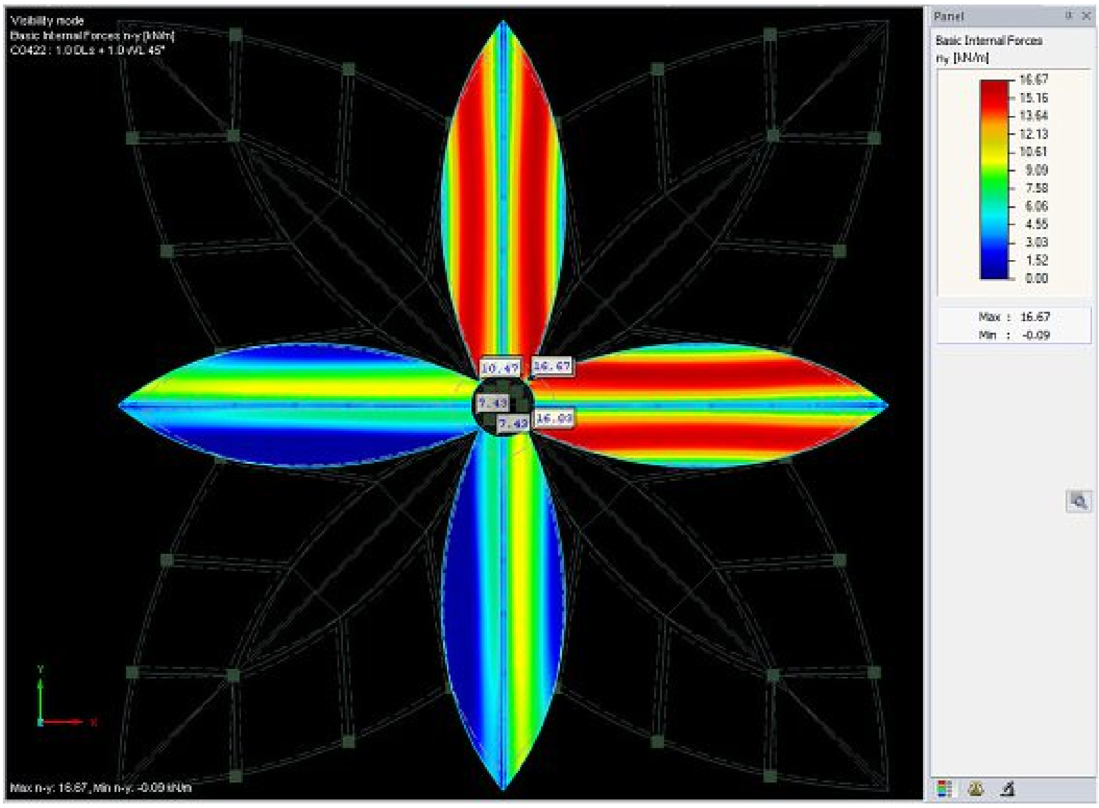

Figure 244: >The Sea Star< HYBRID – Membrane forces n_y – LCC 422 DL+WL45° – Small leaves