Deconstruction: A new construction method for prefab shell structures

Graduation report

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“We moeten bijzonder belang hechten aan het onderzoek naar dergelijke ontwerpen om economische types te bereiken en om goedkope bouwmethoden te ontwikkelen”

“We must pay special attention to the research into such designs to find economical types and develop cheap building methods”

-Ing. A. M. Haas on a colloquium for Shell structures in 1959 (Sanchez-Arcas 1961)

Abstract

Shell structures are expensive structures due to their extensive construction time and costs making them unpopular in spite of their material and structural efficiency. Temporary support structures are now based on the weight of the structure without taking into account what the incomplete structure can carry by itself. Structural characteristics of shell structures and modern computational methods do provide a solid platform to optimize the construction procedure of these nature adaptive and esthetically pleasing structures. This would save time and money through exclusion of set up time, reduced scaffolding costs and enabling of simultaneous construction phasing (building under the roof while the roof is being build).

Recent research into historical and newly available methods has unveiled methods to nearly exclude the use of temporary support. However, these methods have not been tested on large scale designs and do not prove to be fit for up scaling. In the last five years structural patterning and the influence of a panel pattern on force flow have also come up as a research field for building construction. A combination of features found in past methods and recent research can be joined into an improved modern construction method.

To know the minimal amount of supports needed the structure will need to be monitored every step of the construction process. Simultaneously it will have to find the best panel to put in next. To retrieve this information from the ground up, every panel that can possibly be installed will need to be tested. On large scale projects this will be a time costly process. That is why Ir. P. Eigenraam and Msc. S. Luitse have developed their own method: Deconstruction and reversed Deconstruction.

Deconstruction is the initial analysis method that works from the top, the complete assembled structure, down. Based on a finite element analysis (FEA) at each iteration it finds the least stressed panel and removes it. This can be compared to finding the loosest block in Jenga. This will continue until the structure is fully deconstructed. This will provide a reversed construction order that can be used to construct the structure with the least amount of stress and deformation. This construction method is called reversed Deconstruction.

Although the deconstruction algorithm is still under development first analysis show up to 75% reductions of temporary supports during construction. Further reductions can be done by preassembling parts of the structure.

This report will research the possibilities of this analysis and construction method. A historical review of shell construction methods combined with research into force flow through complex free form prefabricated shell structures will provide the pointers and tools. Along these pointers and tools the Deconstruction analysis method will be set up. The method is tested through FEA and concluded upon. It is the search for a smart construction method.

Preface

For my graduation I challenged myself to dive into the unknown. The only thing I knew that it was to be found in a combination of complex geometry, structural design and informatics. Preferably with a bit of hands on construction as well. Even though it did not come to the hands on construction I am extremely happy with my choice of subject. While solving the complex geometrical and structural problems I was constantly improving my structural and programming knowledge in ways I had not foreseen.

During the project I was constantly enthusiastic and motivated. Although sometimes I had doubts on the quality of the end product, I was always challenged and motivated by the exotic nature of developing something new. This was also sparked by the curiosity and enthusiasm that other people, professionals, fellow students and even non-technical people, showed in encountering my project. Somehow it sparked a lot of peoples imagination which motivates me to continue working.

Now, at the end, I would like to thank my mentors Peter and Winfried for always trying to think along with my, sometimes chaotic, thinking process, Arno, for supporting all hardware related issues and visualizations, and last but not least Arend, for helping me along in the world of C# scripting and the enlightening quote “Computers are only as dumb as the command you give them”.

Thank you all for your support and your faith in my work.

Simon Luitse

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1. Introduction

History and state of the art

Shell structures have been around for centuries. From the early Byzantine ages, during which people built on instinct, trial and error and throughout the Romanesque and Renaissance domes and churches. With the mathematical explanation of shells in the beginning the 20th century a "shell revolution" came about on the use of these structural and material efficient structures. By the hand of E. Torroja, F. Candela, F. Otto and H. Isler the shell became a regularly used architectural form. During this age building production industrialized and rapid construction and prefabrication became more important factors in the building industry. The more complex geometry of shells structures could not compete with the rapid construction methodology of the time. Together with the rising prices of labor and construction materials this caused the production of shells to stagnate (Chilton and Isler 2000). In current times shells are not often build due to these high production and construction costs.

Fig. 1 L'Oceanografic, designed by Felix Candela, during construction and completed. Opened in 2003.

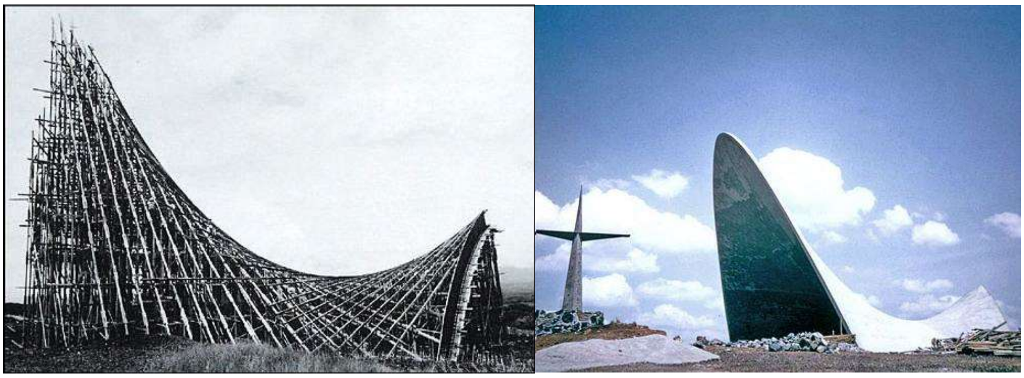


Fig 2 Chapel Lomas de Cuernavaca designed by Felix Candela. Build in 1958. Same construction method as in fig. 1

In contemporary architecture shells are regaining popularity. Due to their nature adapted shape, esthetically pleasing appearance and material/structural efficiency architects are designing shells once more. This is joined by technological advances in materials, prefabrication methods and computational modelling of the complex geometries (Huyghe and Schoofs 2009, Block, Knippers et al. 2015, Pottmann, Eigensatz et al. 2015, Schipper 2015).

Problem statement

Shell construction relies on large amounts of scaffolding to temporarily support the formwork for casting or the prefabricated panels during construction. The erection of these scaffolding structures and temporary supports take up a large amount of the construction time and cost. Current estimates put double curved surfaces at € 1000 to 1200 per m^2 where housing and complex utility buildings range from respectively € 21 to 71 per m^2 (van Dijk, Falger et al. 2013). Formwork, to a large extent, determines the cost of building construction: between 35 and 60% (Schipper 2015). Then add the extra man-hours for setting it up and the cost of all the waste material in formwork. One can conclude that *shell structures are expensive structures due to their extensive construction time and cost making them unfavorable in spite of their material and structural efficiency* (Davis, Rippmann et al. 2012, Block and Rippmann 2013, Pedersen, Larsen et al. 2015, Schipper 2015).

The amount of supports needed in construction is based on the dead weight of the structure. The loading capabilities of the incomplete structure are not taken into account. In prefabricated construction incomplete structures can be loaded to certain extends. This can already greatly limit the amount of temporary supports needed. However, what needs support and what is stable on its own must be analyzed through every step of construction. This can be further optimized by finding a construction order that will need the least amount of temporary support.

Building without scaffolding can greatly improve the construction. No more scaffolding build up, complex formwork shaping/setting, simultaneous building of roof and sublayers, reducing the amount of material needed to build and reducing the amount of workers needed to build the shell (Davis, Rippmann et al. 2012, Pedersen, Larsen et al. 2015, Schipper 2015). Furthermore, the structural analysis of the shell during construction will give a good structural insight into force flow and construction optimization.

Objective

This research will focus on the computational analysis, the design and development of a new construction method that allows for the exclusion of scaffolding and temporary support. In the knowledge that this might not be fully possible the designed method will be optimized to maximize the reduction of scaffolding and temporary support.

The thesis will first define the scope of the research conducted. Defining what is assumed, what is left out and why. This will be followed by the methodology used for research.

First of all an introduction to shells will be given. What is shell construction, what defines shells and how do they need to be read. This will extend into force flow and form finding methods to show how they can efficiently designed and checked.

Secondly an overview will be given on the methods used to build shell structures and interesting developments for the building without supports. This will include a look at other construction industries for supportless construction methods.

This will continue with an insight into shell optimization methods. Here applicable algorithms will be defined together with pattern design principles and construction features like preassembly.

The most applicable or combinable findings will be included in the design of the new method. This will undergo computational optimization algorithms with finite element analysis in each iteration to get a proper view of structural integrity during every step of construction. Research into application of the algorithm will we extended with certain variations on the original method.

Research question

The main research question will state:

Can the Deconstruction principle reduce the amount of temporary supports used during the construction of prefabricated shell structures?

Sub questions focus on the following:

- What are shells?
- What building methods are currently used to build shells?
- What is used in other construction industries to reduce construction supports?

- How do we design a construction method?
- What influence does the prefab pattern have on force flow?
- What influence do panel connections have on the force flow?
- How can we best spread forces over the prefabricated shell pattern?

- What are the advantages of deconstruction on prefabricated shell structures?
- What criteria can best be used to select panels in deconstruction?
- What method variations can further reduce the use of temporary supports?

Methodology

Scope

Definitions

During the course of this research some technical terms are used that can be misinterpreted. To prevent confusion the intended meaning of these terms are here clarified:

The temporary supports used to construct shells consist of several elements: Wood for the mold, steel for support of the mold, Steel as weight carrier, tools to stabilize during installation. Temporary supports in general describes all these elements. The terms scaffolding, tools, material, falsework, formwork and supports all describe certain part and combinations of these elements. However, in this report, all these definitions refer to supporting elements only unless explicitly stated otherwise.

Deconstruction

Because there is no precedent for structural analysis methods for the construction phase on has been invented and developed by Ir. P. Eigenraam and Msc. Simon Luitse: Deconstruction.

The deconstruction method determines a panel order based on Finite Element Analysis (FEA). It starts with a completely assembled structure. Through a FEA a panel is selected to be taken out. Then the geometry is again submitted for a FEA minus the selected panel. Based on the second analysis a second panel will be taken out. This will continue until the structure is fully deconstructed.

Reversing the Deconstruction sequence acts as a building order. This construction principle, which is currently under research, is called Reversed Deconstruction. This will present a building order together with a structural analysis each step of the build process. This insight into the stability, deformation and stress levels during each step in construction allows the designer to check where and when support is needed. The designer can also determine if support is needed or that the stress and deformation can be countered through improving the panel/detail design. This report will cover the research into the Deconstruction method and it’s possibilities.

Free form shell

To best design a method suitable for as many kinds of shell as possible one cannot rely on any kind of structural shape advantages. The shape should be considered as free form shell-like structure. A set of basic rules should determine the panels shapes, sizes, connections, distribution and building sequence.

However, to keep the designing and prototyping phase within the limits of the given timeframe one shell design must be chosen. This will be done from the portfolio of Heinz Isler. Isler's portfolio contains a lot of optimized freeform shell designs that have been built relatively recent with proper documentation (Chilton and Isler 2000). More important, geometries of these shells are available to the researching party. The shell used in the research is the Heimberg swimming pool shell. This is a freeform shell by Heinz Isler based on form finding methods with a hanging cloth. Further information will be provided in the following chapters.

Material

Over the years shells have been built in all materials. Concrete, wood, steel, ceramics, cardboard, FRP's and even glass shells have been build. This research will focus on concrete shells. Concrete shells are the most commonly build shells (Sanchez-Arcas 1961, Rühle 1970, Schipper 2015). The plasticity of concrete together with their compressive character make it an cheap and easy material for building shells.

Fabrication method

The fabrication of shells has been done in many different ways over the years. From masonry to cast in place to prefabrication in all panel shapes and sizes. Recent developments such as 3D printing could be viewed as a possible fabrication method as well. All these construction methods might greatly improve the construction of shell structures. Since the timeframe for this project does not allow to research all methods a choice must be made for the most promising method. This paper will focus on prefabricated panels as a fabrication method because:

- Masonry shells are currently being researched at the ETH Zurich by Prof. dr. Phillipe Block and his research group. This method is done with multiple layers of small sized lightweight tiles and fast setting mortar. This proven (Davis, Rippmann et al. 2012, Block and Rippmann 2013, Rippmann and Block 2013) method allows vaults and shells to be created without the need of formwork or temporary support. However, the method uses a large amount of small tiles that are layered to comply with the thickness of the shell. The small sized building blocks and multiple layering means that a large amount of building actions are required and will exponentially increase with increase of shell span. Prefabricated panels need no layering so building actions will only linearly increase with span

- In place casting is the most commonly used building method for freeform shells (Sanchez-Arcas 1961, Rühle 1970, Den Hartog 2008, Huyghe and Schoofs 2009). Large amounts of variations exist in this field of construction. Material varieties like wood, cardboard, sheet metal and fabrics are combined with supports like static scaffolding, steel grid shells, modular movable reusable frames, expandable frames, tensioned cable nets, large amounts of dirt or inflatable cushions (Sanchez-Arcas 1961, Rühle 1970, Schipper 2015). In spite of this large variety all these methods require temporary support to hold up the formwork. Temporary supports cost time and money to set up and consequently in place casting would only have the possibility to limit temporary supports instead of full exclusion.

- 3D printing has been rising as a production method for the past two decades (Buswell, Soar et al. 2007, Schipper 2015). Technology for small scale prototyping has advanced immensely. With an large array of materials available printers can print with at precision of 600 DPI (equivalent of a desktop printer). On the larger scale however, methods like concrete printing have been known to be very coarse (10 DPI) (Schipper 2015). Furthermore the layered structure does not give the monolithic structural characteristic that we know of concrete. Finally 3D printers cannot print in the air, they can only print onto the previous layer until an overhang of 45 degrees, beyond that it will need support. This means that it can never be closed without the use of temporary supports or that shells are limited to an angle of 45 degrees. This makes 3D printing, although promising for future development, not feasible for this project.

- Prefabricated panels have the most complete and controlled fabrication method (Dallinger and Kollegger 2008, Den Hartog 2008, Huyghe and Schoofs 2009, Janssen 2011, Pedersen, Larsen et al. 2015, Schipper 2015). In the factory one can add on all connections, reinforcements and coatings so that construction time can be limited as much as possible. Together with new developments on flexible molding, time, money and material can be saved using this fabrication method.

In the further development of this report all extents of shell construction needs to be researched. In this shells with different *fabrication* methods will still be researched for their *construction* method.

Approach

The research in this project will consist of a literature analysis of construction methods and prefabricated shell design and optimization followed by computational analysis of the shell by deconstruction. The first analysis (focusing on all relevant existing building methods) will provide design features and gimmicks to test in the structural analysis part. The second analysis (focusing on the engineering needed for the prefabricated structural shell) includes patterning for prefab shells and its effects on force flow to provide the input for the computational model to be analyzed. The final step (focusing on the development of an analysis method for supportless construction) will include the design of the, in this project developed, deconstruction algorithm on a shell and extraction of critical design data.

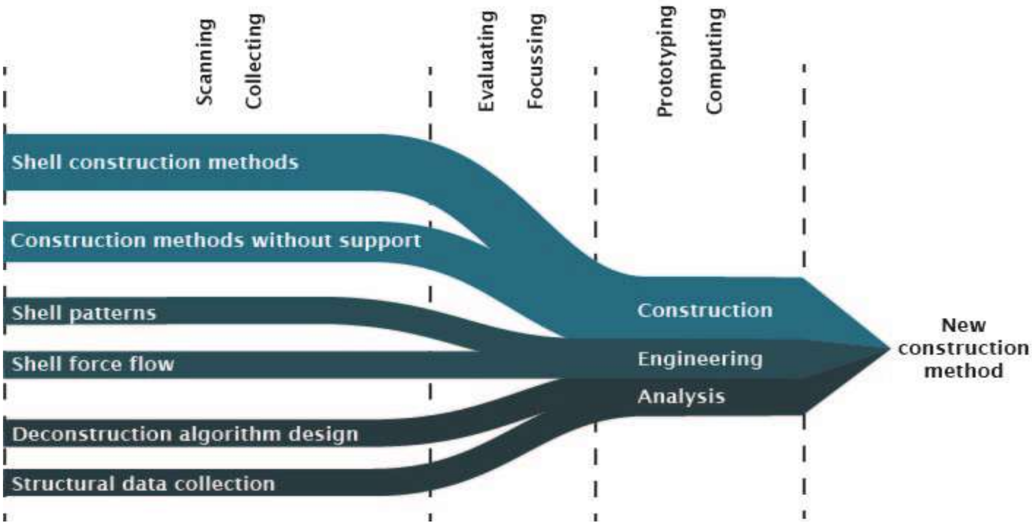


Fig. 3 Flow diagram of research

Relations between literature subjects

The subjects described above are all interlinked concerning the construction of shell structures. One is not to be executed without research into the other areas. In our digital age we have the power to simulate everything in the computer. Even though the analysis will primarily be done digitally a prior knowledge of shell construction and how to optimize it is crucial to solve the problems found in the digital analysis. To achieve this in depth research into shell construction, patterning and optimization is mandatory.

Literature analysis: Construction methods

To get a proper understanding of the technology used in construction methods two literature studies will be conducted. One for all building methods used to construct shell structures and one for all methods used to build without scaffolding or temporary supports. A scan of these fields will provide an array of features to be considered when designing a new construction method.

In this chapter an exploration of the context of construction methodology that is available for use in modern day times is conducted. During the 20th century a lot of experimentation with new faster construction methods have been researched. Both facets of this study will have their own focus points.

- Shell construction, due to its curved and less stock found profile, has always differed from normal orthogonal construction methods (Sanchez-Arcas 1961, Rühle 1970, Schipper 2015). Therefore shell construction methods will not be filtered for applicability to the building without temporary supports concept. This is done to provide a proper context of shell construction in general to, later on, compare the designed construction method with.

- The search construction methods without falsework will not be limited to architecture only. Building industries such as bridge building have a lot of experience in this area. Bridges over rivers and deep valleys do not have the luxury of supporting their construction. In these fields new ways have been found to keep building in unsupported space. This might inspire and architectural construction method.

Literature analysis: Shell engineering

To be able to design a construction method for shell structures one must have a proper understanding of shell theory (Den Hartog 2008, Blaauwendraad and Hoefakker 2013). What kind of shells shapes are there? What kind of effects do certain curvatures have on the structural integrity? How do forces flow through shells? These questions will be answered to give a good idea of the do's and don'ts in building shell structures. These fundamentals will be taken into account when designing panels and deciding on building order. They will also provide insight in the results obtained from Finite element calculations (later referred to as FEA).

Furthermore, the designing of a construction method is inseparably intertwined with the engineering of the shell. Panel size, panel shape, connection features, reinforcements, bearings, etc. all have great influence on whether a shell is buildable without supports or not. Therefore an analysis will be done on prefab shell engineering and methods to improve this

To be able to build the shell without supports the structure must be stable in every stage of the building process. The connection of each panel and their contribution to the completed structure will need to be engineered accordingly.

- Shell engineering will focus on the design of the individual building block needed to build a continuously stable structure throughout all building stages. Subjects like panel shape, variable panel size, temporary stabilizing connection features, connection orientation and post tensioning will provide a list of features needed per panel.

Computational modeling

All research will be evaluated on applicability and usability in the design of the new method. The usable features will be combined and tested computer models. In this chapter applicable test methods will be described.

The modern computational methodology allow engineers to design and calculate detailed force flow through complex shell structures (Blaauwendraad and Hoefakker 2013, Eigenraam 2013, Block, Knippers et al. 2015, Li and Knippers 2015, Pottmann, Eigensatz et al. 2015, Schipper 2015). In current day research FEA is used to check the final design of the structure. This is only a one time check to see if the structure would meet the requirements. To optimize a construction method structural data of every step in construction is needed.

That is why a new use of FEA earlier in the design stage will be used and researched for this project. On every iteration of the algorithms a FEA is made to verify the next step or check the previous. In this way computational modelling and "optimization" algorithms can be improved by structural data. The more constant involvement of structural analysis in geometric modelling will also provide more data for design of elements in the structure making it easier to optimize them. For this a bridge between geometric modelling software and finite element software is needed. In this case the bridge will be made between Rhinoceros 3D, Grasshopper parametric modelling and TNO's Diana Finite element software.

2. Shell construction

This chapter will provide an introduction into the shells and shell construction and shell optimization methods.

Shell characteristics

Shells are thin curved plates that, due to their shape, can carry out-of-plane loads by in-plane-membrane forces (Blaauwendraad and Hoefakker 2013). These membrane forces are resultants of normal stresses and in-plane shear stresses that are uniformly distributes across the thickness. Because membrane forces are easier to transfer than bending forces or out-of-plane shear forces, shells can be constructed with little thickness. This thickness often comes down to a 1/500 thickness to span ratio making them very economical structures (Chilton and Isler 2000). The theory of this membrane behavior is called membrane theory. Unfortunately this theory does not satisfy all equilibrium and/or displacement requirements. Around deformation constrains (supports), concentrated point loads and sudden shape changes (folds) bending behavior does occur. This bending behavior is usually confined to boundaries where membrane forces cannot exist and are often referred to as *edge disturbances*. The major undisturbed part of the structure, when designed right, behaves like a true membrane (Blaauwendraad and Hoefakker 2013). Both theories will be further elaborated in chapter force flow.

Shapes

Shells have a huge variety of shapes. To get a grasp of the possibilities classifications can be made.

Gaussian curvature

Shells can be described by the curvature in the middle of the surface. At any point A on a smooth surface there is a tangent plane. The normal to this plane is the normal of point A. When two orthogonal planes are constructed that intersect along the normal of point A, one can derive two curves from the intersection between the planes and the smooth surface. These two plane curves are called principal sections and their curvature k is called *principal curvature*. When the origin point of the plane curve is on the negative side of the normal the curvature is negative, on the positive side: positive. The Gaussian curvature is described by the multiplication of both curvatures $k_g=k_1*k_2$. This means that is both principal curves curve in the same direction Gaussian curvature is positive ($k_g=-k_1*-k_2$ & $k_g=k_1*k_2$) also called synclastic. If they curve in opposite direction principal curvature is negative ($-k_g=k_1*-k_2$) also called anticlastic. When one of the two curves is a straight line Gaussian curvature is 0 ($0=k_1*0$) also known to be a single curves surface.

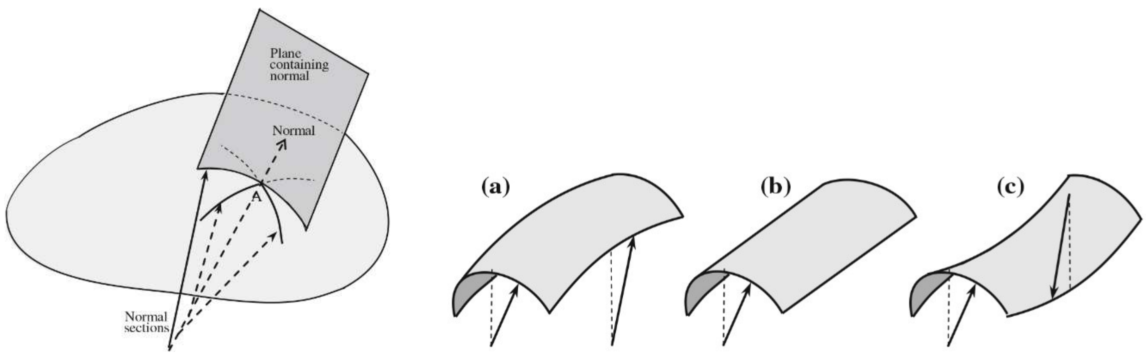


Fig. 4 Visualization of the determination of Gaussian curvature. Example (a) has 2 positive principle curvature hence synclastic, (b) has no curvature in one direction and therefor has a Gaussian curvature of 0, (c) has opposing curvatures hence in anticlastic with negative Gaussian curvature. (Blaauwendraad and Hoefakker 2013)

Developed and Undeveloped surfaces

Developable surfaces are surfaces that can be transformed into a flat sheet without the need to cut or stretch it. Surfaces that need cutting or stretching are called undevelopable. Double curved surfaces are examples of undevelopable surfaces while single curved surfaces can be developed. The undevelopable nature of a double curved surface gives it it's structural characteristics. More energy is needed to deform a undevelopable shell than a developable shell hence are stronger and more stable.

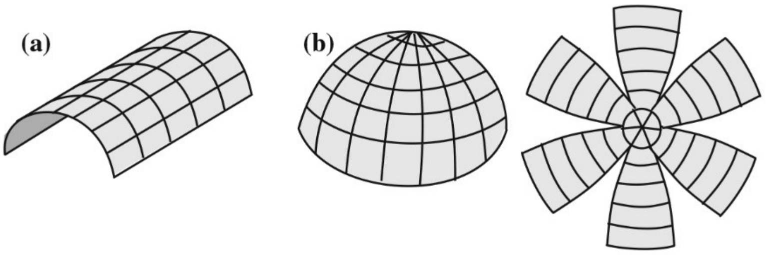


Fig. 5 showing developabillity of surfaces. Surface (a) is developable to a flat surface due to its single curvature. Surface (b) is double curved and therefor undevelopable to a flat surface without incisions.

Generated surfaces

This classification is based on how a curved surface came to be. There are three main definitions for the generation of surfaces revolution, translation and ruled surfaces.

- Revolted surfaces are surfaces that are based on a section curve and a revolution axis. The section curve is revolved around the axis giving it a 3D surfaces. In the case when the section curve is a straight line a cylinder or cone is created. Other examples of revolted surfaces are domes.
- Translated surfaces are surfaces where a section curve is slid along an the orthogonal section curve. The second curve is called the generator curve. In the case of a straight generator curve one acquires a cylindrical surface. Other examples of translated surfaces are elliptic and certain types hyperbolic paraboloids.
- Ruled surfaces are generated by a straight line sliding along two curves. In construction these surfaces are easier to construct because of this continuous straight line. Examples are conoids and certain types of hyperbolic paraboloids.
- Combined surfaces are combined out of several curved surfaces with a discontinuous curvature. They can be composed out of all previously named shell forms.
- Folded plate structures are stiff structures composed out of several flat triangular, rectangular or trapezium plates. Strictly speaking they are not curved surfaces but are also used to create very stiff 3 dimensional structures. In calculation folded plate structures are often calculated by the simpler beam theory.

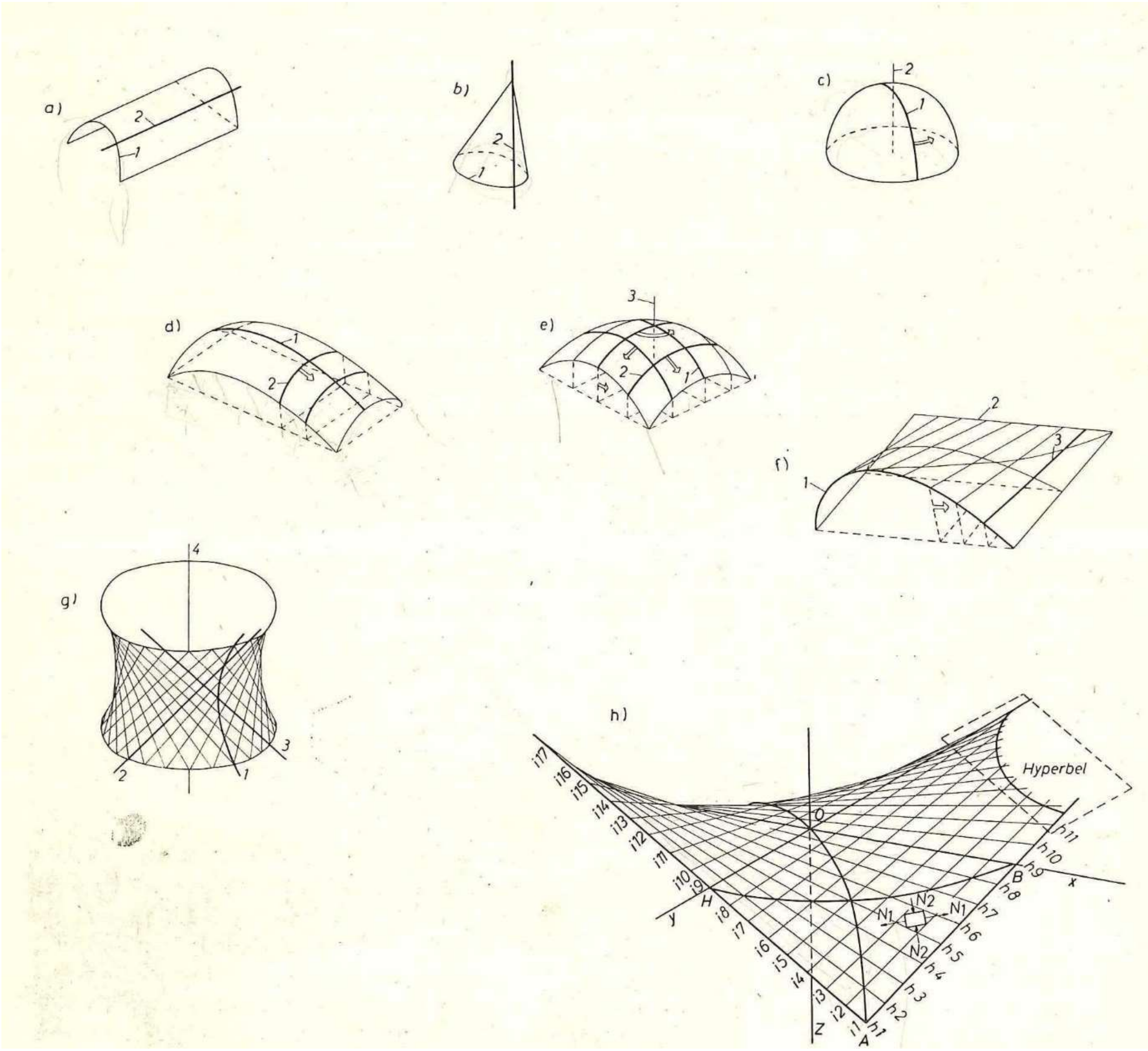


Fig. 6 Examples of surface generation methods. a) Ruled and/or translated; b) Revolted; c) Revolted; d) Translated; e) Translated; f) Ruled; g) Ruled and/or Revolted; h) Ruled

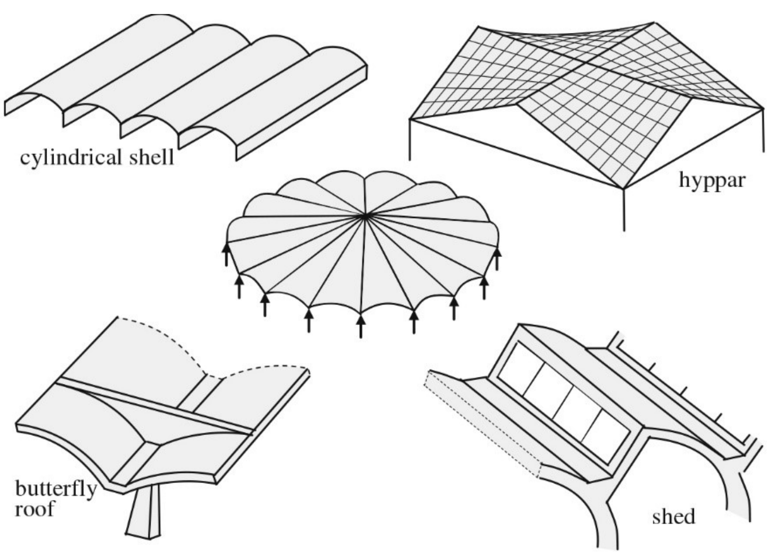


Fig. 7 Combined surfaces and folded plate structures

In modern computational techniques NURBS (Non-Uniform Rational B-Splines) allow us to create more freely formed shapes than described above. These NURBS consist out of mathematically described 2D line, arc, circle or curve elements and can be used to accurately construct complex 3D free form surfaces and solids. Basic principles of shape are still derived from classifications previously described.

Force flows

In the introduction on shells a little was elaborated on the forces occurring in shells structures. This chapter elaborates on both theories and provides the usable form finding and calculation methods.

Membrane and bending theory

As previously described membrane theory applies only under certain conditions:

- When no abrupt changes in curvature are present
- When no sudden changes in thickness are present
- When there are no concentrated loads are present
- When edge supports are tangentially directed to the middle of the surface

When all these requirements are met membrane theory assumes that only normal and in-plane shear stresses apply. The stress resultants, without the bending stresses, that act on shell elements are shown in fig. 8.

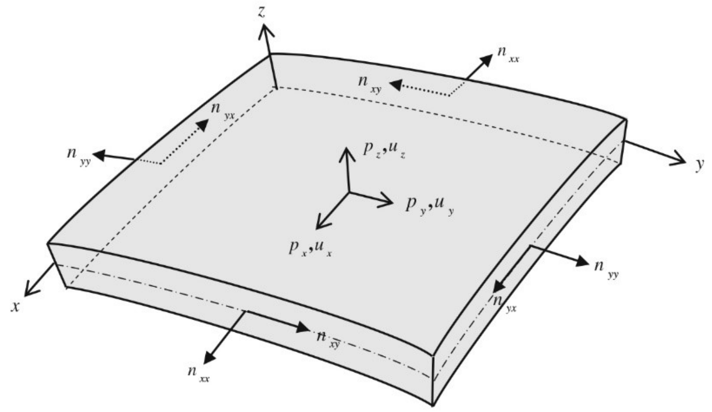


Fig. 8 Resultants of loading on shells.

The loads, *p*, consist of three components: in-plane components p_x and p_y and the out-of-plane component p_z. Displacement is defined in the middle of the element through u_x, u_y and u_z which corresponds with the loads. Stresses occur in the form of normal stresses σ_{xx} and σ_{yy} and shear stress σ_{xy}. These are uniformly distributed through the thickness and integrate to n_{xx}, n_{yy} and n_{xy}, respectively. n_{xy} and n_{yx} are equal due to the moment equilibrium condition. The stress resultants also cause normal strains ε_{xx} and ε_{yy} and shear angle γ_{xy}.

This can be defined in four vectors:

$$u = [u_x, u_y, u_z]^T$$

$$p = [p_x, p_y, p_z]^T$$

$$s = [n_{xx}, n_{yy}, n_{xy}]^T$$

$$e = [\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}]^T$$

The four vectors relate by three basic relationships: kinematic relation, constitutive relation and equilibrium relation. Kinematic relates strain to displacement, constitutive relates stress resultants to strains and equilibrium relates stress resultants to external loads. Relation scheme is shown in fig 9.

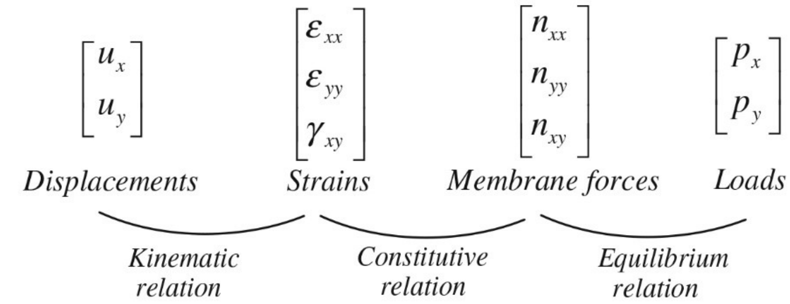


Fig. 9 Relation scheme in Membrane theory

Where membrane theory does not apply bending disturbances occur. These disturbances are described by a more complete analysis called bending theory for thin elastic shells. The bending theory can be seen as an extension of the membrane theory as it only occurs in a certain range and quickly dies out after. Load component p and displacement component u remain the same but the other two components differ. Due to the presence of bending and twisting stresses m_{xx}, m_{yy} and m_{xy} have been added to the stress resultant component s. Strain component e is joined by bending deformations κ_{xx}, κ_{yy} and ρ_{xy}. The changed relations scheme is shown in fig. 10.

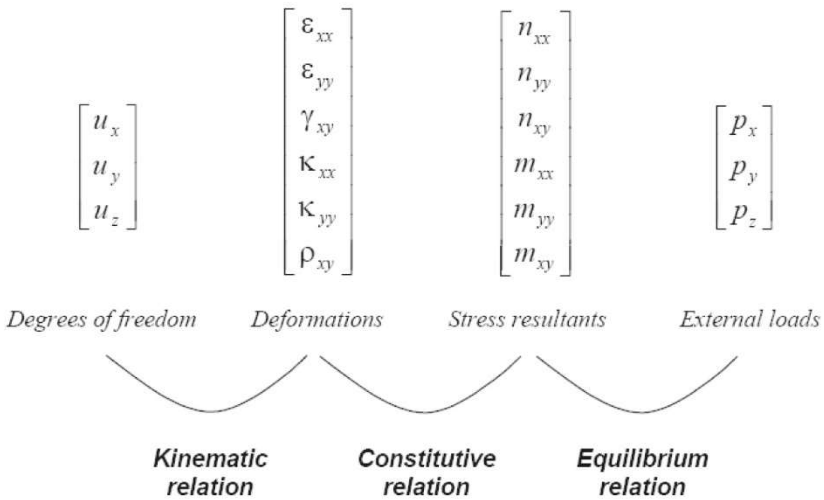


Fig. 10 Relation scheme in Bending theory

Form finding

In the design of shell structures a commonly used method is form finding. This is based on the use of natural form giving forces such as gravity, air pressure or surface tension. These forces are applied to physical elements like chains, cloth or soap to generate surfaces in equilibrium for certain situations.

Hanging models are physical models shaped by gravity. The method uses a wet cloth, chain or net and hangs it upside down to let gravity find the state of equilibrium for the hanging tension forces in the applied boundary conditions. When the shape is inverted we find the compression line for the particular generated model. When point loads are needed one can apply heavy elements deforming the curvature of the cloth or chain(s). This method was commonly used by architects like Antoni Gaudi for the Sagrada Familia or engineer Heinz Isler in his ice models.

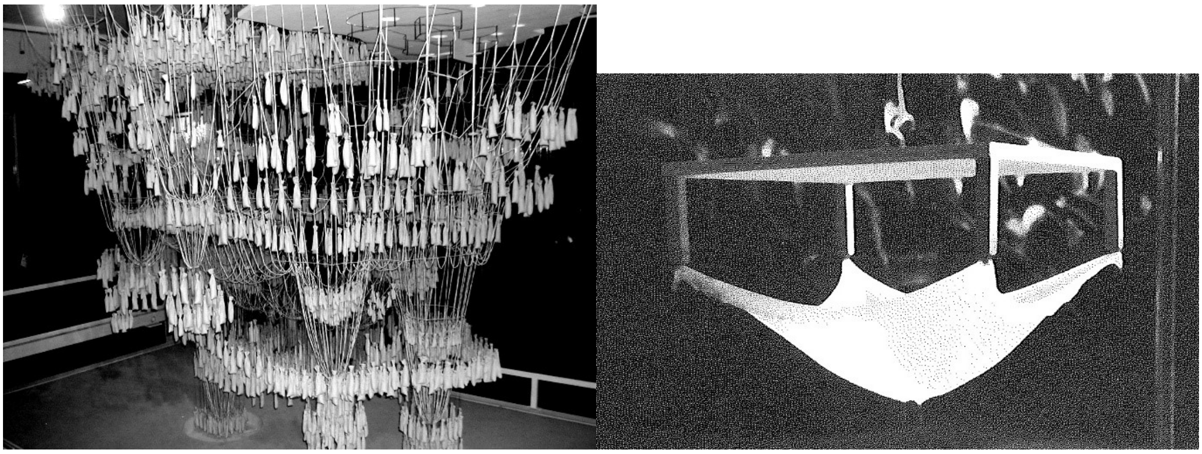


Fig. 11 Form finding methods. Left: Gaudi's Sagrada Famillia; Right: Heinz Isler Hanging cloth models.

Another form finding method makes use of soap films and surface tension. The film is applied to a closed edge and finds the minimal surface equilibrium for that surface. This method is also used by engineers such as Frei Otto for his tent structures like on the Montreal Expo 67. The film can also be combined with air pressure to find the minimal surface for pneumatic architecture.

Fig. 12 Frei Otto form finding methods. Left: surface tension model used for the Montreal Expo 67; Right: the Montreal Expo 67 designed by Frei Otto

These methods are available in computer modelling as well. Physics engines like Kangaroo for Grasshopper (Huyghe and Schoofs 2009, Eigenraam 2013) and equilibrium solvers with dynamic relaxation like Rhino Vault (Block and Ochsendorf 2007, Davis, Rippmann et al. 2012, Rippmann and Block 2013) have been known to generate accurate form found surfaces. In the newest features even pneumatic structures with binding elements can be simulated. These computer aid gives engineers and architect a lot more insight and control over the design they want to create.

The shapes found in these methods can been found all throughout nature as well. During evolution nature has optimized it's structures to form sea shells, eggs and spider webs which in shape closely resemble the shape found with methods described above. On top of that nature also optimized cellular structures like honeycombs and leaf structures. These shapes and structures found in nature are often a source of inspiration for architects and engineers.

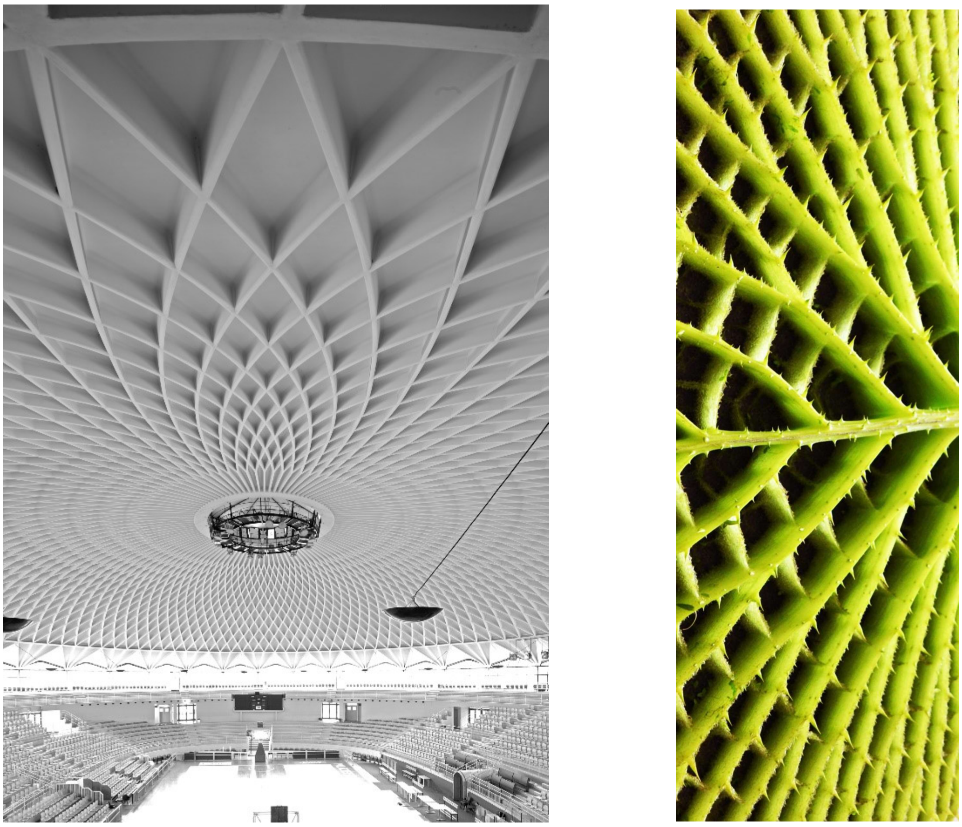


Fig. 13 Form finding by nature and Luigi Nervi. Left: Palazzetto dello sport designed by Luigi Nervi; Right: Giant Amazon water lily leaf structure that inspired Nervi

Finite Element Analysis

The Finite Element Analysis (FEA) is a computational simulation technique that can analyze thin free formed, form found shells or other structures. A common application of a FEA is to find the maximum stresses and displacement in structures and systems. It uses the numerical technique called the Finite Element Method (FEM). For an FEA one needs to define the geometry with all external forces and boundary conditions applied. This is analyzed and can be viewed with post processing tools to get a visual representation of the results.

Input geometry can be 1D, 2D or 3D elements which are divided into small segments by meshing. In this way force and stress distributions through large elements can be calculated in detail. Often meshing is done by standardized meshers in the software packages which gives you little control over the structural level of detail in the model. Other programs like Rhinoceros 3D, which is more specialized in accurate 3d free form modeling, have a lot more and more flexible meshing engines. They even allow the experienced modeler to design his own meshes suiting his or her needs. Combination between these software packages can improve the control over the output and speed up the calculation process.

As previously stated, to analyze every step of the shell’s construction, FEA will need to be involved far earlier in the design process. Instead of afterward verification of the structural integrity FEA will be implemented in every iteration of the, for this project developed, deconstruction algorithm. This will provide all the needed design values and insight into where support might be needed.

Construction

This chapter will describe the construction methods found most applicable. Many more have been researched and will be added in the appendix for evaluation purposes. The most relevant shell construction methods will be explained first. Then some other support free building methods will follow from other building industries.

As explained in the introduction shell structures have been built for ages. Most modern techniques where though up in the fifties and sixties with the use of modern concrete. In the past several experiments have been conducted to build without supports. Below we will first describe what the current standard is for building shell structures with formwork, then an example with prefabricated elements and finally the most relevant methods without or with minimized supports.

Base: formwork

In-place casting is historically the most commonly used construction method in shell construction. Large quantities of timber formwork supported by a dense wooden or steel scaffolding structure to keep curvature precise and put together by high quality carpenters. This was a relatively affordable solution for concrete shells from 1920 till 1970. After this period labor got more expensive and steel cheaper making steel a more affordable construction method (Chilton and Isler 2000). On top of that shapes designed by architects got more complex with free form curvature that does not allow for repetitive curving elements.

In the area of formwork several variations exist (Schipper 2015). Material variations like the use of cardboard and steel sheeting allowed for more flexible forming but also reduced precision (cardboard) and raised cost (steel). Fabric formwork has also been used for in-place casting reducing the needed quantity of supports and possibilities of free form (Veenendaal, West et al. 2011). Unfortunately this method also reduces the accuracy and speed of production/construction. Further experiments with formwork hanging from steel reinforcement grids and pneumatic formwork have been found too flexible and therefore unreliable.

In spite of their variations current formwork methods have always relied on temporary supports. For formwork to work as a supportless building method the formwork will have to support itself. Here possibilities lie in the use of prefabricated elements to create a stable formwork structure (double curved reinforced slab elements) (Sanchez-Arcas 1961, Davis, Rippmann et al. 2012, Schipper 2015). This structure could be used as lost formwork that is completing the structure at the same time. The fabrication of these kinds of elements seems problematic but will have to be researched further.

Base prefab

Prefabrication of elements for shell structures is a building method that slowly split off from in-place casting during the past century (Sanchez-Arcas 1961, Rühle 1970, Schipper 2015). The first semi prefab elements where created on site but not in place. Large molds where created on the ground to fabricate the repetitive shells used for shed roofs of factories. These elements, sometimes up to 30 m in length (Rühle 1970), would later on be hoisted into place upon a orthogonal frame. This was done on site because the larger elements would otherwise not be transportable.

Current prefabrication of method suggest that elements are made in the factory under controlled circumstances for better results (Huyghe and Schoofs 2009, Janssen 2011, Eigenraam 2013, Schipper 2015). All needed elements are placed during fabrication and the finished piece is transported to the construction site only to be put together. This transport limits the size and shape of the elements, especially when great numbers of curved elements are needed. This is why for large free form shells form work is more often used.

Several prefabricated shell structures have been constructed this way over the years. For example: the Evoluon in Eindhoven designed by L. Kalff as exhibition hall for Phillips (Rühle 1970). The large spaceship like shape, spanning 72m and 30m in height, was a dared design back in 1966 when it was completed and attracted a lot of visitors. It consists of a lower cone like shell and a upper dome shell. The construction was done in three main stage as depicted in fig 14. The first stage consisted of 3 x 96 prefabricated elements weighing a total of 2500 tons composing the lower shell. These elements are, while supported, strung together with tension rings and the floors resting on these elements. In the second stage the large tension ring that holds lower shell together and simultaneously acts as a tensioned base for the upper shell. In the third stage lower supports are removed and a new support structure is constructed on the installed floors on the inside. Upon this support structure 822 prefabricated pieces of shell roof are joined together with poured concrete. In total the construction of the Evoluon needed 60 km of scaffolding tubes and 10 km of wind struts with reuse included. The complete construction, foundation excluded, took 2 years.

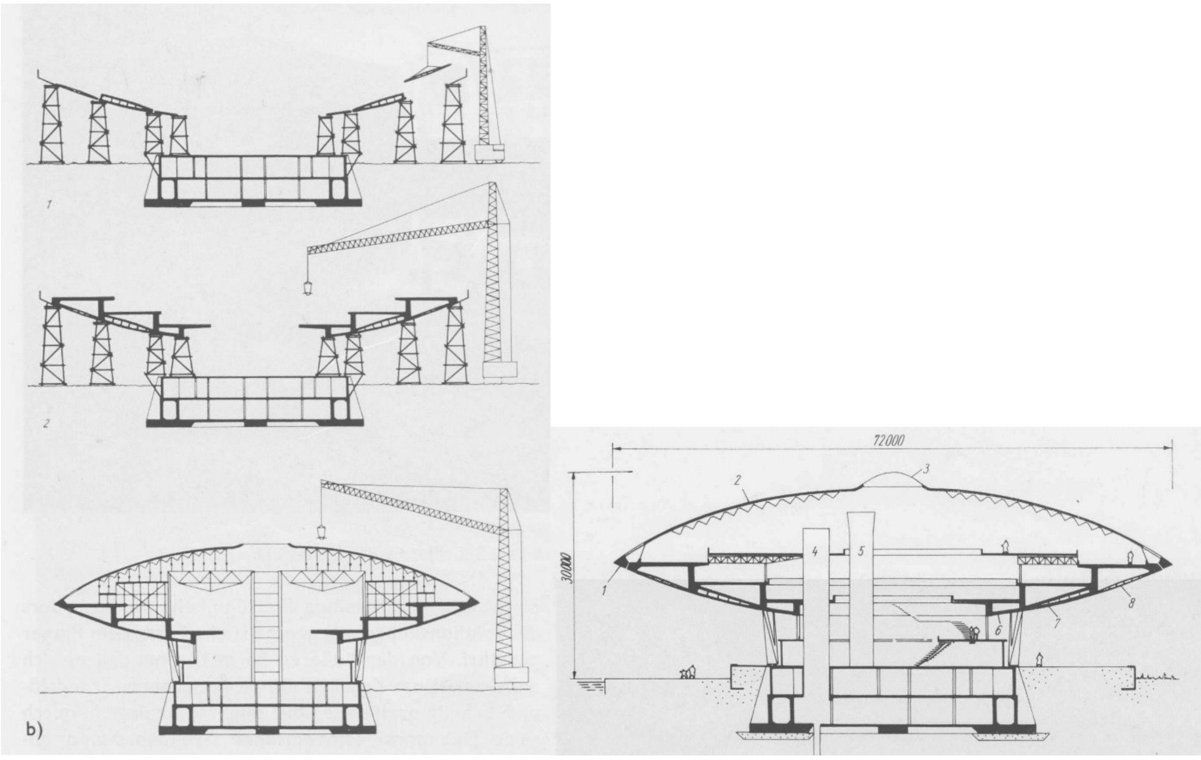


Fig. 14 Construction and measurements of the Evoluon. Designed by Kalff in 1966.

1 Tile vaulting

Tile vaulting, also referred to as 'Catalan vaulting', is a 600 year old Mediterranean construction technique. Making use of small sized brick tiles and fast setting gypsum mortar the method got know along the work of several architects and engineers like Antoni Gaudi and Rafael Gustavino (Block and Rippmann 2013). The construction method proves to be very economical due to the repetitive bricks and fast construction. Several layers of bricks of 15-25mm can be joined in cantilevering state by the fast setting mortar only needing 5-20s to dry(Davis, Rippmann et al. 2012). With the right tiling pattern it can cantilever out for a few rows before the second layer is needed. This means that the method uses almost no falsework.

Fig. 15 Gustavino Vault at the City Hall Metro station New York. Designed by Heins and LaFarge in 1904

In recent research done by Prof. Phillipe Block at the ETH Zurich a prototype of a free form funicular vault has been constructed (Davis, Rippmann et al. 2012). The vault was first form found with a Thrust Network Analysis with the previously mentioned software tool Rhino Vault. Cardboard boxes where laser cut to get the shape right and support the suspending tiles temporarily before stable sections where joined. The method starts with the edges of the openings and the builds up from the supports. Complications where found in some hard curving sections where the flat tiles where found to course to make the bend.

Fig. 16 The prototype build by Davis, Rippmann and Block. Left: the finished vault. Right: The vault under construction with the cardboard "formwork" visible

The prototype has a covering surface of 28.6 m^2 and a thickness of 90-140mm. 2300 bricks at the size of 200mm x 40mm x 120mm where used weighing 1 kg each. The total structure took 2 bricklayers 340 hours to build giving it an approximation of 11.9 hours/m^2 per two workers(Davis, Rippmann et al. 2012).

The prototype was a small scale building with only limited thickness. When span increases thickness and layer increase with it increasing the needed amount of bricks exponentially. This will also exponentially increase the amount of labor making tile vaulting in its current form less applicable for large span shells. The near elimination of supports does make it an interesting case study.

[2 Sport hall “W. I. Lenin”]()

In 1959 the state polytechnic institute of Georgian SSR developed a building method that fully excluded the need for support for dome structures (Sanchez-Arcas 1961, Rühle 1970). The method was first applied on the sport hall “W. I. Lenin”. A dome with a span of 30m composed of 126 prefabricated elements divided into 5 sizes. The panels where fixed row by row in the building order displayed in fig 17 . After each ring all panels are connected by poured concrete making it into a monolithic structure that makes can make use of the compression ring feature of a dome. Each panel had a Z-shape in which the back part of the panel being installed was fixed to the front part of the previous panel. Because the connection was in the middle of the cantilevering panel the moment forces are taken up by both panels. This is further stabilized by a temporarily brace fixed to the installing panel. This brace guides a small cable with distance over the cantilever point to the pervious panel cancelling any further cantilevering moment forces. Visualization is provided in fig 18. It is reported to be constructed by six builders in 22 days.

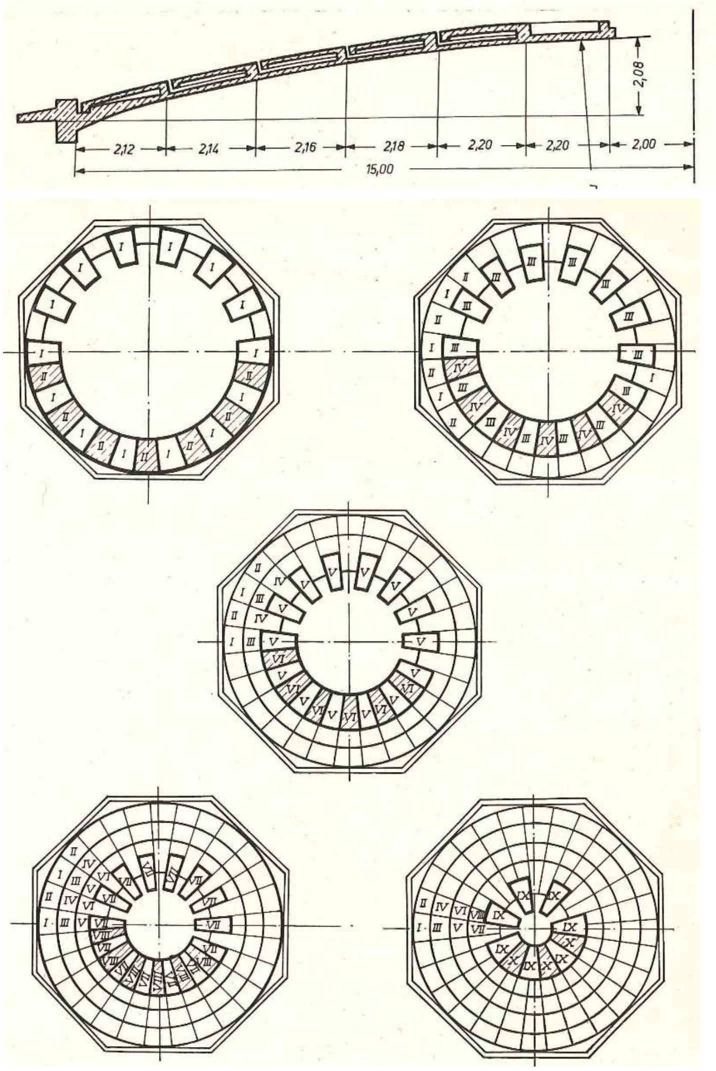
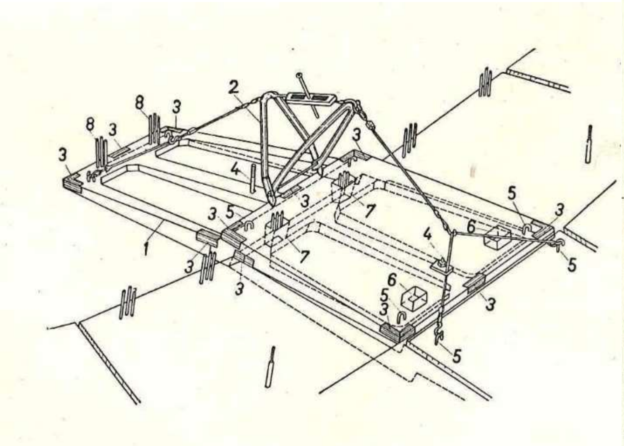
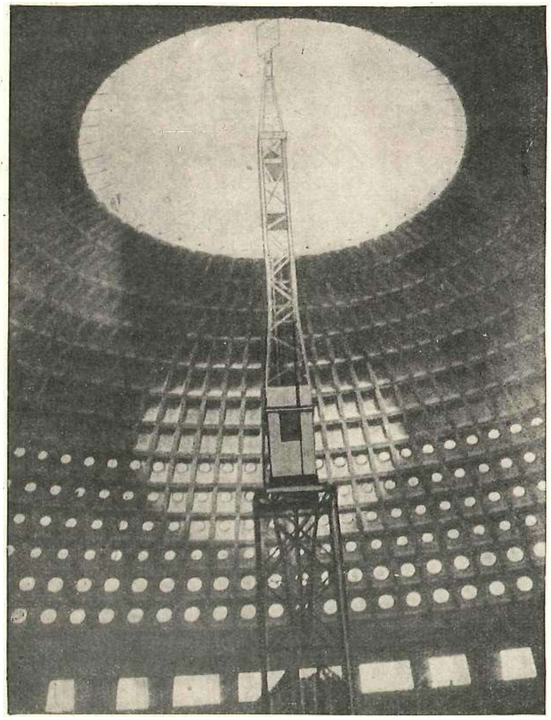


Fig. 17 Section and building sequence of Sport hall “W. I. Lenin”. Panels alternate to reduce the cantilevering moment and optimally use the monolithic dome characteristics.

There is only one more dome reported to be constructed with this technique and hence completely without supports. This is a market hall in Algeria build by architect M. Mouri with a span of 41m. Compared to the sport hall “Lenin” there is a photograph of this building during construction. The rest of the buildings are only reported as projected. Although several sport hall “Lenin” existed in the Soviet Union, one with this dome roof from sixties is hard to find. There is hunch that sport palace

Tbilisi is the structure in question but further research will have to be conducted. It is of course know that in the USSR period a lot of technological innovations and data got lost. Even though some system drawings and descriptions exist, the scarce amount of information available on this method makes it less reliable. Besides that the method make use of the compression rings forming in domes. This will not be applicable on free form shells. The brace tie and the Z-shaped panels on the other





hand can be useful when designing a new construction method.

Fig. 18 Left: The cantilevering moment brace used for installing the panels as developed by the state polytechnic institute of Georgian SSR

Right: The Market hall in Algeria under construction without the use of supports.

3 CNIT, Paris

Some building method are not only interesting for their building method, but also for their building order. The Centre National de l'industrie et de la Technique in Paris build by N. Esquillan (Sanchez-Arcas 1961, Rühle 1970) for instance. The floorplan in the shape of a triangle is divided in constant quads fig 19. Arches span from the corner to the division lines between the triangle center to the middle of the edge. Even though this shell is cast-in-place a large reduction of scaffolding and formwork was established by dividing the construction into 3 stages. In the first stage the center arches where build from all 3 sides. When the arched where cured, they could stand freely as a stable structure. The next two stage build outward from these center arches only expanding a already stable structure.

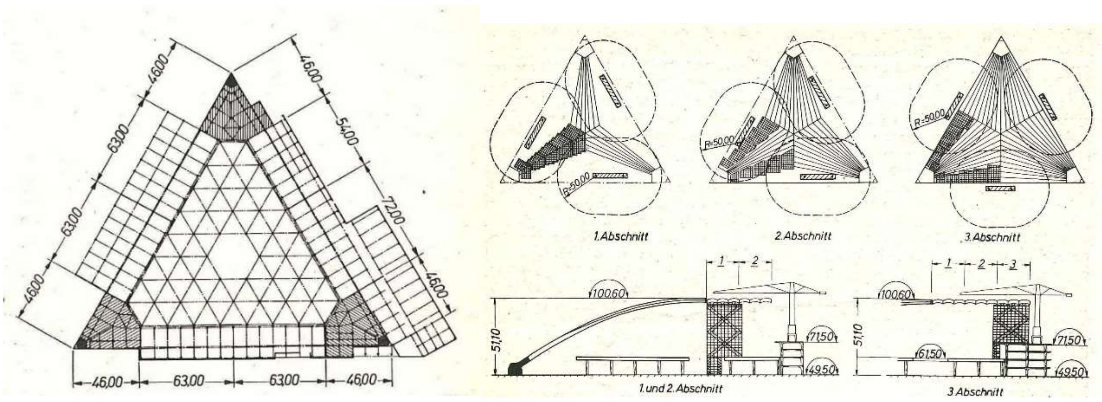


Fig. 19 The Triangular floorplan of the CNIT build by N. Esquillan

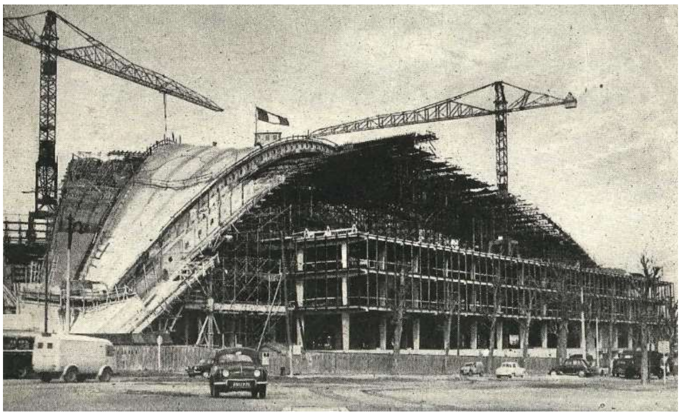


Fig. 20 The CNIT under construction. Picture is taken at the transfer from stage 1 to stage 2.

Making use of the fact that 3 arches leaning into each other would bring about equilibrium, the supports and formwork could be reused 3 times. It is an interesting incentive to look for the parts of a structure that can be constructed first and are stable by themselves.

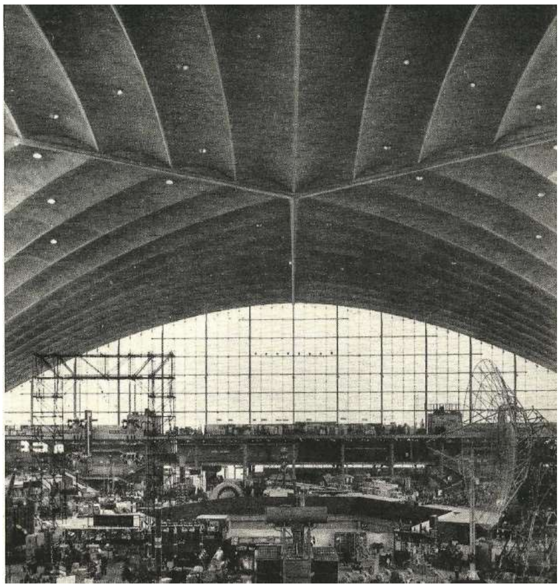


Fig. 21 Internal view of the CNIT with the clear divisions of the 3 arches.

3 Canopy for loading platform Florence, Orlandi

A cantilevering canopy was built for the loading platform of a market hall. The structure cantilevers out 16m and is 60m wide (Sanchez-Arcas 1961). The construction is made out of a wave pattern along the width that is most extreme at the base and dampens at the end of the cantilever fig 22.

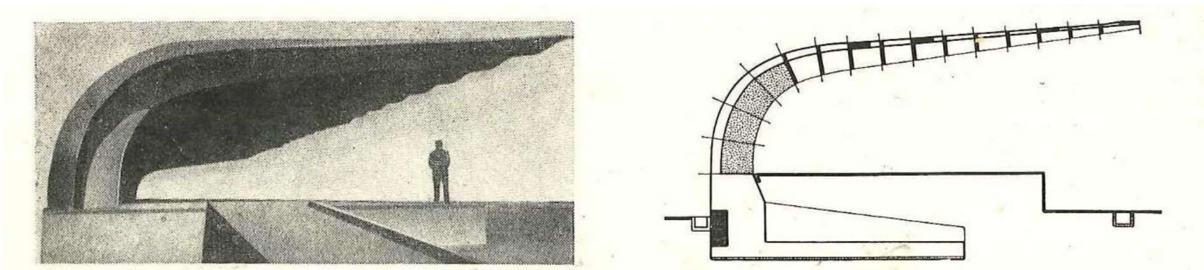


Fig. 22 canopy design of Orlandi for a loading ramp in Florence. Left: Impression of the finished shape. Right: Segmentation in section. The hatched first four segments are cast-in-place.

The structure is divided in 16 parts of which the first 4 are vertical. These first 4 parts are cast-in-place and pre-stressed to form the base. From there on out the parts are prefabricated. In groups of two or three they are joined together and post stressed to cantilever out from the base without support fig 23. The full completion of the canopy took 32 days.

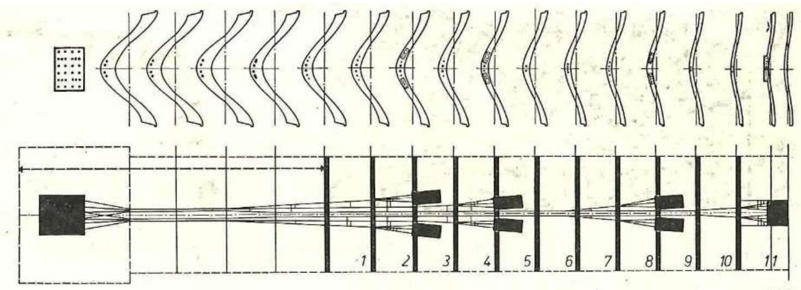


Fig. 23 Placement drawings of the posttensioning threads through the canopy. Threads are split and anchored in sections 3,5,9 and 11.

4 Posttensioning: Pre Vault pavilion/Utzon 40

The idea of posttensioning structures for stability has been used in multiple previous examples (Sport hall Lenin & Orlandi's canopy) and a variation is found in recent research as well. Two tests were conducted, the Pre vault pavilion in 2011 (Block, Knippers et al. 2015, Pedersen, Larsen et al. 2015) and the Utzon: 40 pavilion. The Pre vault pavilion conducted research in flexible concrete casting and the use of cardboard formwork (Pedersen, Larsen et al. 2015)and the Utzon: 40 project in support free building and flexible concrete casting.

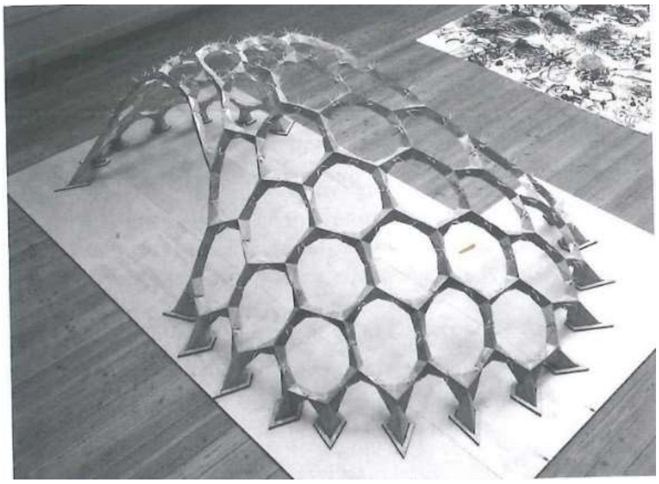


Fig. 24 Utzon 40 final pavilion.

Both pavilions are grid shells made up out of Y-shaped elements. These elements are strung together by an internal post tensioning rifling that is tightened by blots on two sides fig 25. Both methods have unfortunately still encountered problems when closing up the top of the shell and needed strutting. Other methods have been tested as well prior to construction of the pavilions. Application of tension rings, internal and external, but the element to element connection has proven most potential.

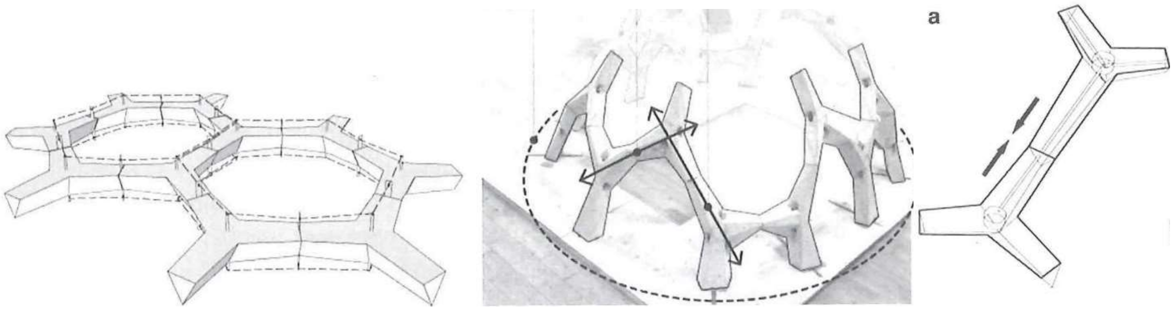


Fig. 25 Left: Outer tension ring method; Middle: Connection procedure; Right: Final connection scheme

Although the projects had a complete digital workflow to determine the casting elements both did not incorporate FEA analysis in their research. Hence this is recommended in the conclusions of the Utzon:40 Project (Pedersen, Larsen et al. 2015). Also larger scale structures is recommended as a base of future work (Pedersen, Larsen et al. 2015). Besides the made recommendations these tests have been conducted on grid shells. Application on a 3D panel structure is jet to be conducted.

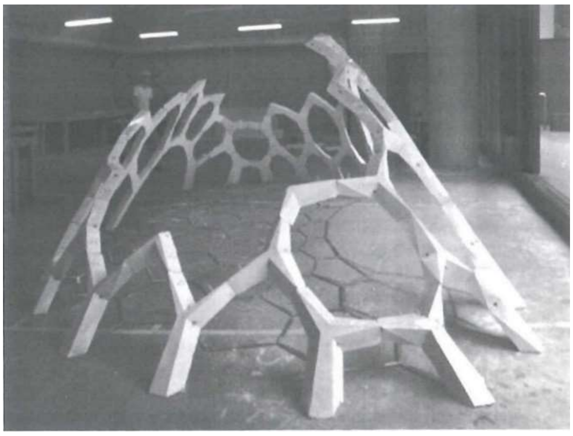


Fig. 26 Incomplete Utzon 40 structure standing without supports. Proof of concept for the small scale grid shell.

5 Preassembly: Skilled- in office, RAP Studio

The last example will deal with a case of support reduction by preassembly. It's implemented in the design of a roof for an free standing office space in the main hall of the RDM campus. The roof geometry was form found using Rhino Vault and the divided into an esthetic triangle grid. The grid was then further developed to match production requirements. Production was done by robotic milling of the panels with finger welds. The panels were nested on the material to align the woods stronger fiber direction with the estimated force direction working on the panel in the assembled structure.

Fig 27 Office space constructed by studio RAP on the RDM campus, Rotterdam

For the structure assembly first the supporting middle column was erected. From then on three arcs, from the central column to the supporting edge, were preassembled and supported. In between there arcs the remaining panels were installed without the need of further support. During the installation of the rest of the panels the preassembled arc stabilized the central column and acted as supports for the rest of the structure.

During the installation of the last panels problems arose with the fitting of the elements. Deformation of the structure caused problems in the fitting final panels which were fabricated with high precision derived from the computer model. The deformation was countered by extra supports combined with forceful insertion of the panel.

More information on the skilled in office can be found in the interviews in appendix A

Connections

The subject of connection is researched in a parallel track by Ir. P. Eigenraam. The simultaneous studies will be combined and tested along with the construction method and FEA's. Below a description of the methods found in research on other subjects is presented. This contains applications of adhesives, bolts, "wet", post tensioned, screwed and finger joint connections. Further research specific into connections will be conducted by Ir. P. Eigenraam.

In the example of tile vaulting (Davis, Rippmann et al. 2012) the tiles are connected by fast setting mortar (fig. 16). Being an unreinforced shell no other materials are used than the tiles and the mortar. This can be seen as an adhesive connection between two flat surfaces. Adhesive connections are not uncommon in the world of shell structures. Since panels are primarily transferring in-plane shear and normal forces and, when properly designed, limited bending and out-of-plane shear forces adhesives are a logical option. Adhesives in combination with mechanical elements are also used by F. Veer (Veer, Wurm et al. 2003) in the construction of a glass structural dome. Downsides of adhesives primary lie in their application conditions. In a lot of cases adhesives are to be applied under clean controllable conditions which are not cheaply available at large construction sites. In the case of mortar conditioning is already less of a problem but bending stiffness is reduced. Adhesives therefor might be applicable but only under certain conditions of application or force limitation.

In the case of the Sport hall Lenin (Sanchez-Arcas 1961, Rühle 1970) bolted and wet connections where used (fig. 18). Bolting was done to secure the center rotation axis of the Z-panels and "wet" concrete connections that attach cast in pins to the already installed panel. Both connection types come in a large range of variations and are commonly used in the construction of panelized shell structures. Further research must be done on the ones most applicable.

In the cases of the Orlandi canopy (Sanchez-Arcas 1961) and the post tensioned grid shells (Pedersen, Larsen et al. 2015) an internal tensioning rod is used. This rod or cable is threaded though the internal, in both cases concrete, volume of the panels. Tension is put on the cable on the exiting side pressing the concrete elements together. Orientation of the panels can be achieved through shape or inserts. These shape and insert elements are not of structural significance although they can be used for countering out-of-plane shear forces.

Fig. 28 Construction of the Landesgartenschau Exhibition hall

The final case describes the Skilled In office and the Landesgartenschau Exhibition Hall (Krieg, Schwinn et al. 2015, Li and Knippers 2015). The plywood panels are digitally fabricated through the milling of panels. Finger joints on all side take up the in-plane shear forces and normal forces. This needs to be done with a high level of precision to not cause point loading in the joining edges. If not, the point loads can cause material failure leading to structural failure. This tight fit of edges over a double curved geometry also requires the edges to have a twist. Without this twist the panels will not align tight enough. This twist can be reduced but not eliminated.

Related fields

Building without falsework is not something that’s only relevant to architecture. Bridge building for instance has been forced to build without falsework simply because they do not have the luxury of a surface to support on. Bridges over fast flowing rivers and canyons require different building/supporting methods. Two main methods have been described in this chapter.

1 Cantilever bridge building

The first method is cantilever bridge building. Bridge parts, when not connected to the next part, cantilever out into free space. This cantilever is compensated in two different ways, by balance and by arm.

The balanced method build out from its support to both sides. By building at an equal pace at both sides the structure is in balance over the support in the middle. Connections between support and bridge deck are over dimensioned to take up the moment forces in the bridge deck as it expands into free space. Illustration and force flow is shown in fig 29.

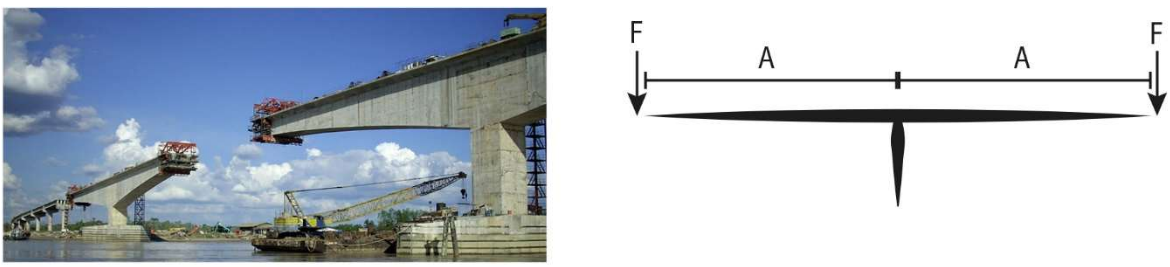


Fig. 29 Balanced cantilever building with force concept diagram.

The second method is by arm. When building from a rock face out balance cannot be kept. In this case construction is preferably kept lightweight and the rock face arm is enlarged. This way one can build out piece by piece into free space. Illustration and force flow is shown in fig 30.

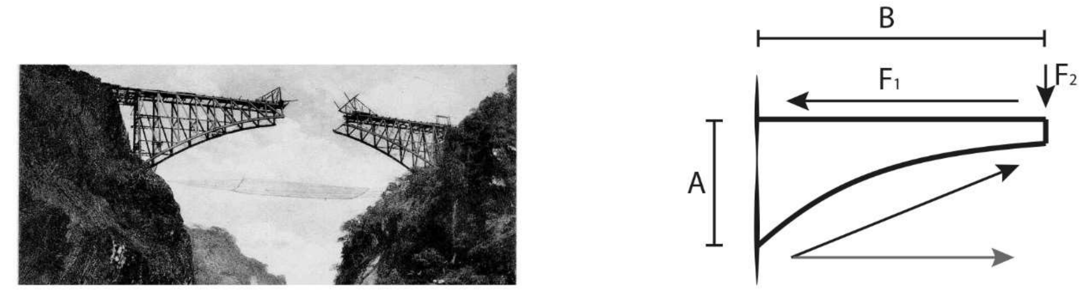


Fig. 30 Cantilever building over canyon with force concept diagram.

Even though both methods exclude the use of falsework they both use over dimensioning to compensate for the forces. Applying this to shell structures would undermine the material efficiency of the structure. However one needs to weigh the pros and cons of such a solution.

2 Cable stayed bridge building

Another method found in bridge construction relies on the temporary support from temporary towers where the incomplete structure is strung up from. This relates to the way cable stayed bridges and suspension bridges are build. Difference lies in the temporality of the support. Where in the cable stayed bridges the towers are a permanent part of the structure, they are mimicked in for other bridge types. An example of this building method is the bridge over the Hoover dam shown in fig 31.

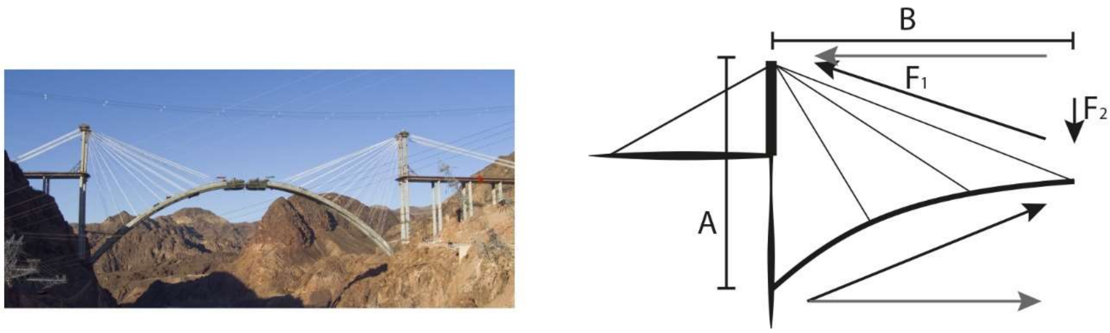


Fig. 31 Cable stayed building with force diagram.

The stated method makes use of temporary support which is in contradiction to the stated research question. However what might be interesting is the position of the support which is not anywhere in the building plane. Supports like this can be positioned in such a way that construction beneath the shell can proceed. One has got to consider the amount of material such a support method would require which might not have the desired financial benefits of building without falsework.

How do we design a construction method?

In the previous chapter and overview has been given on the definition of shells and the construction methods. The following chapter will look at design and optimization methods for prefabricated shell structures and the building order. As stated in the delimitation, shell form optimization will not be included.

Panel patterning

To build a prefab structure one must first determine what the structure consists of. This chapter will provide a view into the patterning of prefabricated structural panels and the accompanied problems.

First of all one must understand that in patterning there are several degrees of complexity. A method of rating this complexity is by the amount of edges coming together in on knot or vertex. The more edges come together the more panels need to be connected lowering your margin of error (Pottmann, Eigensatz et al. 2015). For instance having 6 panels(60°) come together in one point is substantially more complex that 4 or 3.

This was also noticed in the construction of the Skilled in office by RAP studio. In this case the triangulated pattern was chosen for esthetic and fabrication (flatness) related reasons. With more triangles coming together in one point margins have to increase leaving crevices. In the case of the Skilled in office this could fortunately easily be solved with small refinements combined with the light and flexible properties of the material.

Fig. 33 The complexity of multi panel connection points (Skilled in office, RAP Studio)

When multiple panels come together the forces get more distorted giving higher peak stresses as well. This will be further addressed in the panel optimization methods.

One can look to nature for geometric solutions. In nature material efficiency and production energy are more expensive than geometric complexity and patterning is already structurally optimized. For the Landesgartenschau the sand dollar was taken as an example fig 34. Both hexagonal shape and finger joints are derived from this sea shell (Krieg, Schwinn et al. 2015).

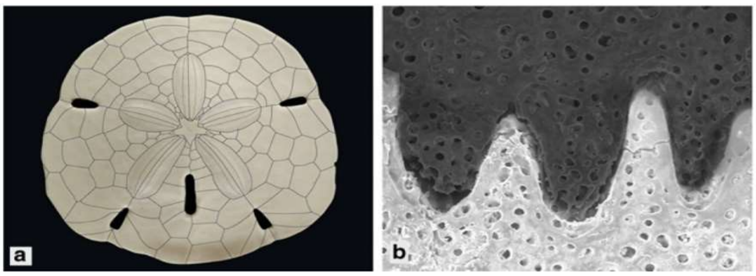


Fig. 34 Left: The sand dollar shell devision; Right: Connection principle of the sand dollar

The pattern was here adapted to the curvature of the geometry. In the negative Gaussian curvature areas the pattern was dovetailed which transferred to hexagonal in the positive areas. When the pattern tested on the 3D geometry of the Landesgartenschau Exhibition Hall the calculations bared a weak point in the pattern on these transfer areas. This weak point was a connection edge where, due to the changing of the panel from dovetail to hexagon, a continuous straight connection edge was situated over several panels. This formed a buckling seam where all stress had to be taken up by the detail. This was eventually solved by consideration of the bending properties of used screwed connection elements. General results also showed that stiffness provided by the trivalent geometry is much larger than that of the screwed connections (Li and Knippers 2015).

Prof. P. Block (Rippmann and Block 2013) provides several contributions to the field of complex 3D patterning. A first contribution is providing an equal fit for all elements in the structure (Lachauer, Rippmann et al. 2010). This is done through dynamic relaxation of a projected pattern. One can set different requirements/controls to limits shape freedom and element geometry. This can be anything from edge length and area size to pattern geometry and production restriction. Points of the pattern can move freely or are bound to certain lines depending on the set requirements. This will always provide the designer with a good pattern fit for the complex curved structure.

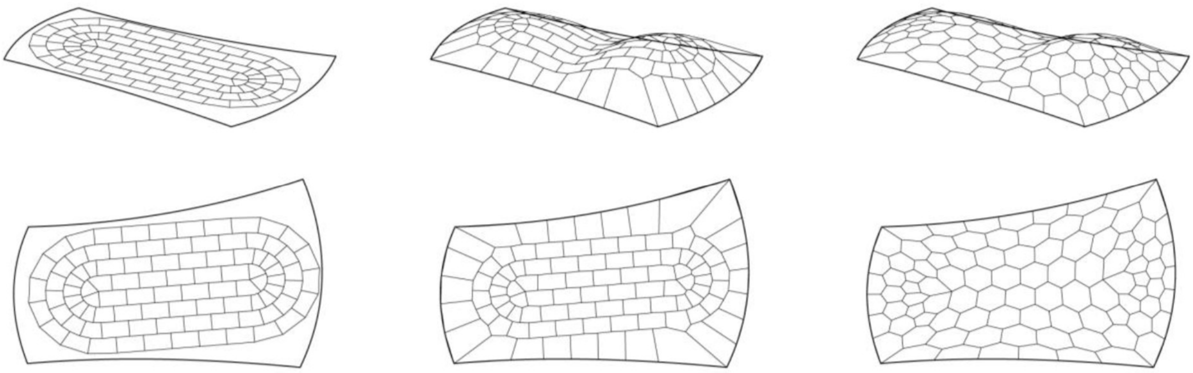


Fig. 35 Dynamic relaxation demonstrated on a double curved shape. Images, left to right, are of 0, 5 and 200 iterations.

The second is an practical example of pattern adjustment to complex geometry. In the design of unreinforced masonry shells, brick form is used. Stated here is a requirement for aligning panel separation lines perpendicular to the force flow to prevent shear forces in the connections. Furthermore, three shapes of bricks where researched: rectangle, hexagonal and dovetail hexagon. Because the paper aim for a dry brick assembly (without mortar) the self-locking dovetail was chosen in which compression keeps the bricks together. Noted is that the many faces with different angles and dovetail shape require a high geometrical precision.

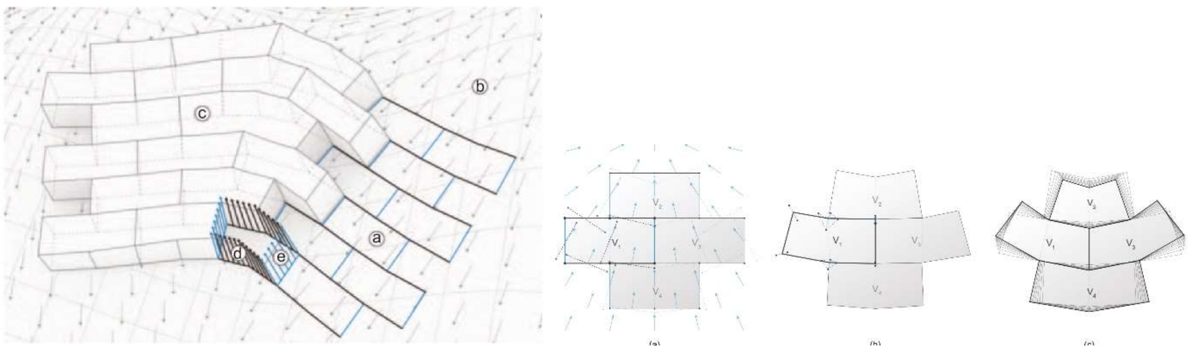


Fig. 36 Orientation iterations to align panel and force flow.

Force flow optimization methods

The computational design of complex geometry has been more and more relevant since computational fabrication methods started taking flight. In these developments optimization methods are most commonly found for shape optimization and optimizing for fabrication requirements. However for structural optimization of the patterns only few scientific precedents exist. The main focus here will be on Landesgartenschau and MLK Jr Park. For a building order optimization there is no precedent.

In this chapter we will first look at the precedents for structural pattern optimization. Afterward, the building order optimization will be addressed.

Force alignment (MLK Jr Park)

As stated above there are only few precedents exist of these kinds of optimization. The main precedent is the MLK Jr Park vault (Rippmann and Block 2013). As a means of making maximum use of compressive nature of the brick they sought to align the faces of the bricks to the direction of the force. The optimization consists of several steps described below.

A first analysis of the complete monolithic shell provides the principle force and direction at specified point on the shell. The brick pattern is then mapped over the shell geometry and taken trough several iterations of dynamic relaxation to make it fit into all corners. The horizontal pattern lines are the linked to a specific vector from the finite element analysis. These pattern lines are then rotated around their center to a 90 degree angle with the corresponding vector. This causes the pattern lines to detach from one another. To reattach these and average point is made of the line ends that were previously joined together. The new lines are drawn from the end point averages. These geometrical alterations are repeated until the max alignment or max pattern alteration is met. The result is a geometry in which the building elements are as close to perpendicular to the flow of force as possible making it ideal for compressive materials.

The method addresses simple structural principles in the geometrical optimization of the element. This should ensure a smoother flow of force and therefor the reduction of peak stresses. This has however not been verified by FEA. Later on in the proposed process this element will also be optimized for production.

Pattern & detail influence (Landesgartenschau)

In the case of the Landesgartenschau the pattern of segmental plates affects the force flow of the shells (Li and Knippers 2015). Since the material is discontinuous at the joints forces are redirected when passing through the joints. Stiffness of the joint also affects the force transfer, stiffer joints attract higher forces. With these properties one can adjust force flow through the segmental panel shell.

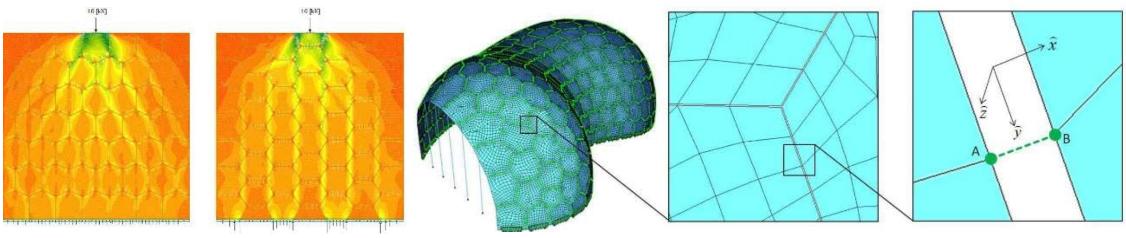


Fig. 37 Left: Force flow through different division patterns; Right: computational simulation of connections by node-to-node springs

The difference between a 90 degree turn on a hexagonal pattern for instance is displayed in fig 37. The distribution of force in the left image is far better than the right image, this is contrary to what one might expect based on the force alignment method. Even though in this project no optimization of the pattern is conducted, the influence of the pattern on force flow is clearly visualized. In the final analysis, that included detail simulation, the influence of the details is also shown preventing more material usage. The implementation of FEA earlier in the design process proves to have great effect on the structural optimization of the prefab panel structure.

Concluding on these two examples a force alignment might give a more optimized pattern but needs to be verified. The influence of the pattern on the flow of force must me included/considered in the optimization. The implementation of FEA on each iteration of the algorithm can visualize the improvement and counter possible impairment.

Unfortunately, due to the limited time span of this research, a full pattern optimization is not possible. However, the principles of these optimizations will be used in the pattern design for the chosen shell.

Assembly optimization

From the designed shell we move on to the assembly of the structure. Because there is no scientific precedent of assembly analysis, one was imagined based on the reversing the construction sequence. In other words: the best assembly order will be found through the analysis of a reverse construction or deconstruction. The order of this deconstruction is determined through several selection criteria derived from Finite Element Analysis (FEA). Finally the complete deconstruction will we compared with deconstruction with preassembled sections.

Deconstruction

The deconstruction method determines a panel order based on FEA. It starts with a completely assembled structure. Through a FEA a panel is selected to be taken out. Then the geometry is again submitted for a FEA minus the selected panel. Based on the second analysis a second panel will be taken out. This will continue until the structure is fully deconstructed. This will present a building order together with a structural analysis each step of the build process. This insight into the stability, deformation and stress levels during each step in construction allows the designer to check where and when support is needed. The designer can also determine if support is needed or that the stress and deformation can be countered through improving the panel/detail design.

The benefits of this analysis are predominantly found in the reduction of needed supports. This is currently based on the weight of the structure without taking into account what forces can be taken up by the structure itself. It does not only determine *if* support is needed but also *what kind*. What is the limiting construction factor at that point and how can it best be solved. This can provide a more efficient way of supporting a structure during construction and with that a reduction of cost and time.

Selection criteria

A FEA can tabulate multiple results like deformation, forces and stresses. This allows the designer to select panels on multiple criteria. Because of the detailed results it can also be decided on several levels of detail like panel average or detail peak stress. For the algorithm used in this research multiple selection criteria will be tried so that an insight is created into the consequences. All selection orders will be documented to see what might be the best selection criterion.

The final deconstruction was done with the following selection order:

1. Lowest average stress panel
2. Lowest average normal force panel
3. Lowest peak stress on panel
4. Highest position in structure

In this order the first criterion will be analyzed first. If there are multiple panels with an equal value, or a value within a certain margin of each other, those two panels move on to the next selection criterion. This will continue until one is left and is extracted. It is believed that four comparisons will always assort a single surface.

Pre-assembly

In interviews conducted with RAP studio and BAM both revealed the use of preassembly in the construction of prefabricated structures. Full Interviews are provided in Appendix A.

In the case of Arnhem central station, constructed by BAM in steel ship-hull elements, a proposal was done to install large beams over several axis in the geometry that could stand on its own. In between these arcs the prefabricated elements would be installed. The plan was abandoned because the beams would need to high dimensions to fit within the esthetic demands by the architect.

In the case of RAP studio's Skilled In office three arcs, consisting out of the panels that would be installed along that axis of the geometry, were preassembled in between the central column and the surrounding support edge. This was done to stabilize the structure and allow the other panels to be installed without the need of more supports.

The method of preassembly can provide stabilizing edges and decrease deformation during the incomplete stages of the structure. it is possible to combine this with the deconstruction method by locking some panels from extraction. It can also be decided that preassembled parts are installed in separate stages.

Conclusions

To summarize a short conclusion is provided. This will provide the base for the following design. chapter.

Panel patterning & optimization

Because a pattern optimization with force alignment algorithm is not possible within the given timeframe a pattern must be designed. The optimization methods however, give several pointers on strengths and weaknesses in structural pattern design.

Tile vaulting taught us that not only the construction method but also the assembly order is of great importance for supportless construction. The assembly patterns in tile vaulting are set up in such a way that, like in Igloo construction, each panel will always have two connecting sides. A single edge functions as a rotation axis over which forces must be countered by the connection. A dual edge connection moves this rotational axis onto the panel so forces are distributed over multiple edges. The moving of this rotational axis does not only distributes the loads better but also reduces the cantilevering area and replaces it with a countering arm as shown in fig. 32.

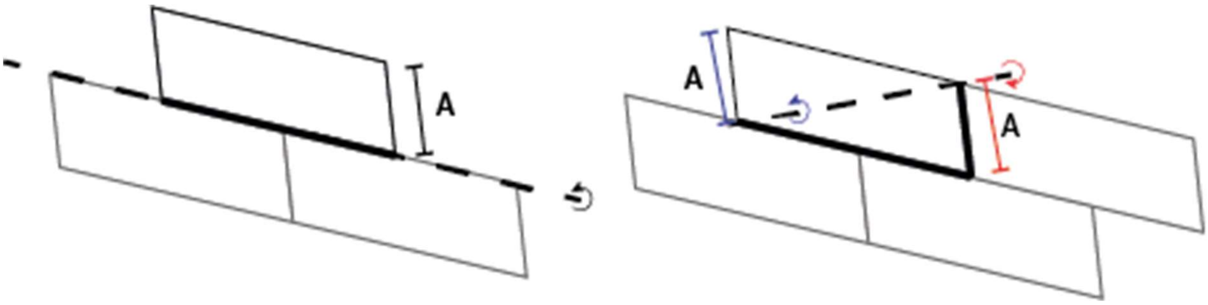


Fig. 32 Single and dual edge connections. The dual edge connection provides a smaller cantilevering area by moving the dotted rotation axis coincidentally creating a countering moment element area.

The general point on patterning is that structural patterning is not done by just mapping over a surface by projection of a flat pattern (Lachauer, Rippmann et al. 2010, Rippmann and Block 2013). When designing a pattern on a complex 3D curved shape one must account for fitting, force, production and geometric complexity. *Aligning to the general flow of force* and equal distribution though *dynamic relaxation* are ways through which to achieve structurally sound patterns on complex 3D geometries.

This backed by the research for the Landesgartenschau (Li and Knippers 2015). The panel pattern has great influence on the flow of force. Details discontinue and redirect the flow through the material. Wrongly designed patterns can cause high peak stresses in the final structure. This should be tested through structural analysis. In this structural analysis the details should be included to get a proper result. This eventually might also help improving the structural efficiency (Li and Knippers 2015). Furthermore the research bares the weakness of a *buckling seam* in a 3D pattern. Long straight continuous edges should be avoided.

Posttensioning

Post tensioning as a building concept might not be scalable to larger spans but the method could still be used as a temporary countering of forces during construction. This could reduce tension and/or counter deformation of details.

Installation gimmick

During installation of the prefabricated elements one needs to hold the attaching element in place. This has multiple functions.

Firstly the elements connections will need to be attached which is preferably done with a minimum amount of stress on the element. As shown in the sport hall "Lenin" this can be reduced by the use of a installation gimmick transferring the forces to more stable elements of the structure.

Secondly the incomplete structure is very vulnerable for deformation. Too much deformation can cause elements to stop fitting. The installation gimmick might be used as a way to counter the most deforming parts of the structure. If this was used similarly in the sport halls construction is unknown but the structural principle is the same as for the installation. The cantilevering panel will be held by the gimmick until more surrounding panels are attached further stabilizing the structure.

Preassembly

The use preassembled parts was discussed in interviews with RAP and BAM. To improve construction speed, parts of the structure would be preassembled to form a stable building base for the rest of the structure. This can severely limit the cantilevering distance and related problems. This might greatly improve the building time and reduce material usage.

Assembly optimization

Currently no assembly optimizations exist. The method conceived is one of reversing the construction: Deconstruction. Because this method is not a proven method the extends of the methods will need to be tested to see what FEA results the selection procedure must be based on.

Preassembly of structurally crucial arcs, axis or edges is a method already used in construction. Although not always structurally analyzed/optimized, the method is used to speed up the building process. Deconstruction analysis can be complemented by the use of preassembled edges and used to determine the preassembled lines.

3. Deconstruction

In this chapter a clear description of the inner workings of the computer model will be provided. Then an existing shell structure is chosen to design upon, followed by the design of a prefabricated panel pattern. This shell structure divided into panels will undergo the deconstruction analysis. Several runs will conclude the best criteria for the analysis, where support might be needed and what kind of support is needed. Besides pure Deconstruction other variations of the method will be tested to find the extends of application of the method.

The chapter will conclude on the feasibility, efficiency and realism of the method and the derived structure.

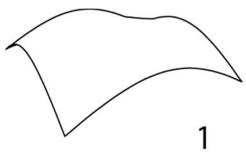
Workflow

A computational workflow is set up. This describes all the steps, from pattern mapping to deconstruction with preassembled elements, to perform a proper deconstruction analysis.

Workflow overview

First an overview will be provided followed by an elaboration of the deconstruction algorithm and the force alignment algorithm.

The workflow start with the picking and simple analysis of the shell(1). This will later help in the design of the pattern and provide base values to later compare and determine the efficiency of the construction method with.



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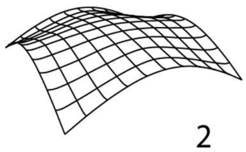
The second step is to determine the panel geometry and design the pattern on the shell(2). The papers of Prof. Block and Prof. Knippers provided several pointers such as Buckling edges and force orientation. Along these pointers a pattern can be designed. This will further be elaborated in the next chapter on prefab design. This pattern will be translated from free form NURBS geometry to the geometry needed by the Finite element program, In our case TNO's Diana. The translation must be done very carefully to ensure the correct results from the calculations. This paneled geometry will be calculated to provide base values



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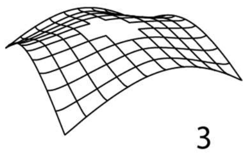
The third step is a first deconstruction analysis(3). Since we don't know what kind of pattern is ideal for deconstruction we again need base values to compare in the later stages of the workflow. This deconstruction provides these values and gives insight on the best analysis method and provides the stresses to design the details upon. The reverse deconstruction algorithm will be elaborated upon in the next sub chapter.



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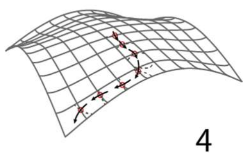
Then a Force alignment optimization is performed(4). This will further try to optimize the flow of force trough the panels to get a better deconstruction result. This will be checked by FEA to see if the changes in the pattern indeed give better results.



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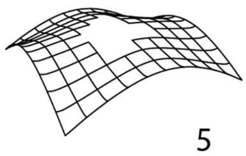
The improved geometry will undergo a final deconstruction(5). In several runs preassembly designs will be tested and the previously evaluated criteria will be put to the test. These deconstruction runs will provide the stress values for detail and panel design. Furthermore deformation values will be extracted for



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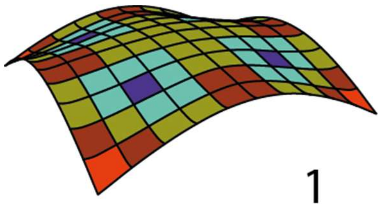
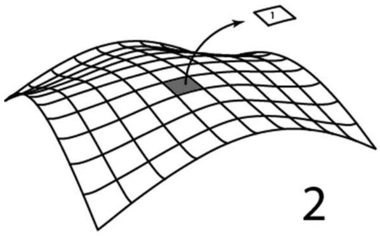
all stages of assembly to see how this can be countered or where support is still needed. The last run will also provide the order of assembly for the designed shell.

Deconstruction algorithm

In the chapter on optimization a justification of the deconstruction algorithm is given. This chapter will describe the step taken in each iteration of the algorithm.

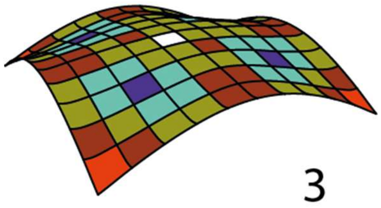


The paneled geometry is translated and provided with details. This will provide the forces for the full assembly and peak stresses that might be caused by redirection of forces. This geometry is then taken through a FEA (1). The tabulated results will be returned to Grasshopper and mapped over the surface. Relevant forces and vectors can easily be extracted in accordance with the selection criteria.



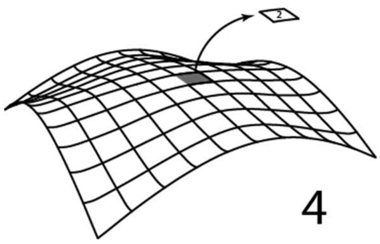
A singular or, in case of extreme resemblance between the results, multiple panels are extracted and logged in a separate text file (2). If the algorithm crashes the derived panel and its tabulated results will allow the designer to pick up where the algorithm failed.

The geometry minus the extracted panel(s) will again be translated so that all details concerning the extracted panel will be extracted as well (3). The geometry is then ready to undergo another FEA. Based on analysis of the semi deconstructed geometry a next panel will be selected (4). This selection and recalculation will continue until the geometry is fully disassembled.



The algorithm allows for the preassembly designs by extracting the preassembled panels and their results from the selection procedure. Because results of all panels are required these elements will be included in calculation on each iteration.

The algorithm will need to undergo several phases of testing and determination of the selection criteria amongst other things. This will be further elaborated upon in the Results chapter.



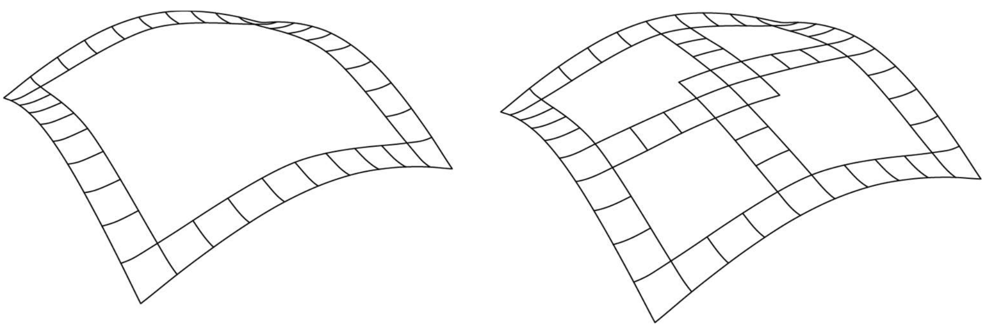
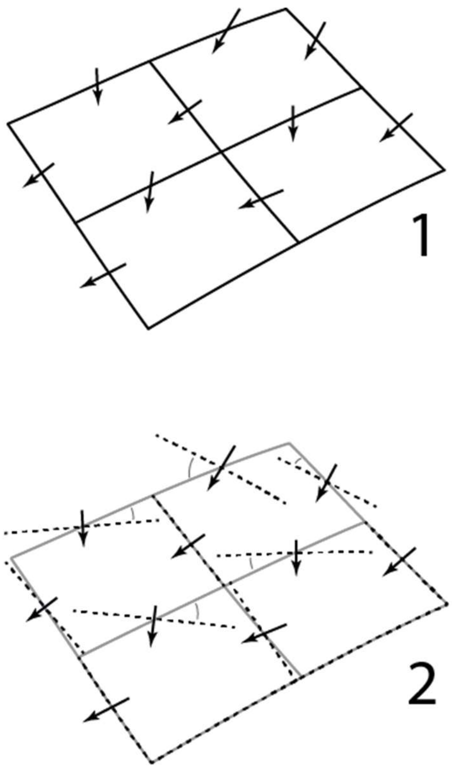


Fig. 42 Basic examples of preassembled edges and other possibilities

Force alignment algorithm

The force alignment algorithm of Prof. Block (Rippmann and Block 2013) is accompanied by a validating FEA per iteration proving the claimed structural optimization. Below a step by step run through is provided.

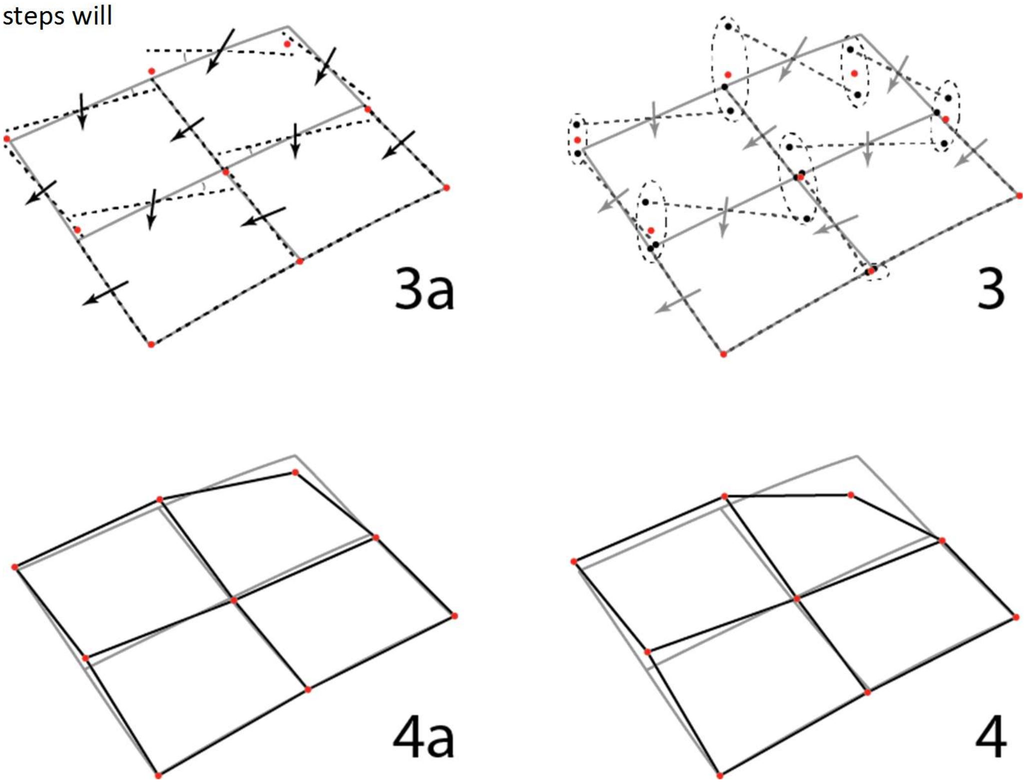


The algorithm starts with a structural analysis of the monolithic shell. This will provide the “ideal” situation of force flow. At all nodes in the structure the vectors are derived. The vector on the edges will be an average of the nearest 2 vectors to the curve middle point.

When the force vectors and the panel edges are matched up (1) the edges will be aligned perpendicular to the force vector (2).

This causes the endpoint of all the curves to scatter. Good data structuring however will allow the edges to rejoin. Of the edge endpoints of that where previously joined an average point will be created (3). This average combined with the average on the other end of the curve will be reconnected.

The new geometry will be submitted to FEA to see if the change in pattern had a positive or negative effect (4). If the result was negative (increased peak stresses or average higher tension stress) only half of the rotation of the previous step will be taken (3a). Too many negative steps will proof the method not fit for pattern optimization.



Prefab design

In this chapter the picked shell and its design will be elaborated upon. First the picked shell and it's characteristics will be described, followed by the design of the panel pattern on the shell. The final 3D panelized geometry will be ready for deconstruction analysis.

The chosen shell

To attempt the deconstruction analysis and find out if shell construction without supports is possible we must first have a test subject to design upon. Preferably a shell already constructed to so that efficiency of construction and structure can be compared afterwards. The chosen shell structure is Heinz Isler's swimming pool for Heimberg.

Fig.38 A outside and inside view of the Heimberg swimming pool by Heinz Isler.

The structure was designed and built in 1979 by Heinz Isler. Heinz Isler was known for his experiments with free form shell structures. To find the double curved shape he would hang cloths upside down and freeze them or harden them with wax/polyesters. These same experiments where used to find the geometry for the Heimberg swimming pool.

The double curved shell roof has a clear span of 32,5 by 32,5 meter with a concrete thickness of 90 mm. The deformation of the completed stable shell is only 1/4000 of its span compared to a current deformation limit for beams of 1/300. The material vs strength ratio is until this day unprecedented in traditional beam-column construction. The span to thickness ratio is 510:1 almost on tenth of that of and eggshell proving this a very efficient and economical structure (Chilton and Isler 2000). The edges of the structure are bend upwards so that this can act as a "edge beam" and divert the forces to the supports. This super-efficient structure will be the base for the further design and analysis.

The pattern

Using the pointers derived from the papers by Prof. Block and Prof. Knippers (Lachauer, Rippmann et al. 2010, Davis, Rippmann et al. 2012, Block, Knippers et al. 2015, Li and Knippers 2015) a pattern is drawn over the swimming pool shell. To explain the different steps taken 3 stages of patterning will be presented. These will be analyzed for flaws and accompanied by new pointers.

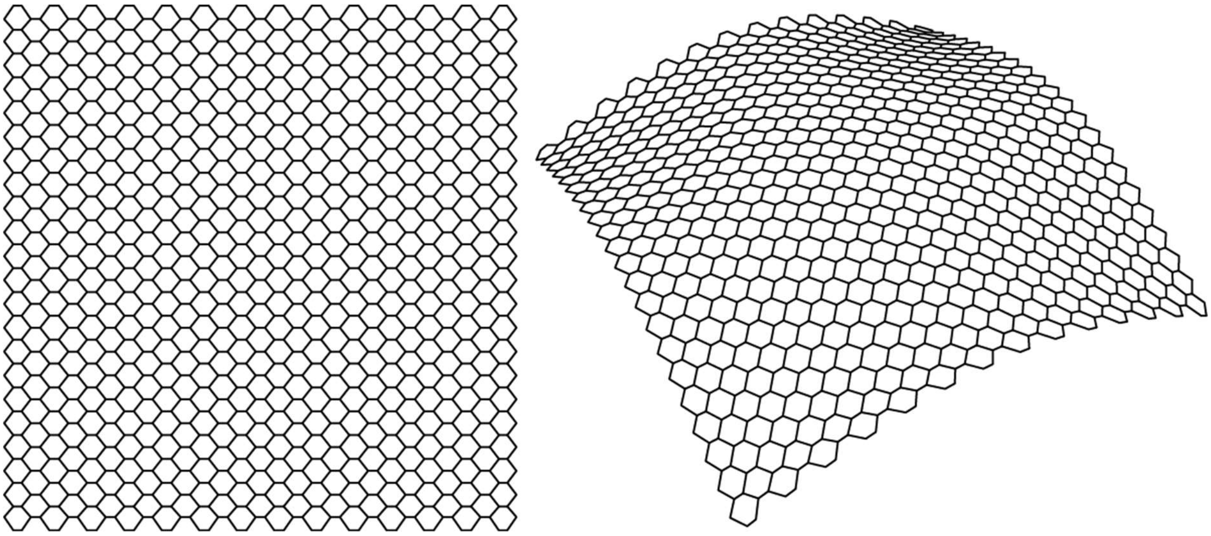


Fig. 39 Pattern stage 1 undirected unrelated hexagonal pattern

In the first stage a choice of geometry is made. The main pointers on geometry is to avoid long straight connection edges, reduce the amount of panels connecting in one point, avoid tight fits (account for margins) and make it multidirectional. A quick run through of basic primitive shapes like square, triangle, hexagonal and dovetail brought forth the hexagonal as the best geometric shape for free form pattering.

The hexagon is an easily applicable shape that is adaptable to various changes in geometry. Due to its six sides it can be skewed in nearly every direction without getting to unworkable deformations. In pattern 3 hexagonal panels connect in one point. This three way connection also prevents the development of long “buckling edges”. The near round panel also easily allows for margins of error and can transfer forces in all directions. The hexagonal pattern will be the base pattern for the further design.

Even though this is only the first stage one can also derive improvements to take to the next stage. For instance the pattern in this stage has no relation to the geometric shape. The panels are mapped according to the geometry of the square geometry instead of the supports and curvature. In the pointers on force flow in the MLK jr park vault (Rippmann and Block 2013) force orientation of the pattern is advised. Furthermore, when one takes a look at the panel patterning connected to the supports we find one panel per side supporting. These end connections should be divided over multiple panels to distribute the forces and improve stability. These pointers will be taken into account in the next phases.

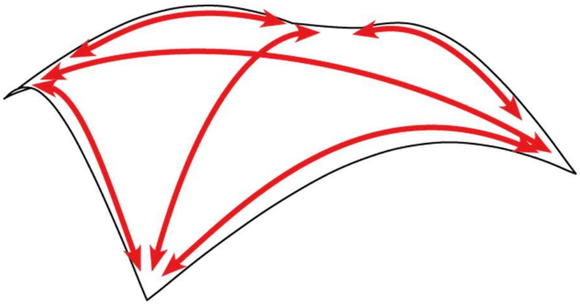


Fig. 40 main directions of curvature and force flow on Isler's Heimberg swimming pool shell

Before we start drawing the pattern for the next stage we must first derive the main directions of curvature and force flow from Heinz Isler's Heimberg swimming pool geometry. Basic knowledge of shell design and structural design give good insight into these characteristics. In fig. 40 the main directions are displayed. This consists of the diagonals going from support to support balancing out the structure and the curved up edges which divert force flow to the supports on either side. Along these main direction we can design a pattern as displayed in fig. 41.

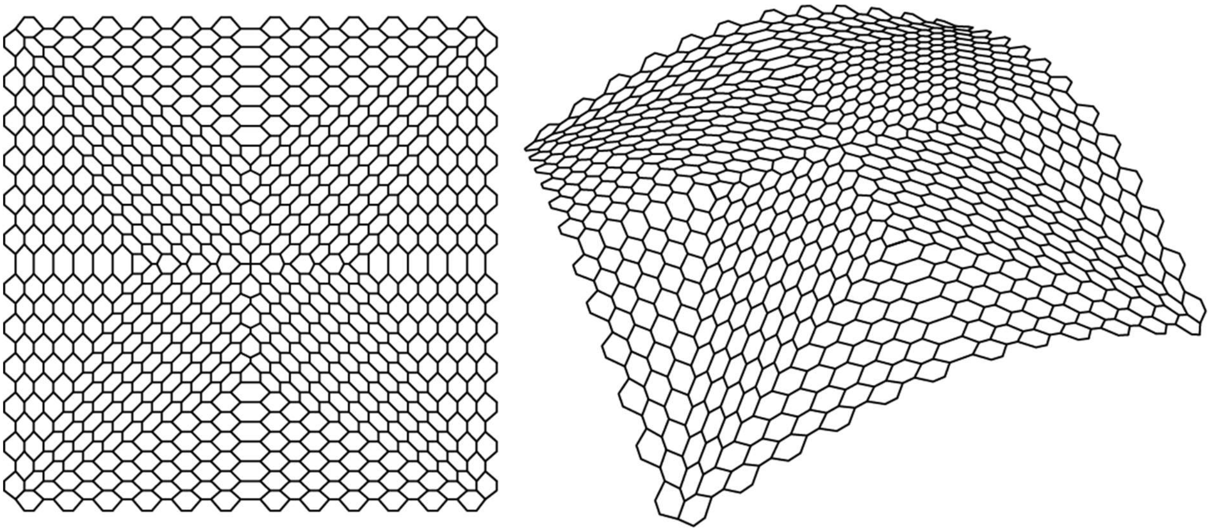


Fig.41 stage 2 The directional pattern designed on the curvature and force flow though the geometry

The pattern starts from two panels in each corner directed in the edge directions. In between these two panels the diagonal direction originates. The pattern from there on divides each corner in 3 parts two ways orthogonal and one way diagonal taking all needed directions into account. This three way division in the pattern direction will also eliminate the "buckling edges" even further.

The main problem in this pattern is the transfer zones between different parts of the pattern. Different sizes and directions could mean weaknesses in the pattern, more smooth transitions are preferred. Here dynamic relaxation comes into play. The transition panels need to be more evened out, relaxing the pattern and, for instance, equalizing the edge length or panel surface area could provide a more balanced pattern.

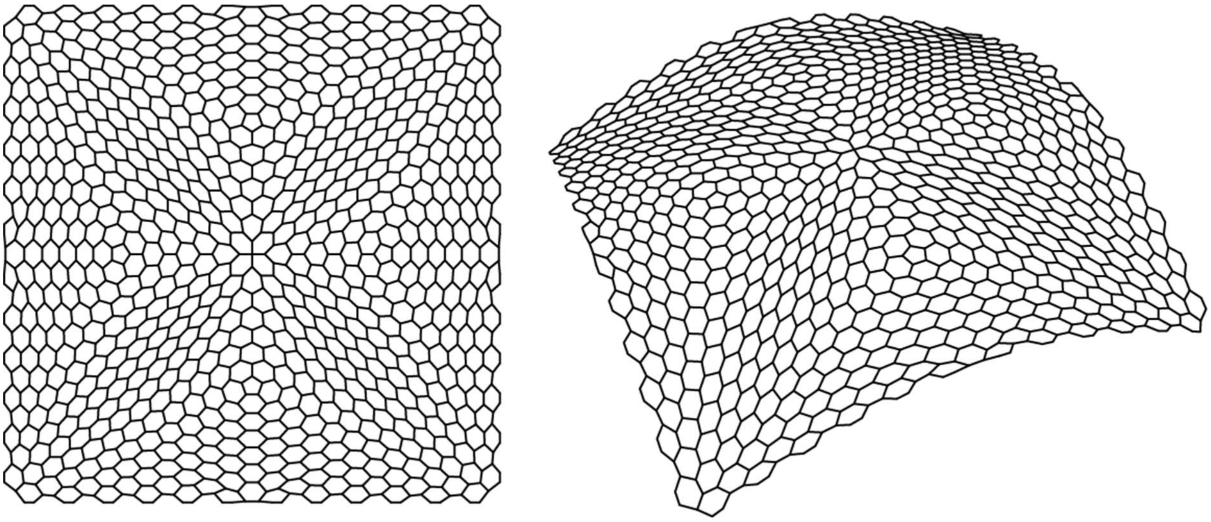


Fig. 42 the final stage. The three way pattern is relaxed and distributes more equally over the surface.

Dynamic relaxation is applied to the pattern while maintaining the surface geometry. The pattern is relaxed so that every panel has equal edge lengths. This allows for the transition areas to equalize and spread the transition. There is still a difference in panel size but this is much more equally distributed while the directions of the pattern are still maintained. This pattern meets the previously set requirements and will be used for the deconstruction analysis.

The relaxed pattern contains 680 panels. The size of the panels variate between 1,2 m to 2,1 m. This is currently based on transport and handling measurements vs workability of the algorithm. The current panel fits sideways into a container so that multiple can be stacked and transported in one container. The smaller panel sizes also give a more balanced deconstruction since less extreme steps are made per iteration.

Computational model

We have a test subject shell and divided it into designed pattern. To implement this into the algorithm it needs a computational translation/design. This chapter describes this computational design of the panels meshing and the design of the panel connections. This is a vital step in the translation from the geometric program (Grasshopper) and the Finite element software (TNO Diana). For this chapter prior knowledge of meshing terminology is required.

Meshing

When meshing a shell for finite element software a few things must be taken into account. First of is assembly order. This concerns the assembly order of nodes to construct a mesh face as well as the mesh faces to construct a mesh. Both instances determine the direction of the face/mesh normal vector. In Finite element software as well as in geometric modelling aligned normal vectors are vital for even results. Nonaligned normal vectors can give reversed results and distort the surrounding results. The translation to the finite element software requires a fully deconstructed notation of the mesh first describing all points in the mesh and then describing which points form which mesh. In this description order is as vital as the original construction order.

Furthermore, in contrast to geometric modelling, finite element software works better with quad meshing. This improves calculation results and display. It is preferred to have quad only meshes instead of triangulated or mixed meshes. Because we are working with a hexagonal panel this requires some creative designing.

First the panel is cut out of the NURBS shell geometry. These hexagonal are split into six diamond by curves drawn from the panel centre to the centre of each edge curve. These diamonds are all allready “quads” but for detailing puposes and detailed results we divide the into 4x4 matrixes. These six 4x4 matrixes are then welded, the term for joining meshes and mesh nodes, together. In this case each panel has 96 mesh faces and 121 mesh nodes allowing for a accurate description of the double curvature and detailed results in calculation. Since, in this case, the panels are relatively small compared to the overal geometry and curvature their individual geometry is almost flat. To maintain accurate results and fitting this slight curvature must be preseverd. That is why all created nodes are related to the original surface before creation and welding of the mesh.

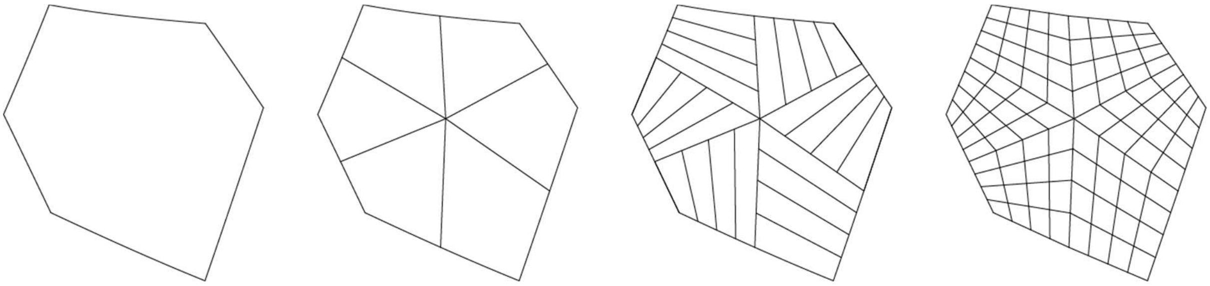


Fig. 43 The creation of quad hexagonal meshes. Step 1 The orivinal double curves NURBS surface. Step 2 Division of NURBS surface by lines from sruface centre to edge centre leaving six diamond shaped pieces. Step 3 Dividing opposite edges in four sections and connecting these. Step 4 Dividing these connecting curves into four pieces again and deriving mesh from the four by four matrixes and welding/merging these together.

This method of meshing is made possible by the large array of mesh creation possibilities in geometric modelling program, Rhino and Grasshopper. This way of meshing would not have been possible in the used TNO Diana 9.6 package. The combination of the extensive geometric features and the strong calculation properties of these two packages form a powerfull conection in the calculation of complex geometry.

Shown in fig. 44 is a comparison between the meshing options. Left is the custom designed meshing used in the deconstruction algorithm, in the middle is a basic mesher by Grasshopper based on geometric accuracy and right is the basic mesher by Diana mesh edit, the meshing program for Diana 9.6. As you can see the geometric double curved definition creates distortions in both in basic Grasshopper and in Mesh edit. This is because the computer is restricted to axial system to work from to keep geometric modelling simple and light and defines its meshes accordingly. Rhino and grasshopper however do allow for the designer to apply his or her creative sollutions making costum meshing of complex geometry fairly easy.

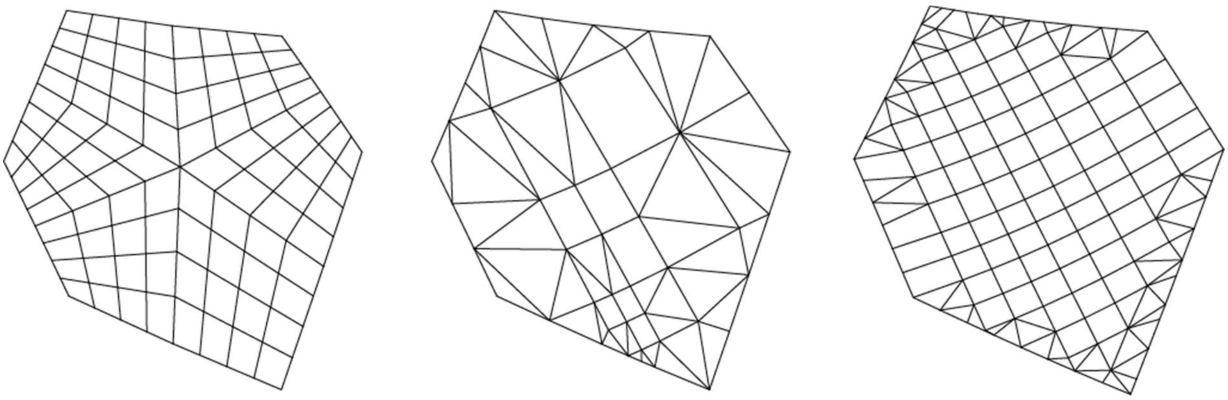


Fig. 44 Mesh quality comparison. left to right Used custom designed mesh, Geometry based Grasshopper mesh and the Diana Mesh edit mesh.

Connections

The connections between the panels are based on the research by Ir. P. Eigenraam. Because of the geometric variation throughout the structure this detail required margins all directions and when connected would have to transfer all forces and stresses between the panels. A welding solution was chosen with strengthening along the panel edge and into the panel in the form of anchoring. Two opposite plates are welded together along the overlapping edges. this can easily be performed under an angle and slightly displaced allowing for all margins needed in connection. The reinforcements of the detail are to distribute the forces over a larger area in the panel reducing the probability of failure between detail and panel.

In the computer model this is achieved by connecting three equally spaced nodes along the panel edge with their opposite twin nodes. This forms the first beam connection and represents the welded plates. The reinforcements along the edge and into the panel are derived from the custom designed mesh. This way all, in the meshing, created nodes are reused greatly reducing the amount of nodes needed for the model. Free creation of details would amount to an extra 58.320 nodes on top of the 82.280 already used making the model significantly heavier. The modelled connections are believed to have similar force transfer properties as the details designed by Eigenraam.

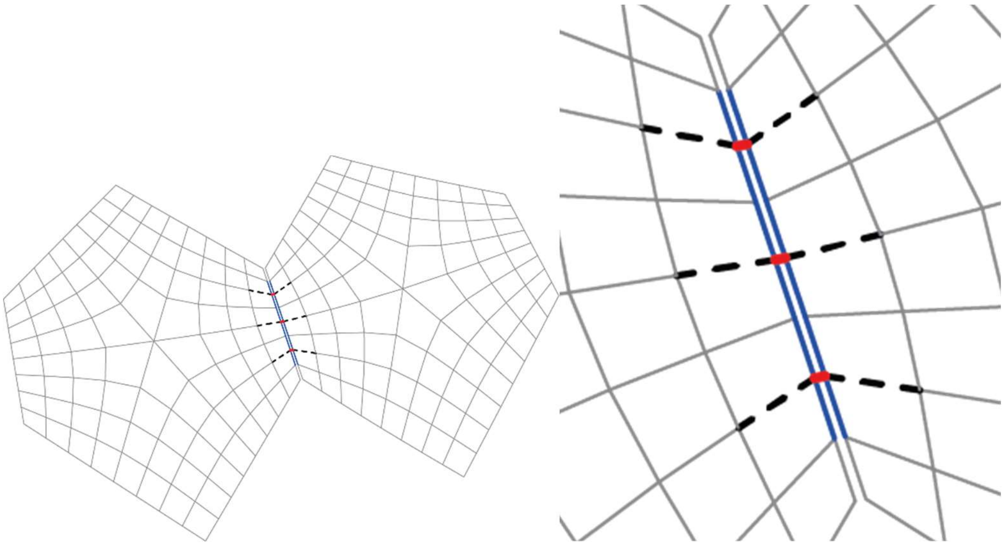


Fig. 45 Modelled panel connections. Connection plates are in red, panel face reinforcement in blue and back anchoring is dotted.

Deconstruction results

The deconstruction algorithm is a newly developed algorithm and as with every new algorithm it needs testing. The best selection criteria need to be determined. The pattern improvements need to be tested, not only in complete stage but also in deconstruction, since we don't know what pattern will be best for deconstruction. Last but not least the preassembly designs will need to be tested to see how these hold up in construction and what kind of support they might need.

Selection criteria

The first tests of the algorithm are done on a 10X10 square divided version of the Heimberg swimming pool shell. This is done to accelerate the testing process. One can imagine the testing on 100 panels will be far easier and faster than testing on the 680 panels of the optimized shell pattern.

Selection stress

First rounds where conducted with directional stresses (Sxx, Mxx, Nxx, ect.) as selection criteria. These stresses are directional according to the global coordinate system on the element. The double x in Sxx marks the x-direction of the force along this global coordinate system. As one can assume directional forces are larger in the indicated direction than in the perpendicular direction. Logically the deconstruction algorithm, which selects the panels with the lowest stress value, will start deconstructing in the perpendicular direction first. This leads to a very unbalanced deconstruction putting far more stress on the panels that transfer forces in the direction of the chosen axis. Since combination of xx and yy forces in 3D space is fairly complicated it is recommend not using the directional forces but the principle stresses (S1, S2 and S3). The principle stresses S1, S2, and S3 are unidirectional and indicate the maximum combined stress (combination of moment, normal and shear stresses) for the panel in direction determined for the element in question. Therefore the principle stresses will be used as the selection criteria.

Within each principle stress there are three results the Top, Middle and Bottom result. Through the combination of the characteristics of Normal and Moment forces the top middle and bottom results always differ. What might be a low stress at the top can be a dangerous stress at the bottom. However the top and bottom results can be very extreme and provide a distorted image of the shells structural integrity. Therefor all result should be monitored during Deconstruction run-throughs. For the further testing S1 middle will be used. Since there are nine results (S1,2,3 x Top, middle bottom) to be monitored at each iteration the best use of principle stresses for selection will need to be researched further. For these first tests on the algorithm simply picking the S1 middle stress will suffice.

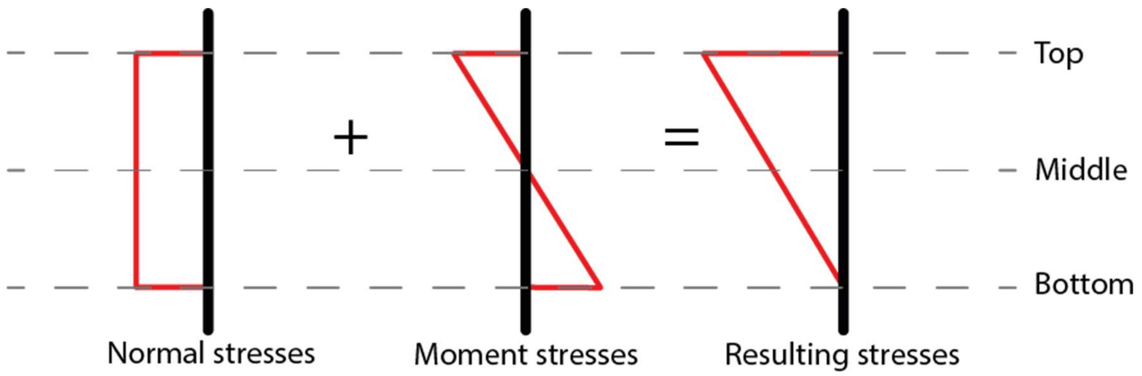


Fig. 60 The combination of forces along the section of the element Normal stresses (Nxx, Nyy & Nxy) and moment stresses (Mxx, Myy & Mxy) are combined to form the resulting stresses (Sxx, Syy & Sxy) on three levels resulting in three different values.

Automatic selection vs manual selection

In these early stage of the algorithm it does not have smart selection procedures. The automatic selection procedure bluntly selects the lowest stress regardless of its position in the structure. In several first runs this led to the extraction of vital panels at, for instance, the base of the structure and at vital connection points in the structure. Extraction of these often led to drastic increase of stress in the surrounding panels, something that would rather be prevented. When viewing the FEA results at the iteration in question, results between the vital panel and other less vital panels where not that far apart.

This led to a more rational approach of selection. Instead of bluntly selecting the lowest stress panel the person controlling the script can scroll through the results. When a vital panel returns the lowest stress the user can skip these and select panels with a slightly higher stress but in a less vital position. This allowed for a longer stable deconstruction. In further development stages of the script these "smart" selection features can be implemented in the automated script.

Single selection vs Multi selection

The first tests conducted had a selection of one panel per iteration. This sometimes led to very unbalanced deconstructions since taking one panel out on one side puts more stress on the intact shell on the other side. This led to on side being deconstructed faster than the other 3 remaining sides which can be viewed as not realistic. When reviewing the FEA results at each iteration, it was noticed that in this symmetrical shell the lowest values always come in pairs. These pairs are most commonly found opposite of each other in a mirroring fashion. Taking out a symmetric pair (or symmetric quaternion) will allow for a longer balanced deconstruction.

In the reality of construction the installation of multiple panels at the same time can be done through the application of an installation gimmick. The earlier named example of sport hall "Lenin" makes use of such a gimmick. Here several panels are installed in one sitting. They are held in place with a gimmick that reduces the cantilevering force by tying the panel back. This could be used to install panels at several places at once. When all in place the connection will be fastened and the force will be applied. This of course does imply that surrounding panels will need to be in the correct 3D position as well. The workings of such a gimmick and implementation on the construction of shells will need to be researched further.

Pattern performance

With the options for selection criteria delimited testing of the designed patterns can commence. Since this is a newly developed algorithm it is unknown what kind of pattern would work best for deconstruction. Therefor all three stages of the pattern are deconstructed. This is done to check their performance in full assembly and during deconstruction. This will hopefully give insight into what geometric alterations work best for the purpose of suportless construction.

Furthermore, it must also be noted that the values for the pattern testing not realistic. The values found in the deconstruction are only intended for mutual comparison amongst the designed patterns. No further conclusions, than overall performance and comparison of performance, will be drawn.

In deconstruction, selection procedures for all three patterns are the same. The designer can remove 1, 2, 4, 8 or 16 panels at once based on the correspondence of their results. The designer can also choose from the first 40 results to prevent being forced to remove key panels that for instance connect foundation and structure.

Pattern performance

Undirected

The undirected pattern is up first. As previously stated this pattern is not ideal according to the boundary condition set beforehand. However, since its performance in deconstruction is unknown, this pattern must also be tested. This will also provide data for comparison for future patterns to be tested.

Before we start we must note that this pattern is mirrored over a single axis. This is in contrast to the original geometry that is mirrored over two axis. This is due to the inaccuracy of this method of paneling. This pattern defect leaves the geometry with a disadvantage in balance against the other patterns. However, it also proves the necessity of balanced patterning for prefabricated shell structures.

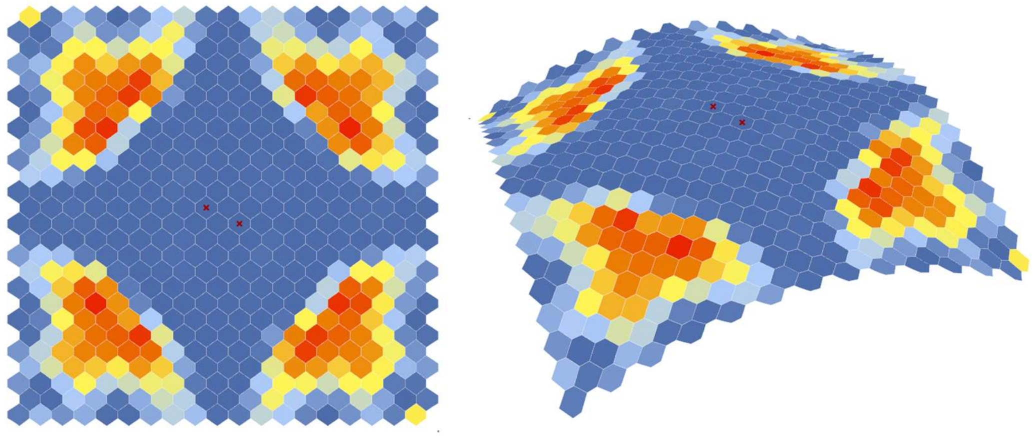


Fig.46 FEA results of the complete assembly in top view (left) and perspective (right)

The principle stress range for this pattern in full assembly is -3.001 N/mm^2 to 2409 N/mm^2 on peak stresses and 0.517 N/mm^2 to 973.074 N/mm^2 on average panel stress. A graph of the increase of stress is show in fig. 47.

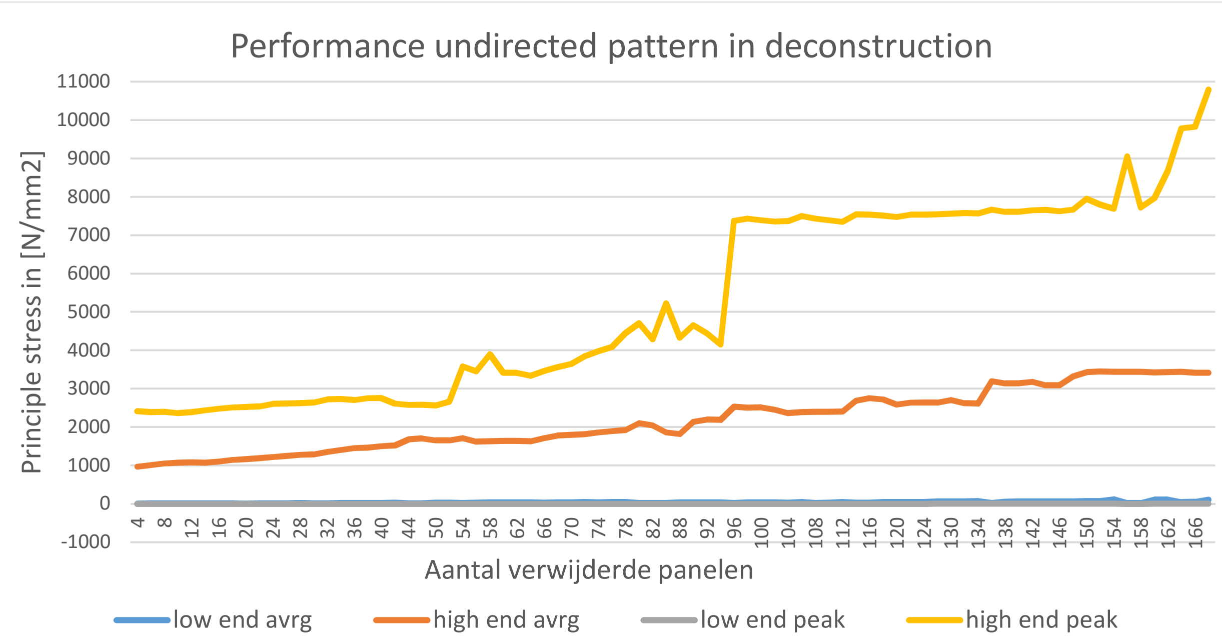


Fig. 47 Performance of the undirected pattern in deconstruction

The graph displays the higher and lower bounds of the overall peak stress and panel average. As can be seen the lower bound values do not fluctuate much. The higher bounds however do increase. Panel average increases quite smoothly and only peaks when key panels where to be taken out. Higher peak bounds however have some points of drastic increase. The high fluctuation that afterwards restore are high detail stresses due to panels that where left cantilevering out. The large increase at 100 panels was caused by the removal of a key panel in structure. Manual selection was applied but manual selection range was set at the lowest 32 stresses which did not include a better option.

These key panels are bridges between different parts of the structure that have very little stress going through them but balance them out. The algorithm, based on lowest stress, selects them anyways despite their key position in the structure. This should be further developed in the next stages of this algorithm.

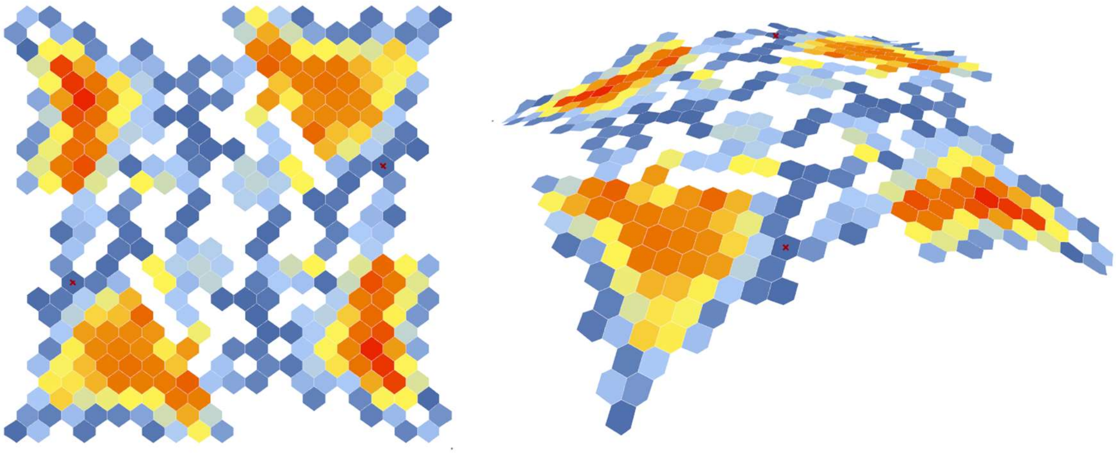


Fig. 48 FEA results of the undirected assembly at last iteration.

Furthermore, the drastic increases in stress were also harder to avoid due to the single mirroring axis. This caused the structure to deconstruct in one direction more than in the other making it less stable, increasing stresses and creating key panels more rapidly

Directed

The directed pattern is expected to perform better that the undirected patter. The orientation to force flow direction and two axis symmetry should improve the distribution of force. However, the edges on which the pattern changes direction are quite abrupt. This might cause forces to remain in a certain part of the structure and cause peak stresses or high average stresses.

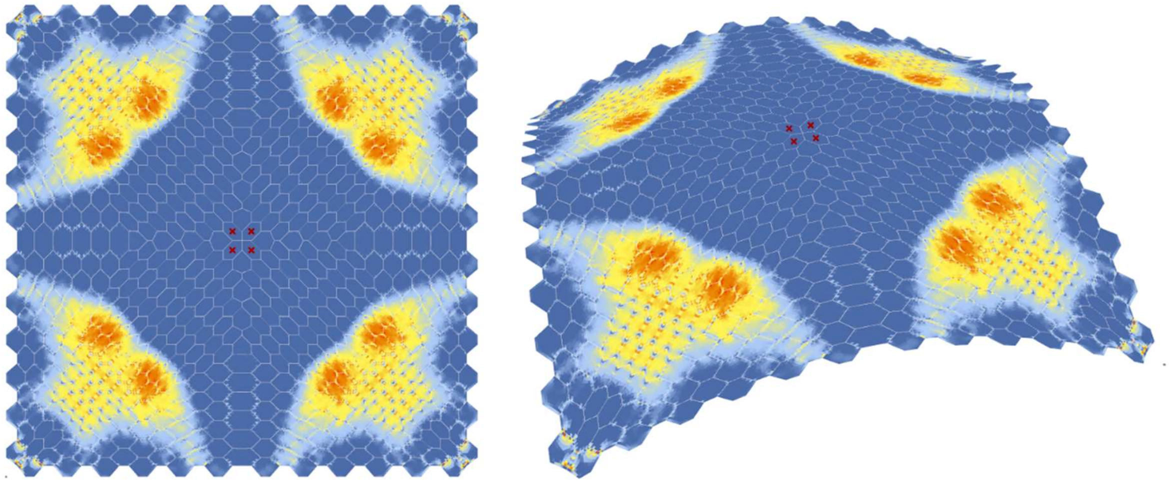


Fig. 49 Detailed FEA results of the complete assembly in top view (left) and perspective (right)

We note first that the peak stress in full assembly of the directed pattern is almost half that of the undirected pattern, however, average stresses are the same shown in fig. 46. This indicates that the directed pattern diverts the forces better into its panels. This corresponds with the assumptions derived from the Landesgartenschau project (Li and Knippers 2015). When we view the detailed results of the full assembly one can also see the influence of detailing by the small "pixelated" fluctuations in fig. 45

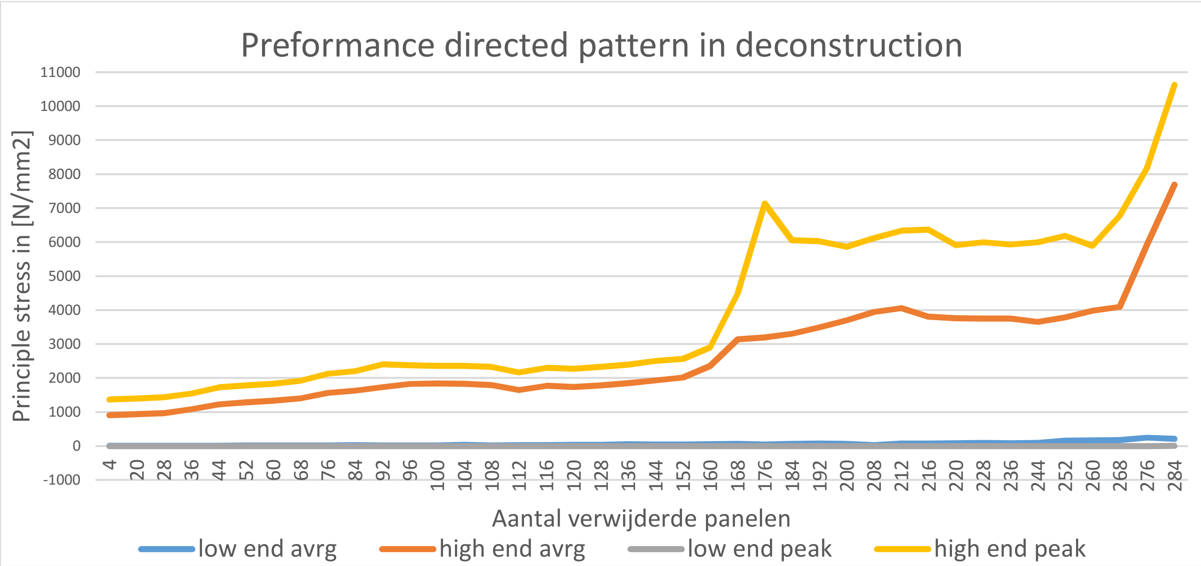


Fig. 50 Performance of the directed pattern in deconstruction

In further comparison with the undirected pattern the directed patterns average and peak stress seem to have a much closer and more stable relation. Until 168 panels are taken out the fluctuations are more or less the same. After 168 panels the removal off a key panel was unavoidable, within the rules of selection set beforehand, causing the sudden increase in peak stress. The removal of the key panel caused other panels, that were previously connected by the key panel, to be left cantilevering out. This causes large stress in the panel details explaining the peak stress increase. Afterwards peak stress and average remain at a distance which indicates instability and large detail stresses.

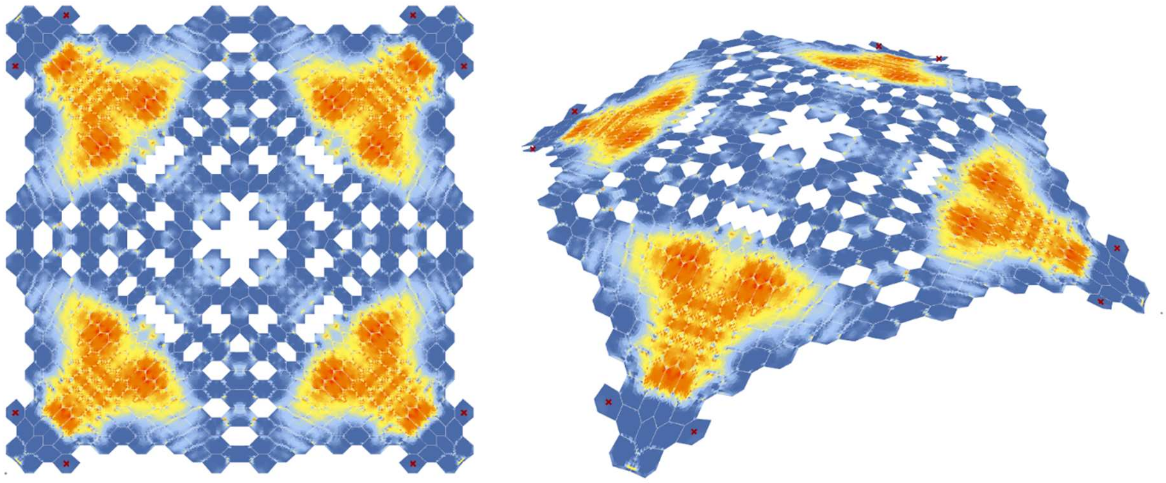


Fig. 51 Directed pattern with 120 panels taken out

One can also see that the deconstruction order first creates a network by alternately taking out panels. In the directed pattern, with large amount of panels in straight rows, in line gaps are already starting to appear when 120 panels are taken out (fig.47). The great diversion of forces around this gap and limited possibilities for force transfer cause problems in later stages (fig. 48). The rows do not align with the curvature which gives some panels in the row a vital role and other less vital or non. This causes the large gaps of low stress panels being taken out instead of equal division.

Near the end of the deconstruction the average forces, high and low, started increasing rapidly. This correlates with the high stress areas seen near the support in fig. 48 while the rest remains relatively low stressed. The force correlates with the diagonal part of the pattern and channels it causing the high stress concentrations.

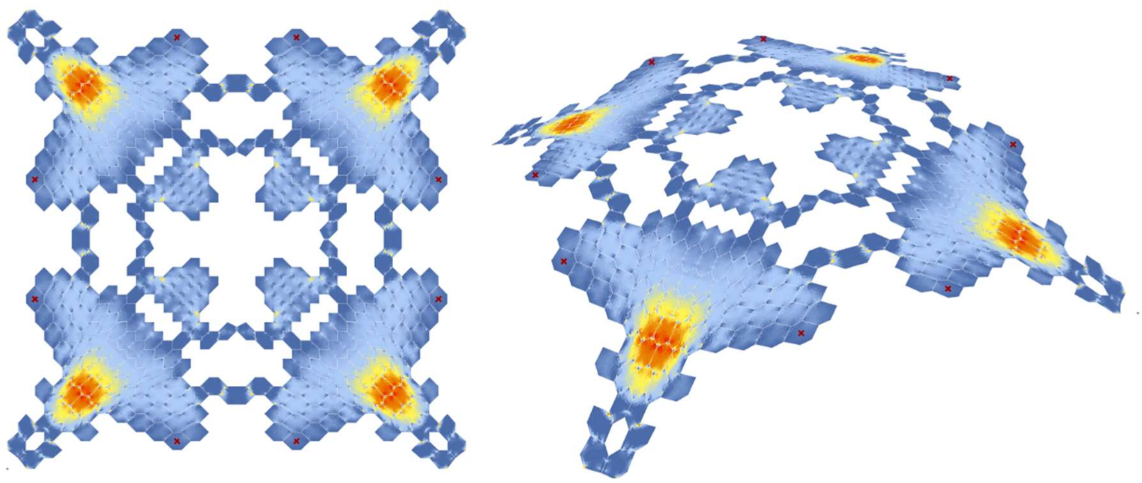


Fig. 52 FEA results of the directed assembly at last iteration

The final iteration left large gaps and few vital panels. This caused a rapid inclination of the peak stress and average stress due to large chunks being carried by few panels. The deconstruction in this manner is far less chaotic than the undirected pattern but causes deconstruction to focus which might prove unfavorable. The final result of 284 panels shows that extensive stable deconstruction is possible.

Relaxed

The final pattern tested is the dynamically relaxed directed pattern. This pattern removes the hard transition and adapts to the flowing curvature of the shell. It is expected to spread the loads best over panels and details. However the relaxed edges might cause strange stresses to occur due to faulty edges.

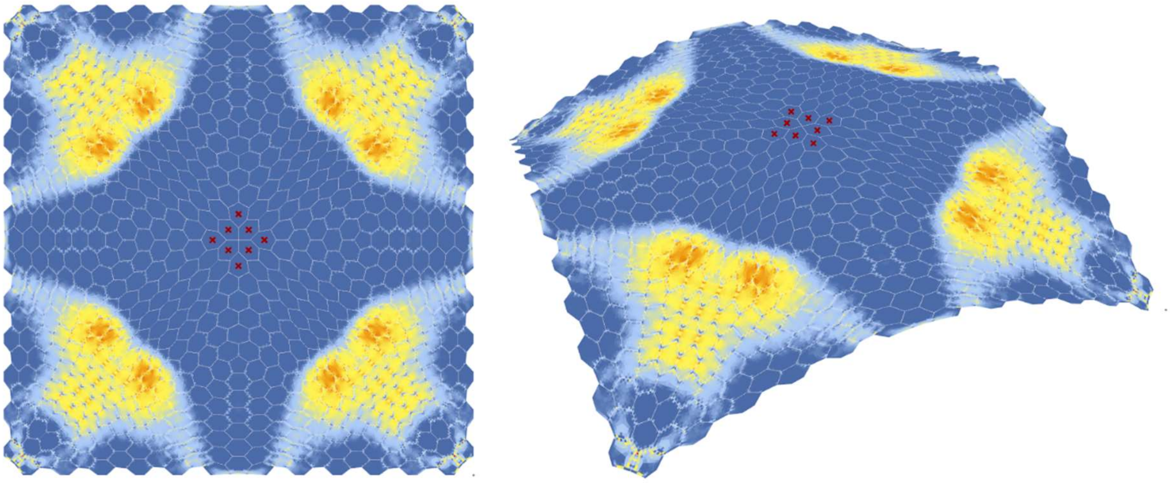


Fig. 53 Detailed FEA results of the relaxed complete assembly in top view (left) and perspective (right)

The starting values for peak and average stress are the same in the relaxed pattern as in the directed pattern. The color patterns representing the stress concentrations generate the same shape but in the relaxed pattern the stresses in the plane seem to be less concentrated. This shows the improved spreading of forces.

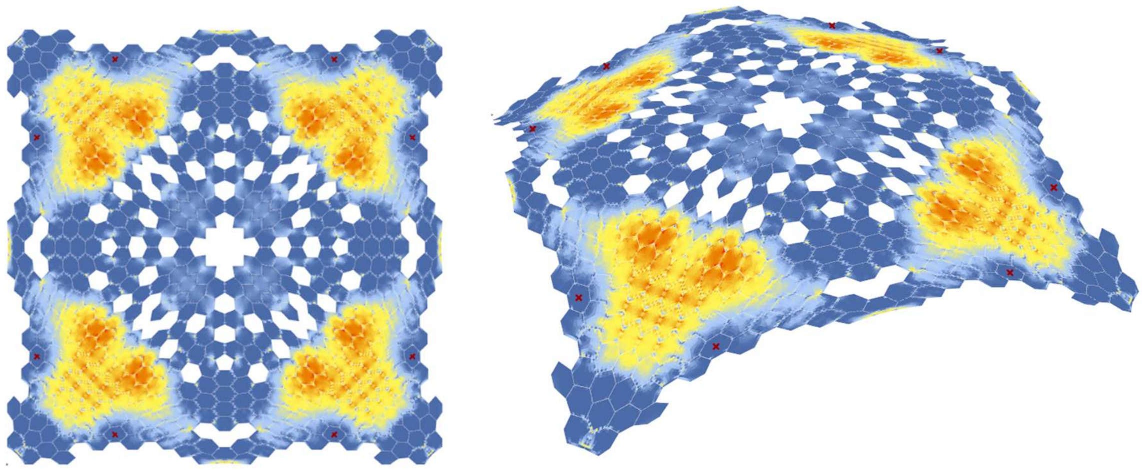


Fig. 54 The relaxed pattern with 120 panels taken out

During the deconstruction it is noticed that, similar as with the directed shell, the edges and center are taken out at an early stage. This goes against the assumption that forces would flow orthogonal and diagonal from support to support. On the final iteration of the relaxed pattern the vague yellow lines reveal what seems to be a mix between these two directions. This might prove to be the true flow of force.

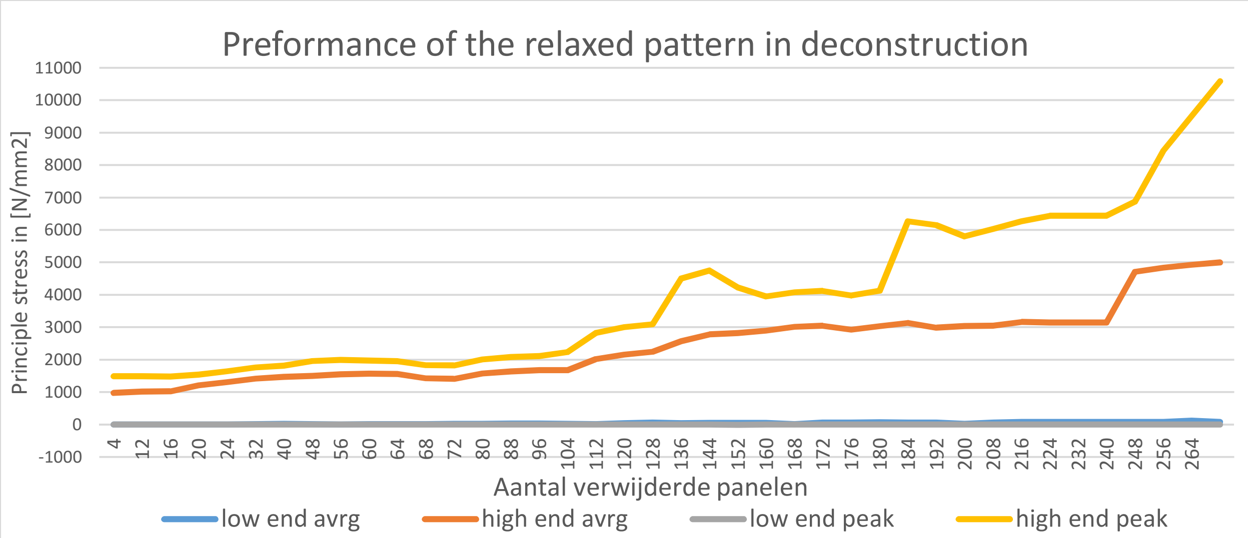


Fig. 55 Performance of the directed pattern in deconstruction

In contrast to the directed pattern the relaxed pattern also does not create large gaps but a more spread out smaller stretches along the direction of the force. This correlates with the assumption that the relaxed pattern spreads out force better. This is also seen in fig. 55. The average stress stays on a steady gradual increase while the peak force, with the exception of a few excesses, remains related. In the end however key panels had to be selected causing it to destabilize. However, final average forces are half that of the directed pattern showing again the better spreading of force. Even in instable condition.

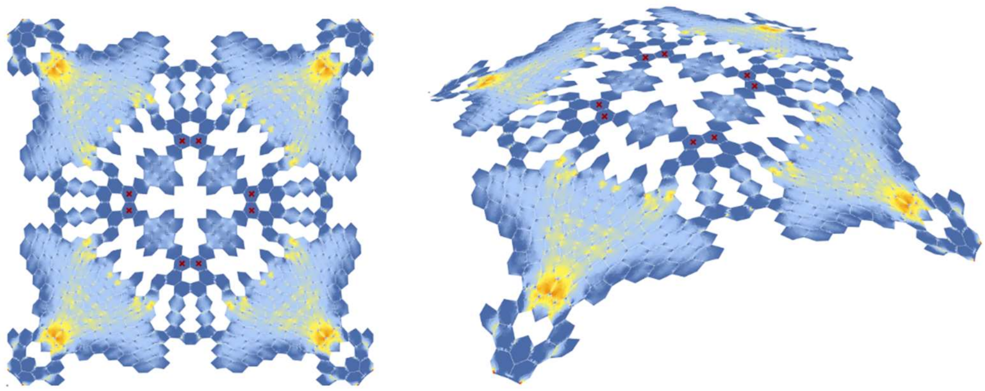


Fig. 56 FEA results of the relaxed assembly at last iteration

The final panel count for the relaxed pattern is 272 ending 12 panels short of the directed pattern but far greater than the undirected. The slight loss might be explained through wrong panel choices by the designer. The margin of loss however are relatively close and the prove for the better pattern will need to be tested in more run-throughs of the algorithm.

A other finding is the revealing of the true reduced force flow lines displayed in vague yellow in Fig. 56. These arced lines are a blend between the orthogonal and diagonal and align with the curvature of the geometry. Theoretically preassemblies along these lines should work best but in this complex 3D curving structure this is hard to say. Configurations along these lines will be tested.

Comparison

As a short conclusion the patterns are compared in performance and relating problems. In fig. 54 the graphed results are put on the same panel removal rate. The directed and relaxed pattern had panels removed 4 to 8 at the time and the undirected only 2 per iteration. To put them on the same scale the some iterations of the undirected panel were left out. All shown iteration where on or around the same amount of panels.

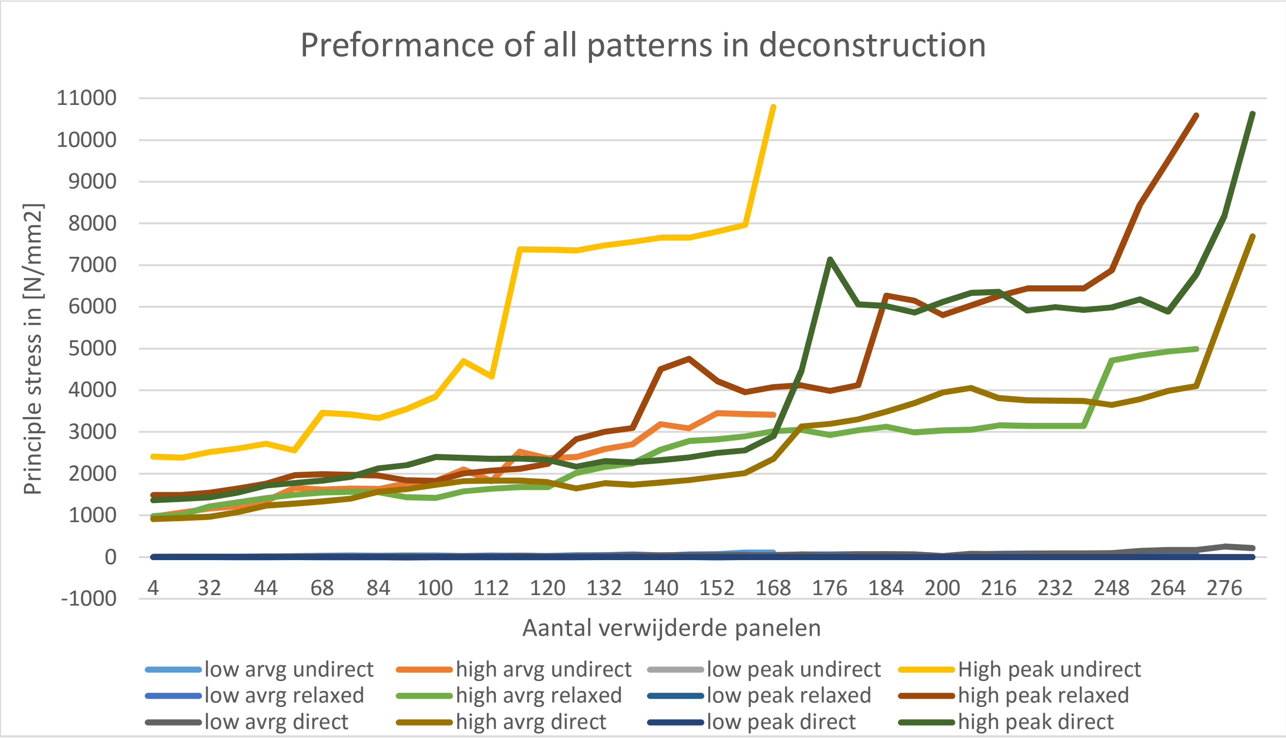


Fig. 57 FEA results all patterns compared on the same scale of panel removal rate

The combined graph clearly shows the improved performance and stability of the directed and relaxed patter. They both have key panel peaks and drastic increases to comparable stresses between 170 and 180 outtakes. The directed pattern and relaxed pattern alternate on best performance in which non clearly sticks out. The directed pattern lasts longer but with a drastic increase in high and low average force per panel. This is also shown in the last iteration of each pattern in fig. 55. The directed pattern shows relatively high concentrated stress where the relaxed shows more spread and evened out stress.

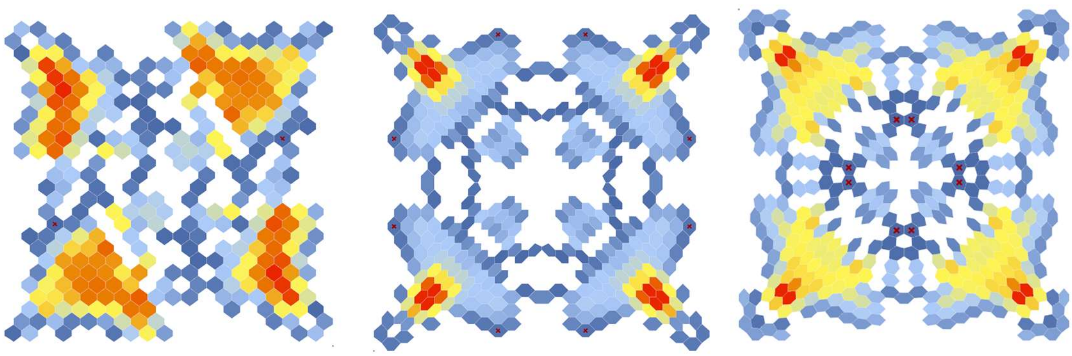


Fig. 58 Final deconstruction iteration compared undirected (left), directed (middle) relaxed (right)

The undirected shows a clear single axis mirrored deconstruction pattern. This caused a diffracted and unbalanced deconstruction. The other patterns leave a ordered deconstruction pattern with 2 clear mirroring axis. This additional mirror axis does not only ad stability and order but also increases the amount of panels that can be taken out per iteration. Removing one panel at the time in a symmetric structure will cause unbalanced deconstruction in which the structure starts leaning towards the first deconstructed end putting more force on the other ends disrupting the deconstruction picking order.

Final verdict of best deconstruction pattern is currently too close to call and subjected to the subjective choice of the algorithm operator and will require more research and accurate values. Further method testing will be conducted on the relaxed pattern.

Method performance

For testing the algorithm several test are conducted. This starts with an evaluation on pure Deconstruction. To further test the extends of Deconstruction, two variations on pure deconstruction are tested: Preassembly and auto support placement (ASP). Preassembly is based on the method used by RAP studio and will work from a preassembled stable structure/arches. Support generating is a method which generates supports as soon as the vital limits are exceeded. When fully deconstructed the shell is tested again with all the generated supports in place.

In all further testing the panel average of S1 middle will be used to select the least stressed panels. This will clear out all small distortions in the calculations. The structural limits of the material have been set between 5 $N/mm^2 < \sigma > -20\ N/mm^2$. Deformation limit has been set at 50 mm. Horizontal axis always represent the iteration count. In this chapter the results of the most vital stresses are shown in combination with deformation. The complete overview of stress results can be found in appendix B.

Pure Deconstruction

The first findings on the deconstruction algorithm is that in its current state, simply selecting the lowest stress value, it will not give a positive result. For the algorithm to function certain sets of rules need to be defined. This set of rules will need to contain features such as multi selection on mirroring structures, avoidance of support panel removal, key panel removal or even avoidance of key panel creation. Without these rules the deconstruction algorithm will result in chaotic removals and destabilization of the structure. At this stage of algorithm development human interference suffices but only up to a certain degree. The designers choice should also always be guided by the FEA of that deconstruction stage (select from panels sorted by increasing stress). In future development these rules can be implemented but human interference should always be an option.

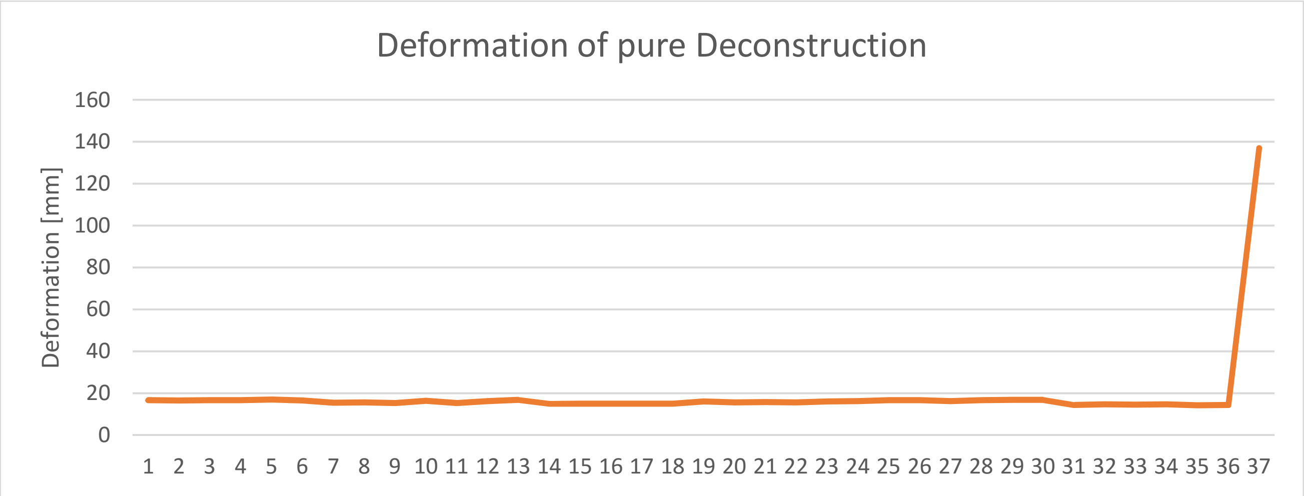


Fig.59 Deformation results of a pure deconstruction

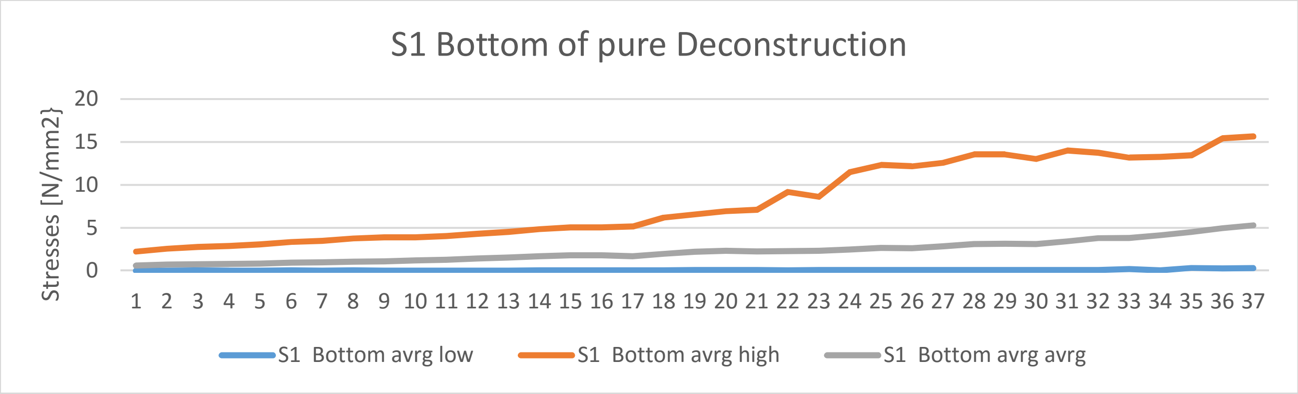


Fig.60 S1 Bottom stress results of a pure deconstruction

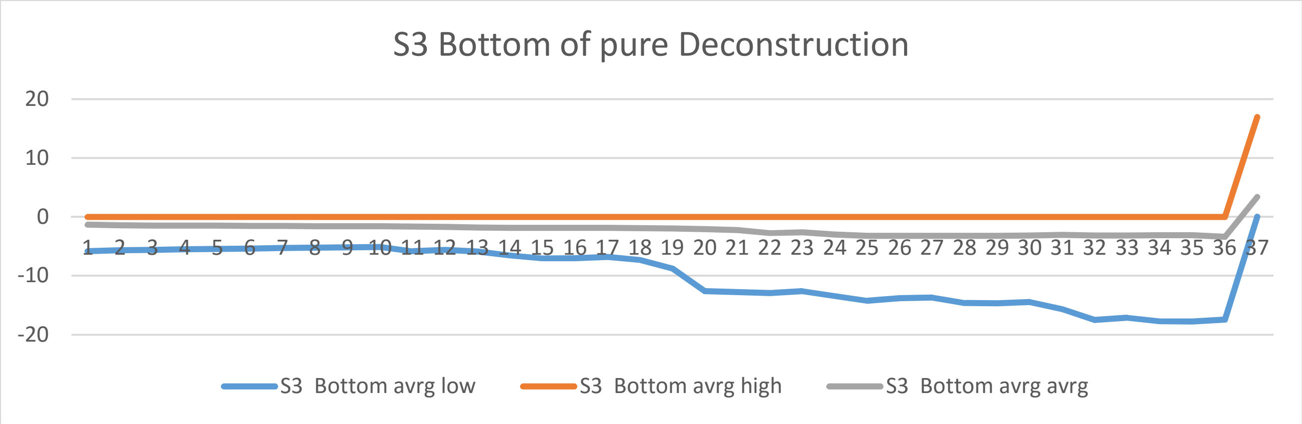


Fig.61 S3 bottom stress results of a pure deconstruction

As seen in the pattern performance outcomes the structures can be deconstructed to a certain extend from which they rapidly destabilizes. The 32,5 m span of the used case study proves too great to cross without supports. This of course is no great surprise. The run-through ended when all panels exceeded the set limits for stresses. The first exceeding panel was found at iteration 17 after approximately 140 panels had been removed.

What is interesting is that the force flow lines that showed themselves in the deconstruction of the relaxed pattern fully reveals itself in the last done iteration.

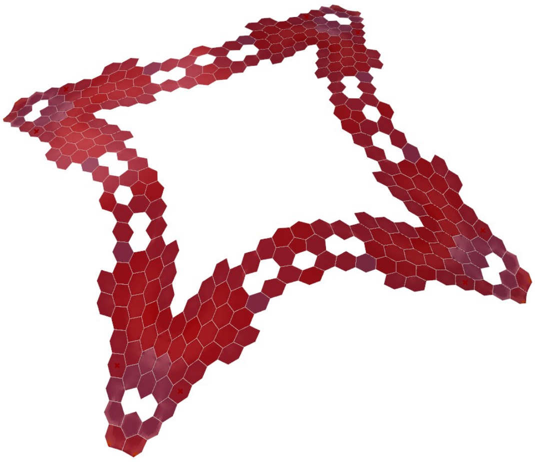


Fig. 62 Final iteration result of the Pure deconstruction. All panel exceed the set limit of 5 N/mm² in different parts of their body

Preassembly

The preassembly method works with preassembled arches/structure that cannot be selected by the deconstruction algorithm. The complete structure is deconstructed around this designed preassembly leaving a stable designed structure. The stability and structural integrity is validated by FEA before deconstruction..

The implementation of preassembled arches into the deconstruction algorithm can significantly reduce the forming of key panels and reduce high peak stresses. The vital force flow axis in the structure can be determined by hand or found trough deconstruction as seen in the relaxed pattern deconstruction. Removing non vital panels reduces the structure to its essential revealing the main stress flow lines. This can be used to find the lines for preassembly.

With the implementation of preassembly the possibility for preassembly in stages should also be taken into account. First assembling lower parts along a first stage of preassembled panels and on completion adding more preassembled parts to the more stable structure to further construct the shell should also be optional. This can reduce the amount of preassembled panels in earlier stages and allow assembly and preassembly work to be done simultaneously.

In fig. 59 a revision of the main force flow line are given. Whether this is the best lines for preassembly needs to be researched.

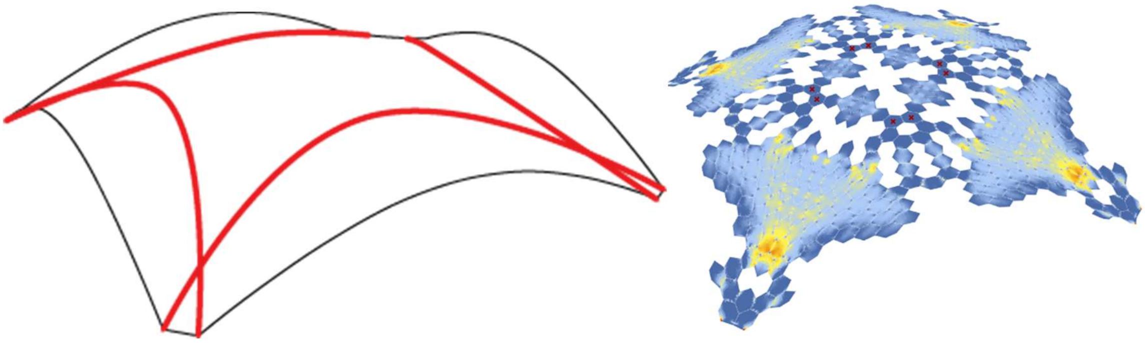


Fig. 63 A revision of the force flow line of the Heimberg swimming pool shell based on the final results of the final iteration of the relaxed pattern.

Several preassembly structures have been tested to see if the assumptions stated above are true and if this is the best configuration for preassembly. In the comparison of the results deformation, stresses and amount of panels used have been taken into account. The less deformation, the better the next panels will fit. The less stress, the easier the panels can be installed. The les panels used, the more effective the deconstruction method. All preassembly configurations and their FEA deformation results are displayed in Fig. 60 & 61

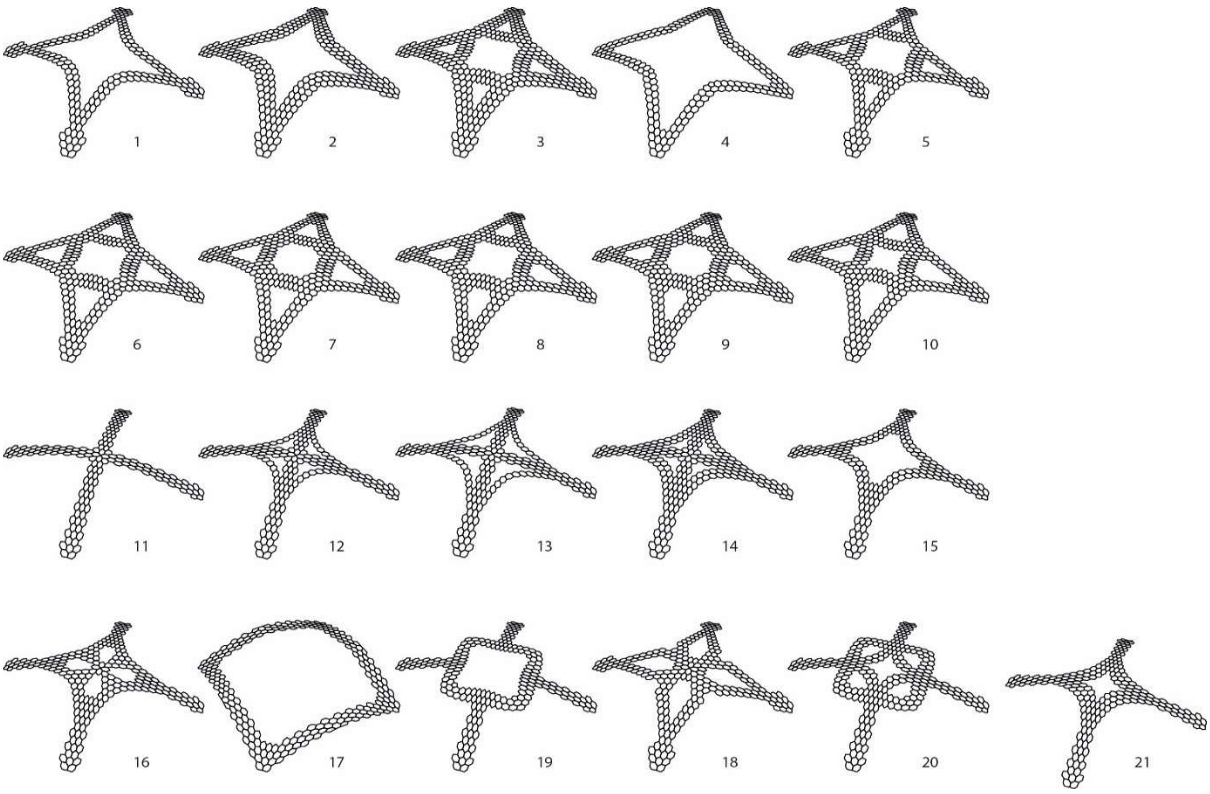


Fig. 62 Tested preassembly configurations

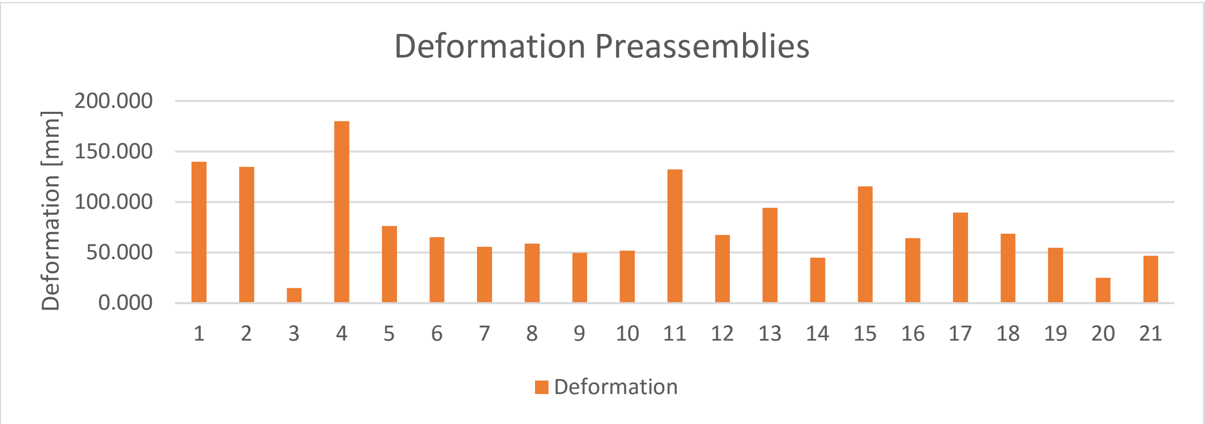


Fig. 61 Deformation results per preassembly configuration

At first glance on deformation number 3 seems to preform best in deconstruction, however, when taking the stress results and panel count into account (presented in appendix B) number 20, 21 and 14 seem more favorable. Configuration 3 has a very high panel count (296) which is almost half of the total structure. This leaves little deconstruction to be performed. Configuration 20 preforms well but is fairly complex in geometry which might will present difficulties in preassembly. 14 & 21 are selected to undergo further testing.

The configurations derived from the force flow lines (number 1, 2 and 4) preformed fairly bad due to the inconsideration of stability of the structure. In full assembly these lines might represent force flow but on their own they achieve little stability.

Preassembly 21

Since preassembly 21 only contains 196 panels this preassembly will be tested first. The design is inspired by the Force flow lines. Because the force flow lines design (number 1) on their own are not stable enough. The arcs are more compressed towards the center. This preassembly had a deformation of 48 mm with stress levels within the required range. However, the weakness of this preassembly is the long straight arcs going from corner to the split, which might be buckling sensitive.

Several deconstructions where performed on preassembly 21 of which the displayed deconstruction was the most successful.

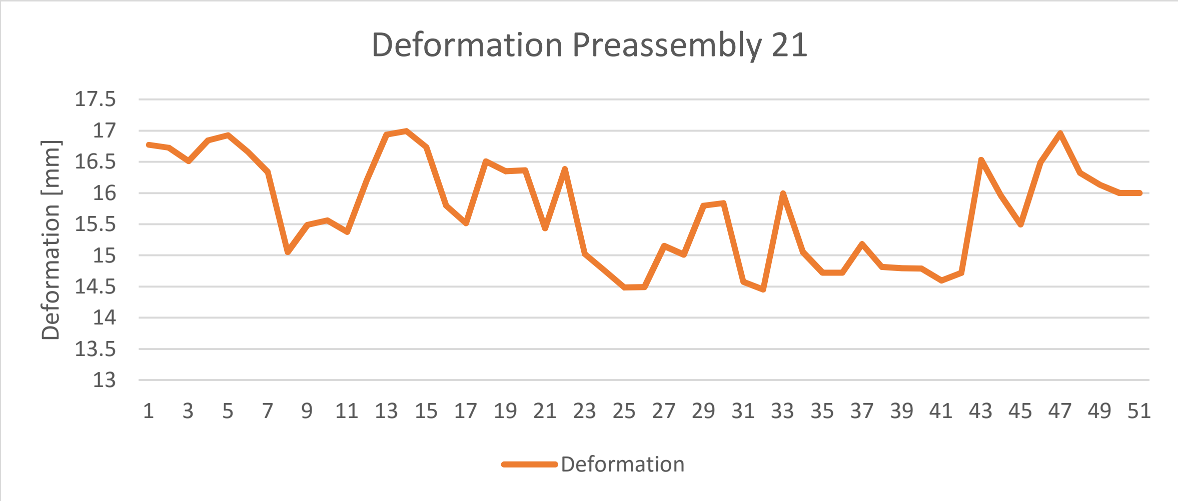


Fig. 62 Deformation [mm] results of Deconstruction test with preassembly 21

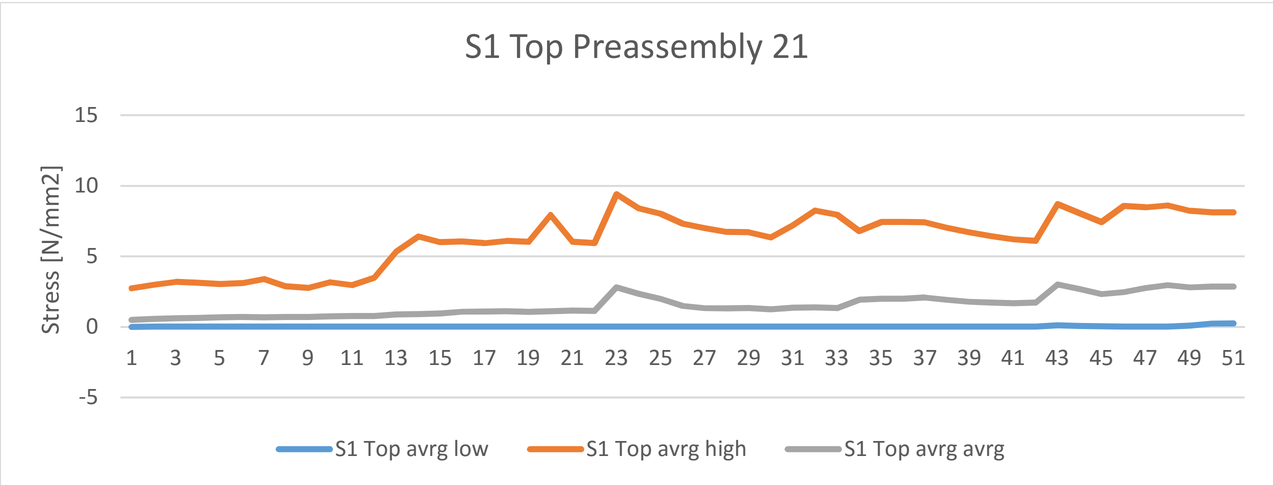


Fig. 63 S1 Top stress [N/mm^2] results of Deconstruction test with preassembly 21

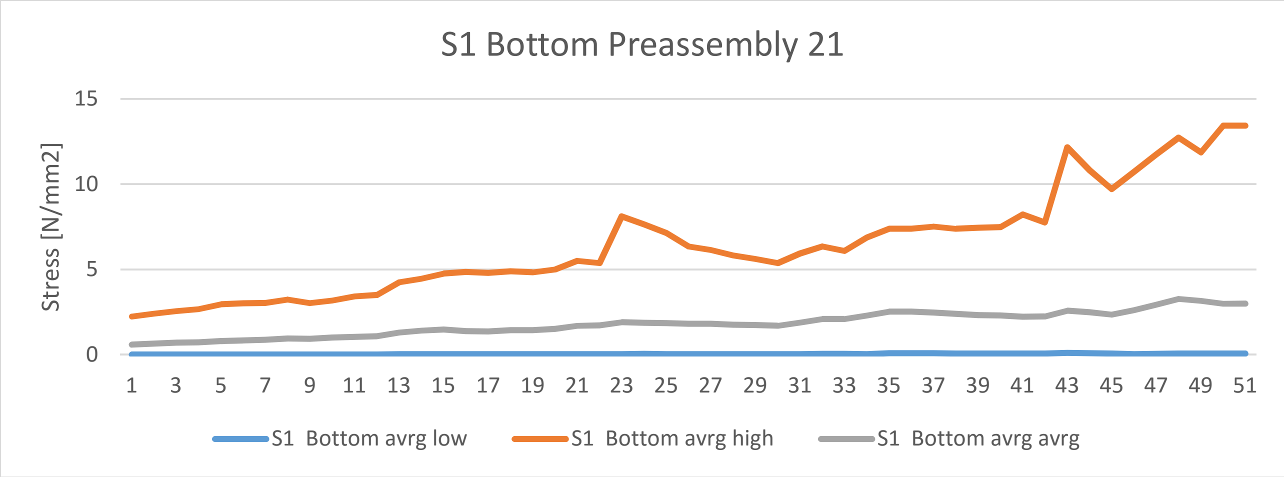


Fig. 64 S1 bottom stress [N/mm²] results of Deconstruction test with preassembly 21

The results of the deconstruction shows that deconstruction with the set preassembly to be unstable. The stress result rapidly pass the 5 N/mm^2 line and only increase further. This had to do with the central cluster, that leaves the outer edges unsupported. When this part of the structure is being deconstructed the structure start failing because it cantilevers out too far from the stable center. This causes the spikes in the results. The slight increase in stress is caused by the significant part still intact in the center and the sides being deconstructed. The tested preassembly works on its own due to its low panel count with only the necessary panels for that configuration. With more non-constructive panels hanging on the structure as well the structure starts failing.

Preassembly 14

Preassembly 14 spreads out a little wider than number 21 and has less buckling sensitive legs. The preassembly contains 232 panels, 40 more than number 21. However, the extra body and further extensions to the sides might prove more stable. The preassembly deforms 44 mm and also remains within the stress limits.

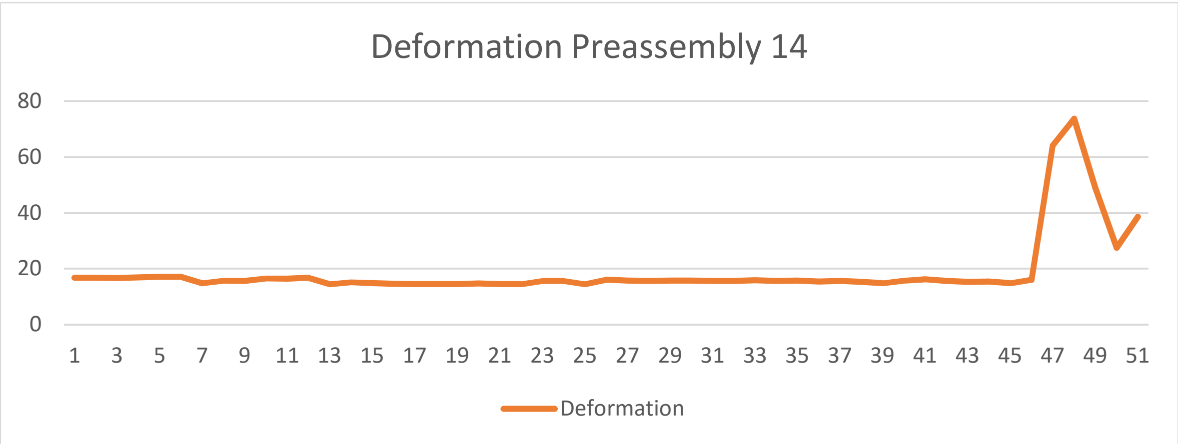


Fig. 65 Deformation [mm] results of Deconstruction test with preassembly 14

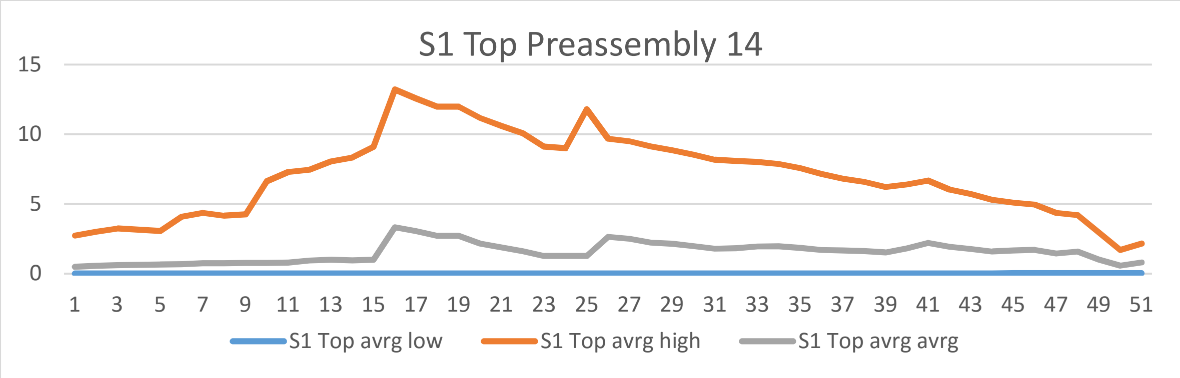


Fig. 66 S1 Top stress [N/mm^2] results of Deconstruction test with preassembly 14

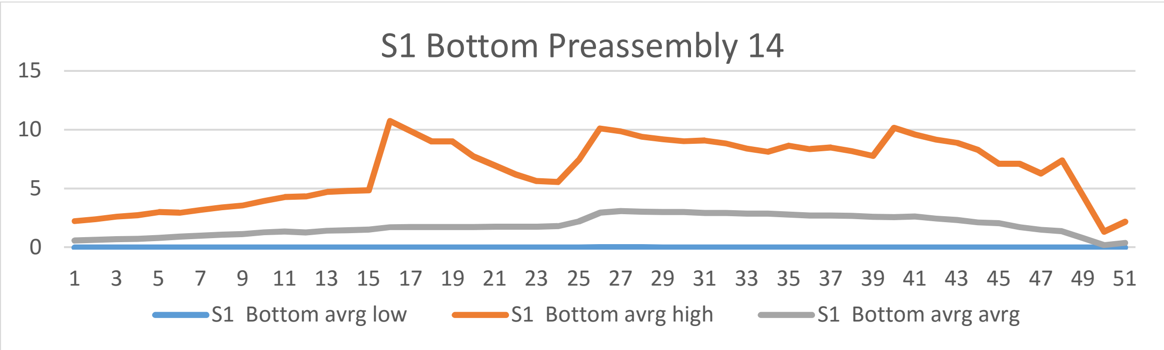


Fig. 67 S1 bottom stress [N/mm^2] results of Deconstruction test with preassembly 14

Preassembly 14 results also exceeded the set limits. The graph shows the same spike behavior as on preassembly 21. A big difference is that this preassembly decreases in stress after the peaks. This indicates a bit more stability but the cantilevering spike do exceed the spikes from preassembly 21. The large increase in deformation in the last iteration is due to the instability of the remaining legs. This is not seen in preassembly 21 because deconstruction on that configuration didn't proceed to that point because of severe failing tendencies.

Both preassembly configuration failed on the tension force (positive forces) in the structure. A large part of these tension force are caused by cantilevering parts of the structure. These come to be after a vital bridge is disconnected leave two parts in cantilever. With human interference these connections can be countered earlier in their creation so that spikes in stresses can be dampened. The first tests on these preassemblies prove they are not fit in their current state. However, the concept of preassembly needs to be researched further to find more ideal configurations that will remain stable. This needs to be combined with extra selection rules to prevent large cantilevering bodies in the structure. Furthermore, the discussion remains on the large amounts of panels used in a preassembly of this size. When one third or half of the structure is already set up with reduced supports or on the ground how much efficiency can still be gained. However, due to time limit these questions and implementations cannot be researched further.

Automated support placement

Automated support placement starts with normal Deconstruction but when the stress/deformation levels are exceeded the algorithm generates a support under the exceeding panel or on a more vital spot based on the engineers judgement. This will be taken into account on the next iteration. If the supported panel is removed the support is removed as well. When the structure is fully deconstructed the Deconstruction starts over with all supports in position from the start. Because the supports have influence on force flow through the structure deconstruction order will change according to the new flow of force. If the structure still exceeds limits in the second deconstruction additional support can be placed and taken for a third deconstruction.

This method only places support where they are acutely needed instead of based on the structures weight. This can greatly reduce the amount of supports needed during construction.

As stated above the supports are generated on the first run. Results of this first run are displayed below

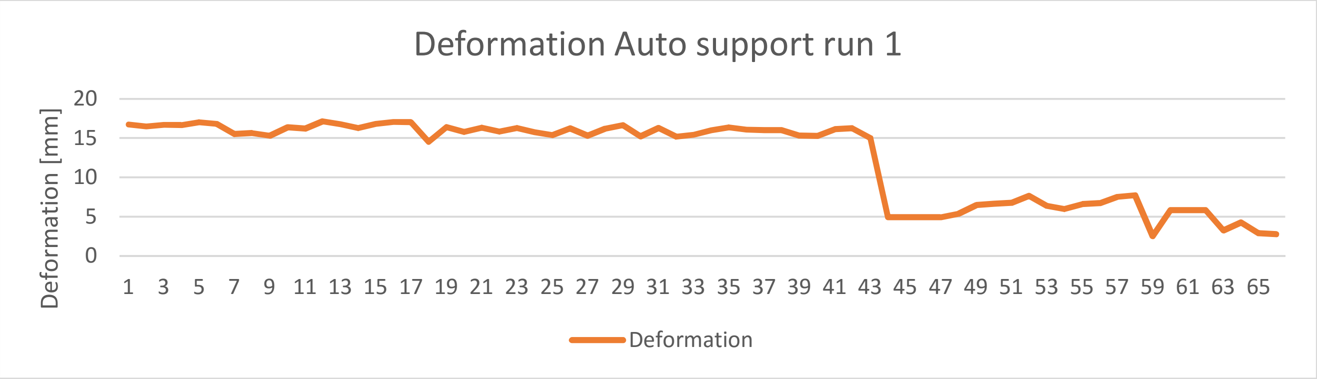


Fig. 68 Deformation [mm] results of first Deconstruction with automated support placement

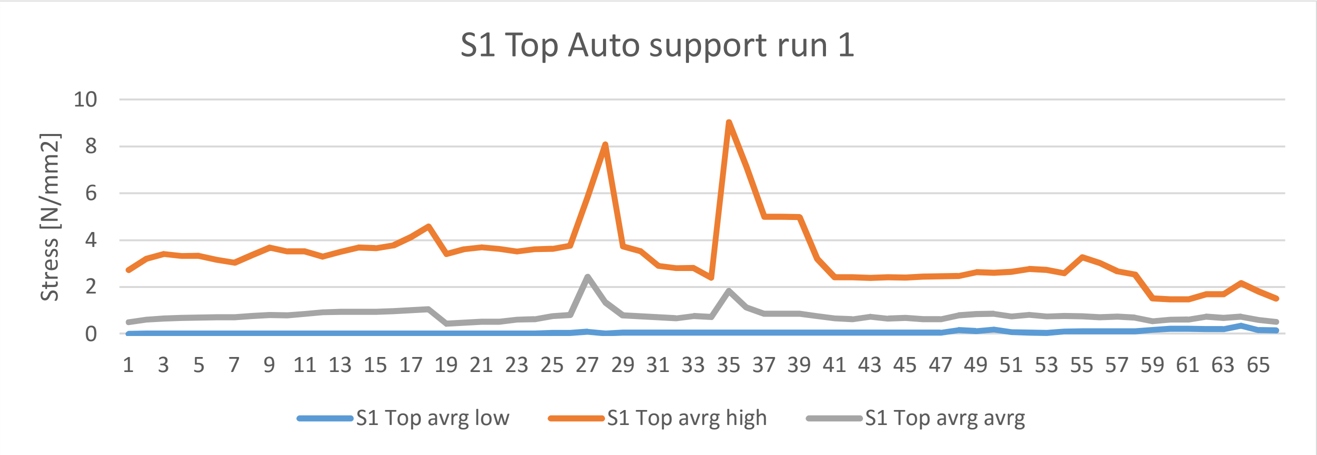


Fig. 69 S1 Top stress [N/mm²] results of first Deconstruction with automated support placement Run 1

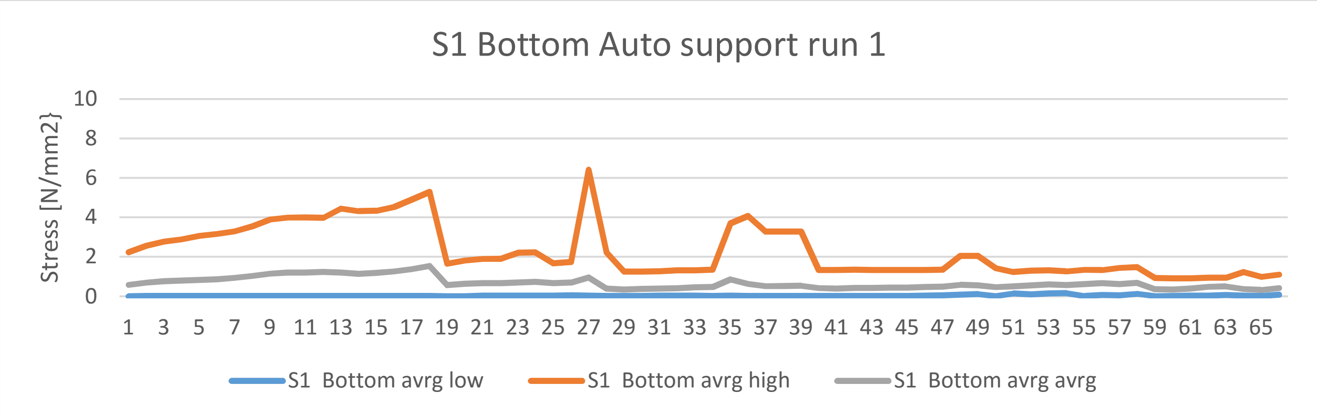


Fig. 70 S1 Bottom stress [N/mm²] results of first Deconstruction with automated support placement

From this first run the automated support placement seems to be a success. On single iterations the stress exceeds above the limit but is immediately countered in the next iteration by the placed support. During the full deconstruction supports where placed under 60 panels shown in fig. 71. This is a huge reduction compared to all 680 panel being supported. The supports near the foundation where not even placed out of structural necessity but to be able to deconstruct the structure to a further extend. Structurally only 48 supports where generated.

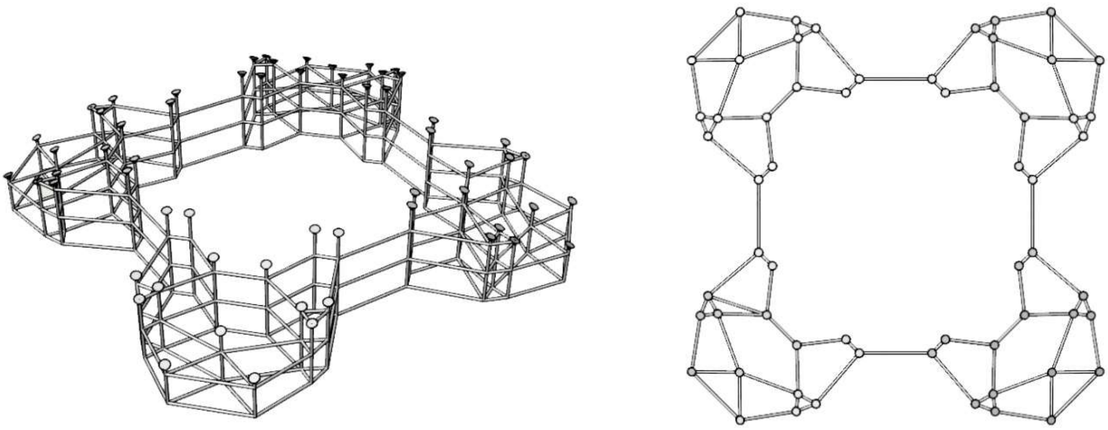


Fig. 71 Impression of generated supports by automated support placement

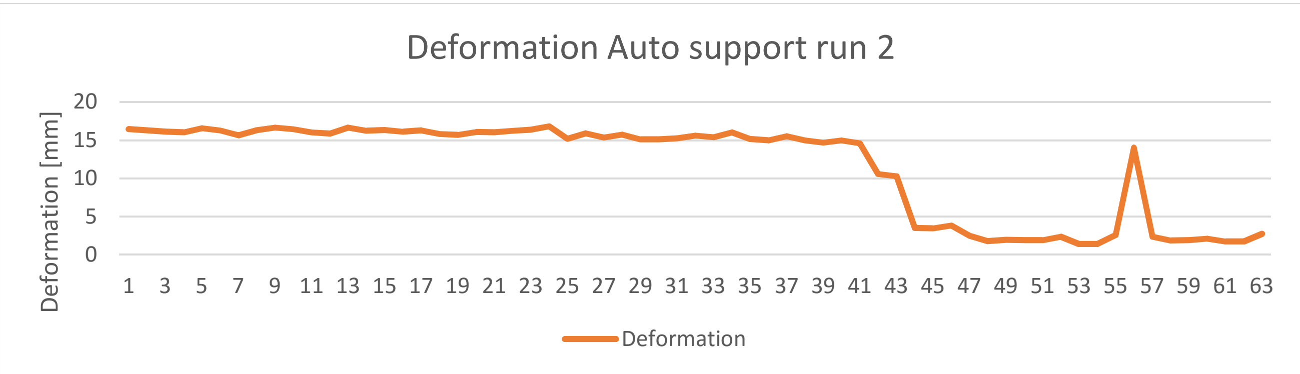


Fig. 72 Deformation [mm] results of second Deconstruction with automated support placement

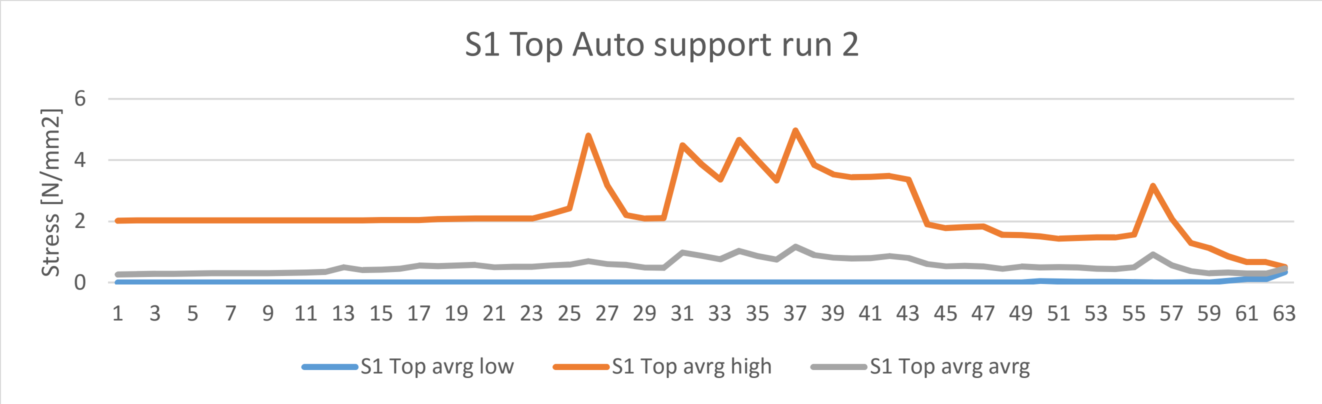


Fig. 73 S1 Top stress [N/mm²] results of second Deconstruction with automated support placement

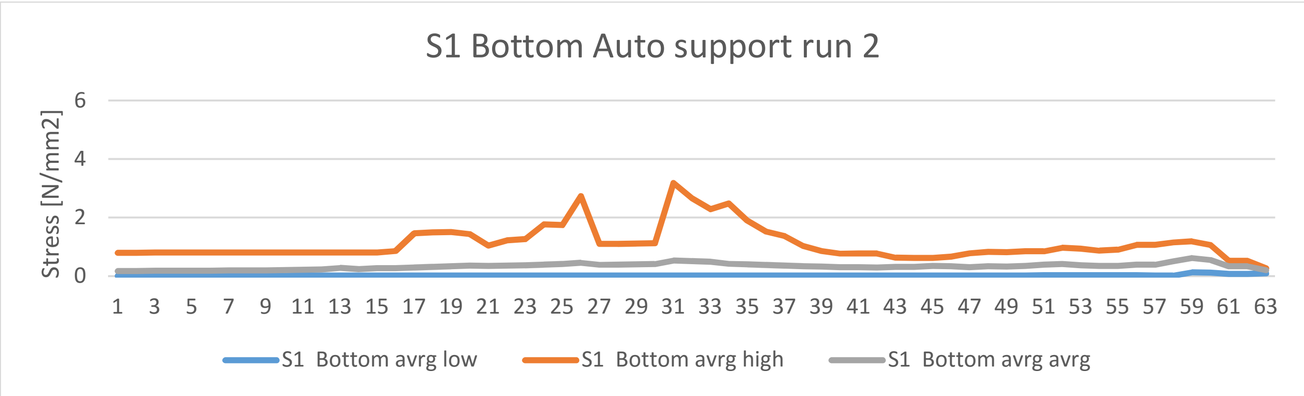


Fig. 74 S1 Bottom stress [N/mm²] results of second Deconstruction with automated support placement

In the second run all supports from the first run are positioned. The deconstruction order has a drastic change as can be seen in Fig. 75 which displays the 25th iteration of both runs. This is of course expected since every support point changes the force flow through the shell.

On the second run was a success. Full deconstruction was achieved with the used support without stresses peaking outside the set limits as can be seen in the graphs. At some points small 3 to 4 panel bridges had to be taken out which caused the small spikes. In construction one can imagine these “bridges” being preassembled on the ground before installation. In the order of deconstruction certain improvements can be done as well. At certain points a previously removed panel would have fitted better than the two remaining as can be seen in fig. 76.

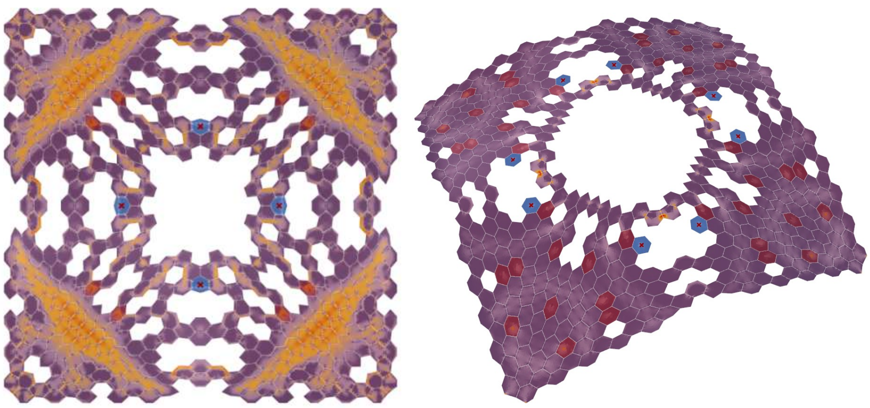


Fig 75 The 25th iteration of the first run (left) and second run (right)

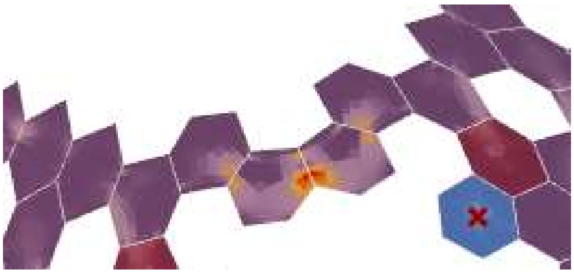


Fig. 76 Visualization of possible improvement in deconstruction order derived from second run

Combinations

The automated support placement method shows great promise. Preassembly, however, seems to cope with instability problems. A combination between the two could provide further optimizations reducing the amount of supports ever further. A combination could also reduce the amount of panels needed in a preassembly. The combination is tested in two configurations. With the supports under the preassembly (internal) and with separate from the preassembly (external).

Internal combination

A internal combination has the greatest potential to reduce the amount of panels needed in a preassembly. It can also allow for more spread preassemblies in which the arches need to be stable on their own, the extra supports can stabilize them. This enables a whole range of configurations that otherwise seemed unfavorable but have a more spread character with less cantilevering distances.

The internal preassembly test was done with preassembly 1. This configuration was previously found unfit due to too much deformation (125 mm) and stresses way over the limit. This preassembly was however designed on the force flow curves and gives a nice balance between the central parts and outer edge preventing the possibility of large cantilevers. The supports are placed to divide the arcs into three equal parts. This is approximately the point where in support generation the first supports are placed. Configuration 1 with supports uses only 184 panels and 24 supports shown in fig. 77. The combination has only 10,94 mm deformation.

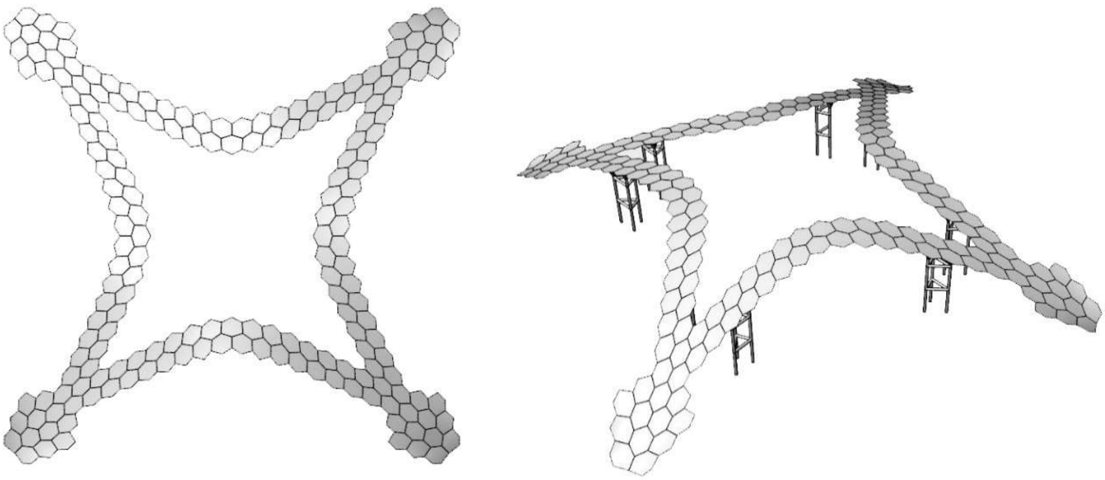


Fig. 77 Preassembly configuration 1 with supports.

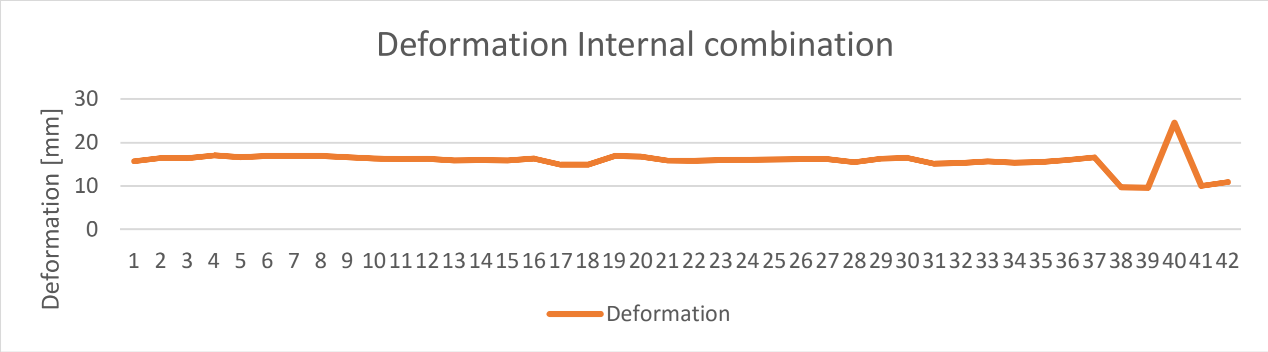


Fig. 78 Deformation [mm] results of Deconstruction of preassembly 1 with supports

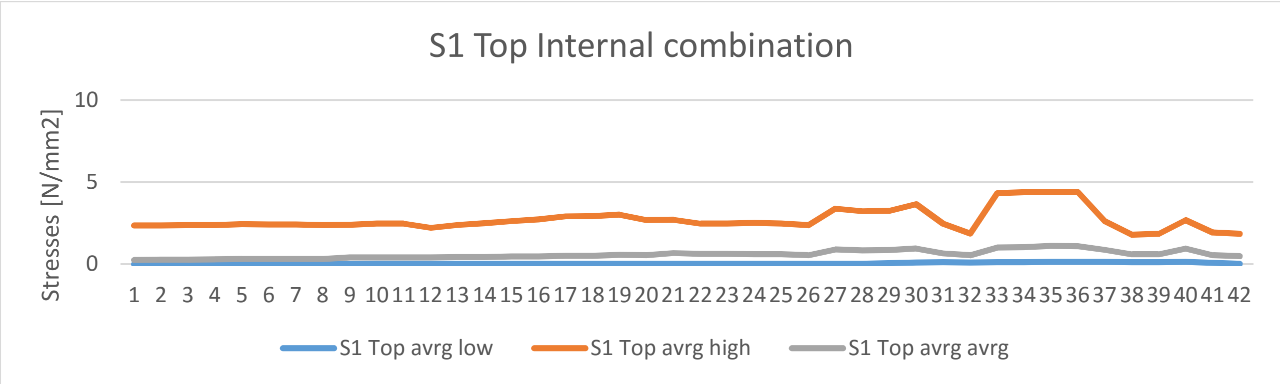


Fig. 79 S1 Top stress [N/mm^2] results of Deconstruction of preassembly 1 with supports

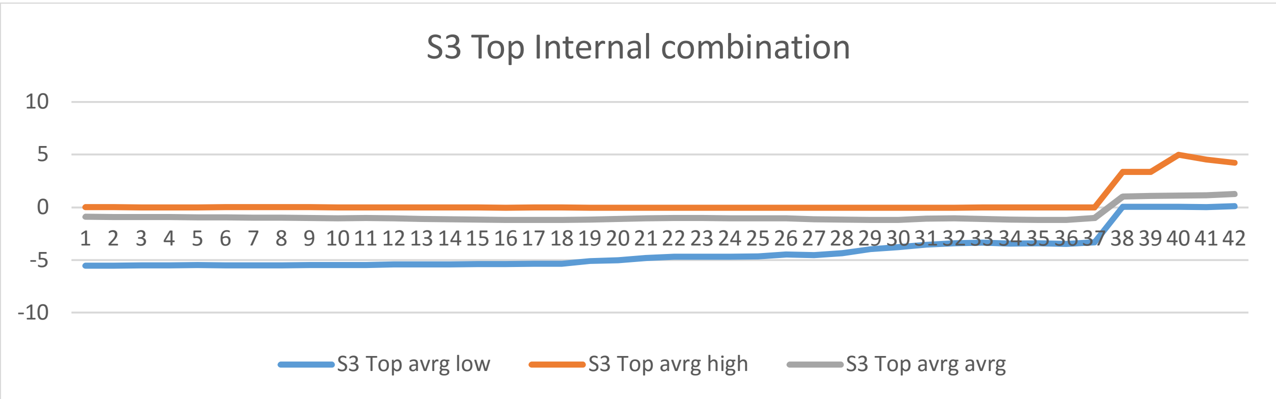


Fig. 80 S3 Top stress [N/mm^2] results of Deconstruction of preassembly 1 with supports

Results for the supported preassembly are positive. Although some manual interference was needed at certain points it deconstructed within the set bounds for stress and deformation. Compared with the automated support placement it only uses half the supports, mainly because the structure stays connected during deconstruction and the vital arches stay intact. However, a discussion can be held over the focus of efficiency.

Even though the combination uses less supports and panels than the previously tested preassemblies and support configurations the focus of efficiency is up for discussion. What is better? supports or preassembled panels? What is more time efficient? And what configuration would cost less? Now that different options are known for the structural efficiency further research will have to go into the secondary benefits of these configurations.

External combination

Preassembly configuration 21 is tested once more but now with the addition of automated support placement. No panel count reductions are made to the configuration since it still has to stand on its own without supports.

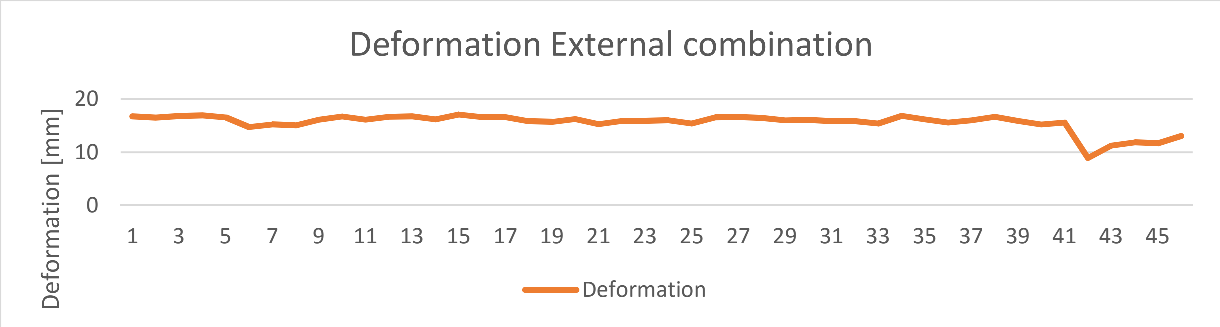


Fig. 81 Deformation [mm] results of Deconstruction of preassembly 21 with automated support placement

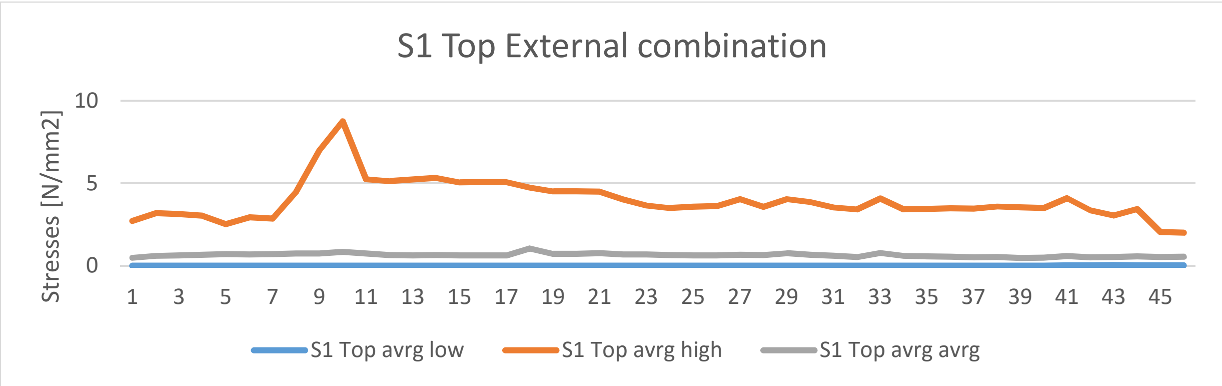


Fig. 82 S1 Top stress [N/mm²] results of Deconstruction of preassembly 21 with automated support placement

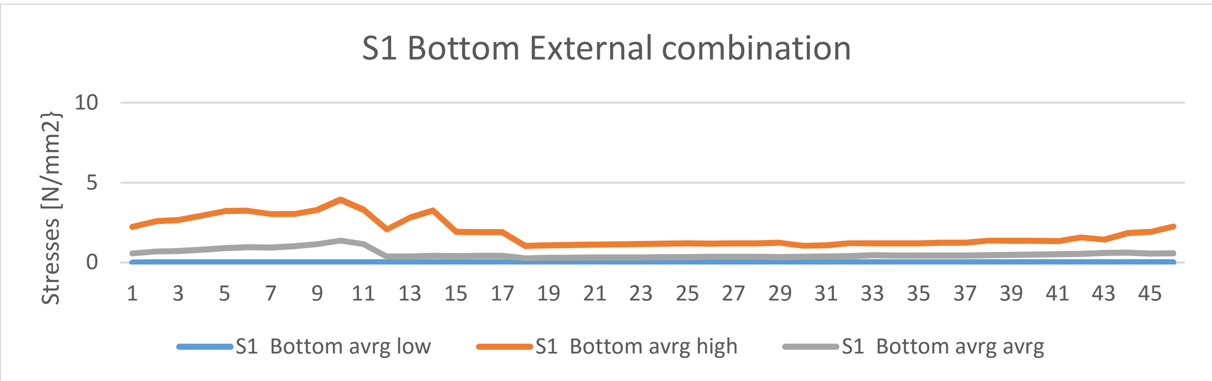


Fig. 83 S1 Bottom stress [N/mm²] results of Deconstruction of preassembly 21 with automated support placement

The external combination of support placement and gave less positive results than the internal combination. In fig. 81 a large peak can be identified after which 24 supports where placed. After this support placement the stress levels remained around 5 N/mm². These are the panel average stresses which indicates that detailed stresses might will most probably will further exceed the set limit. More supports could have been placed but one can argue for its efficiency compared to the other options of automated support placement and the internal combination. Furthermore, the connections that have to be made between the preassembly and the supports might prove complex during construction. Overall this method seems less favorable than the previously tested. For a final verdict this will have to be tested to a further extends with several configurations.

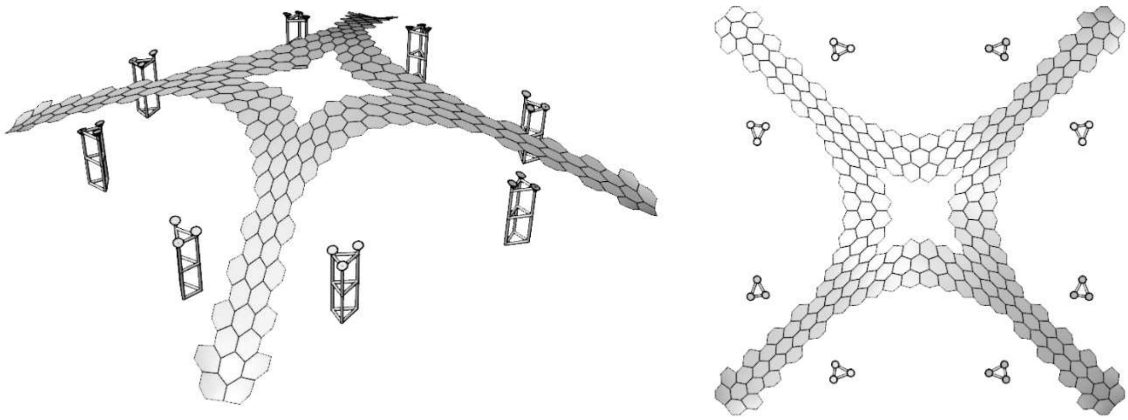


Fig. 84 Impression of the preassembly with externally generated supports

4. Final Conclusions

We started off to try and answer the following question:

<u>Can the Deconstruction principle reduce the amount of temporary supports used during the construction of prefabricated shell structures?</u>

The short answer is yes. The best test of the deconstruction algorithm gave a 75% reduction on the needed amount of temporary supports. For preassemblies one would use even less temporary supports but one still has to assemble the structure on the ground and the connect the preassembled parts. This might prove more complex that putting up supports.

On shell construction

A lot of shell construction methods have been tried over the last century. Several methods are still used in the same way they were 60 years ago. New experiments with post tensioned connections and free form tile vaulting prove to be good methods but need to be developed for larger scales. From all the found examples lessons can be learned and when designing a new construction method one should always look into these “dated” methods.

New computational method allow us to more accurately describe complex geometries and predict/monitor the structural integrity of a structure, whether it is under construction or fully assembled. This allows for our new analysis and construction method: Deconstruction and reversed deconstruction. A form is designed and for this form a structural pattern is optimized. This structural pattern then can undergo several variants of the deconstruction method to see which one works best for this form and construction planning. Through this method every shell structure can get a reduced temporary support structure. For a more detailed description I like to refer to the beginning of chapter 3.

On structural prefab patterning

When designing a pattern of structural prefabricated panels on should always try to achieve symmetry. Balanced and stable force flow improves the structural integrity in full assembly and in deconstruction. Deconstruction on more symmetric pattern can be done faster. Installing multiple panels at once can be done through countering the forces with an installation gimmick until all panels are in place. Development of such a gimmick should be researched.

Directional patterning is advised. It improves force flow and can “guide” it towards the desired supports. However, directional patterning can also channel force flow causing undesired concentrated panel stress. Dynamic relaxation can improve this channeling of force by making hard transition gradual. The process of dynamic relaxation can also distort panel geometry causing unwanted high detail peak stresses in the structural prefabricated geometry. Boundary conditions and optimization goals should always be closely monitored.

The usage of the force alignment algorithm with finite element checks per iteration should be tested to improve structural shell patterning. This might correct problems found after directional pattern design or dynamic relaxation. Its effects should be tested to see if it improves deconstruction results.

The assumption on the main flow of force needs to be corrected. This is not as black and white as a orthogonal and a diagonal direction but much more intertwined. Fig. 59 gives a depiction of the actual main flow of force. This might also conclude to a different pattern for this particular shell

In the case of the Heimberg swimming pool all deconstructions extracted the edge panels at an early stage. This shows that the edges of this shell are more covering than of structural vitality. It should be noted that the flipped up edges of the fully assembled shell are meant to divert the stress from the edges to the support, in deconstruction however they have no vital role.

On Deconstruction

Deconstruction as an workable tool is in an early stage of development. Without the correct handling it can result into chaotic unstable deconstruction. Extra selection rules need to be defined and implemented before the algorithm can be fully automated. Even then an engineer should always be allowed to interfere with certain choices.

Pure deconstruction is a very ambitious goal to strive for. In the case of the Heimberg swimming pool this would mean a minimal 16 m cantilever without supports. This is impossible without severe changes to the panel thickness and materials. When one changes the thickness of the shell that drastically just to build without support the degree of efficiency should be questioned. Then you're just moving material around. Pure Deconstruction, and therefor reversed deconstruction without supports, on its own is in my eyes not possible within the bounds of efficiency.

Automated support placement (ASP) has proved itself as a credible method of support reduction for prefabricated structures. The placement of the supports are now done on the panel that exceeds the set limits. This can still be questioned/researched. The placed supports however do support the structure in such a way that even in a second run stresses and deformation stay within the set bounds. In comparison to traditional supporting structures great efficiency is shown. Bases on a 2 by 2 meter grid support structure traditional methods would use approximately 252 supports. The optimized method uses 60 supports of which 48 are structurally vital and 12 are placed for further deconstruction. A comparison is depicted in fig. 85. In my opinion this is a great reduction.

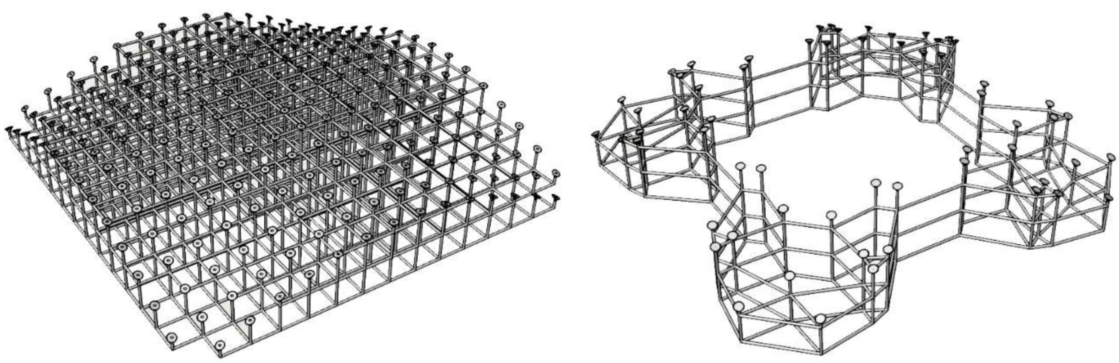


Fig. 85 Comparison of traditional supporting (left) and optimized supporting (right)

However, so far the panel average stresses have been monitored. This takes out a lot of the local peak stresses of which some are calculation distortions by the FEA and some are just. The monitoring of a smoothed version of the peak stresses should also be implemented in the algorithm. Further research will have to go into the extraction of the distortions so that more detailed readings can be performed.

Preassembly as a base for reversed deconstruction showed some problems with the configurations. The chosen configurations where of course designed for this project based on structural insight and the variations can be accepted as a complete test of the method. However, thorough research into the possible configurations of preassembly within this design was not conducted. I believe there are still possible configurations that have not been tested and might prove better than the ones that have been tested. Nevertheless, one can argue the efficiency of assembling almost one third of a structure on the ground, lifting these heavy assemblies in position with all the additional complications and then adjoining the other two third with stresses on the verge of exceeding.

The tested combinations of preassembly and ASP showed more promise. The addition of properly placed supports, under or just besides a preassembly, can make the preassemblies perform better with less panels and less supports than ASP. The internal placement (under the preassembly) also allows for a lot more configurations that can better sooth the force flow of the complete structure. The majority of the preassemblies tested had to be stable on their own which has little to do with the fully assembled structure. In the external combination one can also foresee difficulties in the connection between preassembly and additional support. Deformation and severe stressing might make joining more complex. Therefor, and for the better performance in testing, the internal combination is preferred over the external combination.

What has not been monitored closely is the support reactions. This should also be done to see what kind of supports are needed. Because of the complex workings of a shell structure this could change throughout the deconstruction process. This could even change between carrying supports and try downs. In further research into deconstruction this should be taken into account.

Deconstruction is now tested only on a panelized symmetric shell. This can also be done on Asymmetric shells and grid shells. The basic concept of calculating what the unfinished structure can carry and what needs support can generally be applied on complex building construction. This can greatly reduce the amount of material needed and the costs and construction time that go with it.

Optimization of the calculation time of the algorithm is an ongoing process. The calculation time has already been reduced by a tenfold with the help of some custom component programming. For the algorithm to be workable for first time grasshopper users it needs to be greatly simplified by writing custom components. This will limit the amount of copying and creation of unused elements currently done by grasshopper and with it its needed computing power.

Selection criteria

The principle stresses are a good selection criteria. It is generally advised to do deconstruction with the principle forces derived from the middle of the element. This will give the least distorted view. However, top and bottom results should always be generated for secondary checks.

The Normal principle forces N1 and N2 might also be interesting for deconstruction. This is the pure maximized normal force which can visualize the “shell effect” during deconstruction. This will have to be researched further.

As previously stated, at the current state of the algorithm manual selection should always be possible but based on the FEA results. In future more rules need to be implemented to prevent the removal of vital panels in the structure. This should also include multi selection of mirroring panels.

Recommendations

The future of improving shell construction lies in further development of the deconstruction algorithm and research into structural prefab patterning.

Improvement of the deconstruction algorithm can be done on:

- The extends of information that should be provided of all stage of construction
- Stress based selection
- Selection rules on vital panels
- Proving force alignment optimization with finite element analysis per iteration
- Shape optimizations based on the Deconstruction FEA results

In related research field on can look into:

- Structural patterning and structural pattern improvement on complex 3D geometry
- Development of temporary construction gimmick for the stressless insertion of structural prefabricated elements into complex 3D structures.
- Fabrication and physical testing of structural prefabricated elements with the flexible mold
- Most suitable structural panel design (material and engineering) for shell structures constructed with the deconstruction method
- Application of deconstruction on Grid shells and/or asymmetric shells

Summary

Shells are very economical and efficient structures in material use and structural integrity. Unfortunately the way they need to be constructed is expensive and time consuming. Whether they are cast in place or prefabricated, the structure is almost always supported with large amounts of scaffolding casting time and money to set up.

New computational modelling techniques for complex 3D geometry will allow us to analyze the construction of these shell structures. This can be done through deconstruction of the fully assembled prefabricated shell based on finite element calculations at each iteration.

In the past century several methods have been developed to improve the construction of shell structures (Sanchez-Arcas 1961, Rühle 1970). Unfortunately none have been able to achieve a great reduction of supports for large free form shells. Several elements of these methods can be used for inspiration, such as stabilizing installation gimmicks, patterning orders, post tensioning and pre assembly. These can be applied in the development of a new method based on the newly available deconstruction analysis.

To convert a monolithic shell to a structure that can be deconstructed it will need a structural oriented division pattern. Rules and points of improvement for such a pattern are described in papers by Prof. Knippers (Li and Knippers 2015) and the Block research group of Prof. Block (Lachauer, Rippmann et al. 2010, Rippmann and Block 2013). For the test case a mirroring hexagonal directional pattern is designed for the Heinz Isler's Heimberg swimming pool. This pattern is later dynamically relaxed to distribute the pattern more gradually over the double curved shell.

A computer model is set up with a custom designed mesh fitting the needs of the structure. On each panel edge three small beams, representing the connections connect all panels. The newly developed Deconstruction algorithm is then applied selecting panels for extraction based on the lowest principle stress result of the finite element analysis. In the test case the shell has mirroring geometry so mirroring multi selection is applied to maintain stability and equal deconstruction.

In conclusion: Deconstruction as a principle can be used to reduce the amount of supports needed in construction. Tests indicate a temporary support reduction of approximately 75%. However, at its current state it needs improvement by additional selection rules for vital panels, multi selection and easy manual interference. The data provided by deconstruction calculations can be used to project the main force flow curves. It is advised to determine the preassembled elements along these curves so further support reduction can be made. Choices between support and preassembled pieces need to be weighed.

In further research Deconstruction can also be applied on grid shells and other complex structure types. The concept of looking what can be carried by the incomplete structure and what needs to be supported can be applied on general building and bridge construction.

Within the Algorithm more research need to go into the selection by stress and selection rules for vital elements. Accompanied by more research into structural patterning, the installation gimmick and the actual construction, I believe this can make the construction of shells a lot more attractive.

Personal reflection

At the start of this project I had great ambitions. Two algorithms were going to be used, models were going to be build and physical testing results of panels with details were going to be used in the final algorithm. On top of that a part of the structure was going to be built on a 1:1 scale as a prove of concept. These grand ideas were unfortunately not realistic and had to be scaled down.

The first problems I encountered were in the geometric complexity and the its translation from Grasshopper (the geometric modelling program) to Diana (the finite element software). These were predominantly on the different definitions and boundary conditions for geometry. Differences between these programs gave errors during calculations in Diana for which only limited support could be provided at the faculty.

At a certain point between P3 and P4 we provided a demonstration of the algorithm to a selected group of professional engineers and students. TNO Diana was also represented, but unfortunately these specific people were not able to answer my questions. They did redirect me but eventually the problem got solved not without a lot of effort. Seeking support with the creators of the Diana seemed like a big step and I only wanted to take it if it was essential. Looking back I should have contacted them far earlier on when I ran into the first unknown errors. Looking forward the algorithm should be develop further in closer contact with Diana.

The focus that was put fixing the model errors was, in hindsight, far too great. The focus was more on detail than on the bigger picture of my graduation. However, fear of not being able to get the computer model running and ending up with nothing always played a vital role. In retrospect, I should have started optimizing and automating the algorithm in a simple model before trying to operate the full scale model. Although this provided good insight into the bottlenecks in the algorithms calculation speed it would also have saved me a lot of time in the earlier stages. In the end I had to call in help in C# programming to remove these bottlenecks. I'm still very proud of the current calculation speed of the algorithm that came down tenfold from 30 minutes to 3.5 minutes. This also had to do with several computer upgrades that had to be installed.

Between P2 and P3 I was constantly postponing major decisions. These were eventually made while making the P3 presentation. This had to do with the hard time I had with letting go of the original grand ambition. If these decisions would have been made in an earlier stage I could have presented a more complete product now which would have satisfied me equally.

In the end the end product is still in its early testing phase. Nevertheless it shows great promise. In further development the deconstruction algorithm can greatly reduce the costs and duration of shell construction. This has a possibility to reintroduce the economical and efficient shell structure into modern building culture.

During the project I was constantly enthusiastic and motivated. Although sometimes I had doubts on the quality of the end product, I was always challenged and motivated by the exotic nature of developing something new. This was also sparked by the curiosity and enthusiasm that other people, professionals, fellow students and even non-technical people, showed in encountering my project. Somehow it stimulated a lot of peoples imagination which motivates me to continue working.

Appendix A: Interviews

Octatube

Interview Octatube Barbara van Gelder

10-12-2015

Intro over afstudeer project

- Er zijn veel partijen reeds bezig met de flexibele mal. Voor beton is deze inmiddels ontwikkeld. Met de zelfde methodiek zal deze ook voor FRP's beschikbaar zijn. Voor staal kom je dan eerder op gridshells uit aangezien deze minder materiaal nodig hebben en meer hoogte kunnen creëren.

Hoe wordt momenteel het steigerwerk bepaald

- Dit gebeurd door middel van een montage plan. Hierin wordt meegenomen wat de krachtswerking is gedurende de bouw om daarmee de hoeveelheid steigerwerk te bepalen

- Tijdens de bouwtijd word er geen rekening gehouden met verschillende extreme belasting combinaties. Hier wordt alleen gerekend met eigengewicht en eventueel mensen die er over moeten lopen. Belasting combinaties komen pas van kracht bij langdurig gebruik en zware sneeuw/regen belasting. Er gelden dus ook geen veiligheidsfactoren zoals in standaard berekeningen. Er wordt wel rekening gehouden met veiligheidsfactor op eigen gewicht + bouwvakkers. Bij zware weersomstandigheden wordt extra bij gestut.

- In het maken van dit montage plan wordt doormiddel van fasering/bouwvolgorde gekeken naar kosten optimalisatie.

Voorbeeld Rabin Centre

Het Rabin centre is een gebouw met 3 grote FRP vleugels rustend op enkele kolommen. Deze is opgebouwd uit verschillende in de fabriek gemaakte panelen van 3 bij 12 m. Deze werden via speciaal vervoer naar de bouwplaats verscheept en daar aan elkaar gemonteerd in voormontage aan de grond. Hiervoor werd een stellage gebouwd om de delen te stutten. De geassembleerde vleugel werd in zijn geheel in gehesen.

- Een belangrijk ding om op te letten tijdens montage op de bouwplaats is de natuurlijke elementen die spelen. Temperatuur, vochtigheid en windkracht kunnen hierbij een grote rol spelen.
- In de aanloop naar de bouw van het Rabin Centre is er een uitgebreide analyse geweest van de verschillende mogelijkheden van assemblage. Hierbij is afgewogen om kleinere, of grotere, panelen te produceren i.v.m. vervoerbaarheid vs. assemblage. Uiteindelijk is de keuze gevallen op speciaal vervoer met panelen van 3 bij 12 m.

Zou het mogelijk zijn om kosten (tijd/geld) van bouwprocessen te vergelijken?

- Het vergelijken van kosten plaatjes van het bouwproces is bijzonder complex. Hierbij spelen zo veel verschillende factoren mee in de keuze voor een bepaalde methode. Vorm van het gebouw, structurele efficiëntie, ondergrond, bereikbaarheid locatie, beschikbare materiaal, beschikbare bouwvakkers, bouwvakkers cultuur, trends en de voorkeur van de aannemer spelen bijvoorbeeld allemaal een rol in het bepalen van de uiteindelijke prijs. Dit is dus eigenlijk niet, of bijzonder complex om, te vergelijken.
- Bouwkosten zijn meestal afhankelijk van het bouwbudget. De materieel kosten komen, bij ons, vaak uit rond de 3% van het totale bouwbudget. Hiervan is kraan/steigerwerk verhouding meestal 50/50 kostenverdeling.
- In de woningbouw is men een project begonnen genaamd “halftime” waarbij aannemers collectief proberen de bouwtijd te halveren met innovaties. Dit heeft al tot grote bouwtijd reducties gezorgd.

BAM

Interview Mischa Fagler & Maarten Meuleman

28-01-2016

1. **Intro**

Mischa Fagler: Advies & Engineering vanuit BAM Speciale taak: passing in omgeving

Maarten Meuleman: Werkorganisator bij het project in tender, voorbereiding en ruwbouw fase

2. **Arnhem centraal**
   a. **Bouwmethode onderzocht, welke?**

      Hout bekisting, gefreesde bekisting en schenkels. Bij de laatste twee was de afwerkingskwaliteit alleen een vraagstuk. Dit zou uiteindelijk nog veel nabewerking nodig hebben. Schenkels zijn alsnog gebruikt voor overgangselementen van beton naar staal.

      De staal scheepsbouw methode zorgde uiteindelijk ook voor een verlaging van de arbeidsintensiviteit op de bouwplaats. Grote delen werden geprefabriceerd en van de voren op de scheepswerf gepast. Daarna weer ontkoppeld en op de bouwplaats in gehesen.

      i. **Voor en nadelen onderzocht?**

         Van allen zijn de voor en nadelen onderzocht en in een goed-matig-slecht vergelijking naast elkaar gezet.

         In de beton variant was er ook het grote nadeel dat men slecht kon voorspellen wat het beton ging doen gedurende en na de bouw. Aangezien bijvoorbeeld ontkisting voor een schaaldak simultaan moet gebeuren, en dat zo goed als onmogelijk was in deze situatie, was slecht te voorspellen hoe de schaal zou reageren. Hier speelt het feit dat deze schaal geen geoptimaliseerde schaal is ook een grote rol. Verder speelde droging en weersomstandigheden wederom onvoorspelbare rollen op korte en lange termijn. Daarbovenop komt nog de afwerkingsgraad, vele benodigde extra partijen nodig voor beton, complex vlechtwerk en de grote hoeveelheid extra benodigde ondersteuning.

b. **Waarom uiteindelijk niet beton, geld/tijd?**

Risico. Natuurlijk hadden tijd en geld er mee te maken maar de voornaamste reden was risico. Bij het maken van een stalen schaaldak zou er 1 partij verantwoordelijk zijn voor engineering, prefabricatie en installatie. Dit was de scheepsbouwer. Bij het maken van een betonnen schaaldak zouden er 10 verschillende partijen verantwoordelijk zijn voor verschillende aspecten. De beton leverancier, de wapenings leverancier, wapeningsvlechters, enzovoort, enzovoort. Hierbij zou ook de twee grootste bekistingsleveranciers hun halfjaarlijkse besteding in dit ene project moeten stoppen.

Daarnaast is beton te onvoorspelbaar. Hoe deze op korte en lange termijn zou reageren op de krachten. Hoe de marges op de onderliggende glazen gevel voorspeld moesten worden. Met staal is dit een stuk makkelijker te voorspellen.

Al deze redenen gecombineerd gaven simpelweg een te groot risico.

i. **Kosten en bouwduur in beton?**

Aan het begin zijn door de gemeente Arnhem bouwtijd en bouwkosten vastgezet. Het doel was het product binnen deze tijd en prijs te bouwen met een zo hoog mogelijke kwaliteit. Dit was geen gebruikelijke benadering waarbij aannemers vechten om wie de laagste prijs kan bieden. Hierbij werd de vrijheid gegeven in de oplossingsrichting.

De analyse tussen beton en staal is duaal geweest tot aan het eind van de tender fase. Hierna is er alleen doorgegaan met staal. Totale gewicht van het beton dak zou 1300 kg/m^2 bedragen met daarvan 170 kg/m^2 wapening. Het staaldak in scheepsbouw bedraagt 160 kg/m^2. Een derde optie voor een ruimtelijk vakwerk had 120 kg/m^2 gewogen maar had een te grote hoogte nodig. De hoogte van het staaldak nu blijft binnen de perken maar is niet geoptimaliseerd om overal zo slank mogelijk te zijn.

Tot slot zou de onderstempeling van een betonbekisting ook niet mogelijk zijn geweest. Aangezien de gehele constructie afgestempeld moest worden op de balken van de onderliggende parkeer garage was er maar beperkte ruimte voor stempels. Het vertienvoudigen van de onderstempeling has simpelweg te veel ruimte gekost en had daarnaast ook niet gelijktijdig ontkist kunnen worden.

c. **Uiteindelijke koste schaaldak?**

€37.5 miljoen voor 6000 m^2 BVO => €6000 p/m^2

d. **Uiteindelijke bouwtijd schaaldak?**

Wat reken je wel en niet mee. Van waar tot waar? Het gebouw is opgeleverd binnen de bepaalde tijd maar wil de daarbij de prefabricatie tijd ook hebben. (Uiteindelijk geen antwoord)

e. **Waar zou de grootste besparing zitten?**

De grootste besparing had gezeten in de hoeveelheid staal en de tijdelijke ondersteuning daarvan.

De hoeveelheid staal is niet afgemeten op de benodigde sterkte maar of de gegeven hoogte het zou houden. Dit was voornamelijk door de onervarenheid van de scheepsbouwer met gebouw opleggingen. Doordat de scheepsbouwers voornamelijk gelijk verdeelde druk over een scheepsromp tegenkomen zijn zij niet veel gewend aan puntopleggingen en puntlasten in een schaal. Dit was ook de aanleiding om de hoogste lokale verstevigingsdichtheid te nemen voor de gehele schaal voorkomend uit een bootromp belasting. Dit is om tijd niet meer aangepast. Dit gaf veel overbodige stijfheid.

3. **Algemeen**

a. **Meer ervaring met schaal constructies?**

Nee, alleen stadion daken (Arena & Gelderdome)

i. **Zo ja, herhaling Arnhem vragen per onderdeel**

ii. **Keuze voor aannemen schaal project? Gelieft of gehekeld**

Schalen worden simpelweg niet veel aangeboden. De schalen die worden gebouwd zijn meestal niet geoptimaliseerde vrije vormen. Wanneer er een schaal aangeboden wordt staat BAM daar open voor.

b. **Prijs m2 dubbel gekromd vlak?**

Geen pijl op te trekken, prijs zegt te weinig

Staal is hierbij wel veel duurder dan beton. Staal kost €10/kg, wapening €1/kg en beton €200/m^3

i. **Hoeveel is daarvan ondersteuning? (uitgaand van staal steigerwerk)**

Staal ondersteuning was in het geval van Arnhem Centraal 3x zo goedkoop als beton. Het grote gewicht van beton zorgt ervoor dat het frequent ondersteund moet worden. De gewichtsreductie van staal bezorgde tevens een stempel reductie.

Een vaste prijs is wederom niet te geven omdat dit ook vaak afhankelijk is van de dikte van het beton en het soort beton wat is gebruikt.

ii. **Hoeveel is daarvan manuren en hoeveel uren gemiddeld per m2 dubbel gekromd vlak?**

Niet te zeggen

c. **Huidige manier van bepalen steigerplan/ondersteuningen?**

Volledig doorrekenen en daarop hoeveelheid steigerwerk bepalen voor verschillende punten op het cruciale pad. Hierbij wordt bekisting en ontkisting meegenomen in het bouwproces.

i. **Optimalisatie in ondersteuningen/steigerwerk?**

Optimalisatie wordt vooral gedaan in het bepalen van de bouwvolgorde en benodigde ondersteuning in deze stappen. Hierbij worden alle bouwfases doorgerekend.

ii. **Bepaling opbouw volgorde?**

Dit wordt bepaald door de randvoorwaarde en het kritische pad van alle andere bouwdelen. Daar binnen word gekeken naar een belasting optimale bouwfase.

d. **Ervaring met alternatieve bouwmethoden?**

i. **Vrezen/prefab schalen/andere**

Prefab, keuze hiervoor is echter afhankelijk van de randvoorwaarde. Daarbij heeft prefab wel de voorkeur. Dit verschilt echter per aannemer.

ii. **Keuze prefab/monoliet?**

Deze keuze is meestal gebaseerd op velen factoren. De eerder genoemde randvoorwaarde van locatie, ondergrond en transportmogelijkheden kunnen hier bijvoorbeeld bij van kracht zijn. Daarnaast kan men het ook onwenselijk vinden om nog een of enkele partijen erbij te moeten betreken voor het storten van het beton. Competentie van de beschikbare bouwvakkers speelt ook een grote rol.

Over het algemeen is de keuze voor monoliet of prefab persoonlijk per bedrijf. Bedenk daarbij of het project midden in een weiland staat of in hartje Amsterdam.

iii. **Durf alternatieve bouwmethode?**

De bouwwereld staat open voor alternatieve bouwmethoden maar deze moeten niet dichtgetimmerd zijn. Veel bouwbedrijven willen graag hun eigen interpretatie er aan kunnen geven om controle te kunnen houden. Zij blijven immers verantwoordelijk.
De keuze voor een bouwmethode komt voort uit een risico analyse gecombineerd met veiligheid.

RAP studio

Interview Leon Spikkers Studio RAP

15-03-2016

1. **Intro**

   Leon Spikker is Co-Founder van Studio RAP started the firm to make complex architectural shapes buildable through smart computational design combined with automated production techniques. They work as an consultant for architects working out fabrication problems and producing the elements for construction.

2. **Skilled-in Office**

   The Skilled-in Office was an assignment from the RDM company. A double curved shell roof was to be designed supported only by itself and the glass wall around it.

   For generation of the form they used Rhino Vault (a Rhino 3D plugin) that uses graphic statics to find the mathematical horizontal and vertical equilibrium for a floorplan. The found surface was divided into flat triangles determined by clock and counter clockwise spirals that where drawn on the surface. Malleability was checked on the two longest sides combined with the angle between them. When it failed malleability constraints another spiral line would be added or spiral division increased.

   For fabrication the panels where analyzed for their force transfer direction by their position in the shell. According to this transfer direction the triangle was place so that wood nerves would align with the force. This was combined with efficiency nesting to reduce the amount of waste material.

   During construction the middle cone was first constructed to a height of 2 meters. From that base arcs where pre-assembled to the surrounding steel frame to stabilize the cone. These arcs where strutted and formed the base for further construction in between the arcs. The remaining shell was built in in rows towards the end. This process saved a lot of strutting during construction.

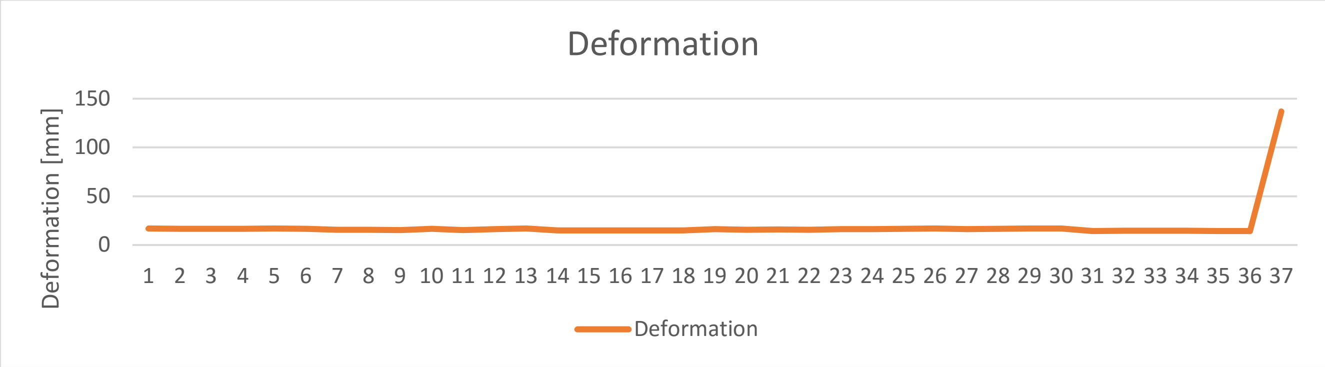
   The computational workflow contained the determination of shape and panel pattern. Further integration of structural analysis or FE calculations was not used.

3. **Further projects**

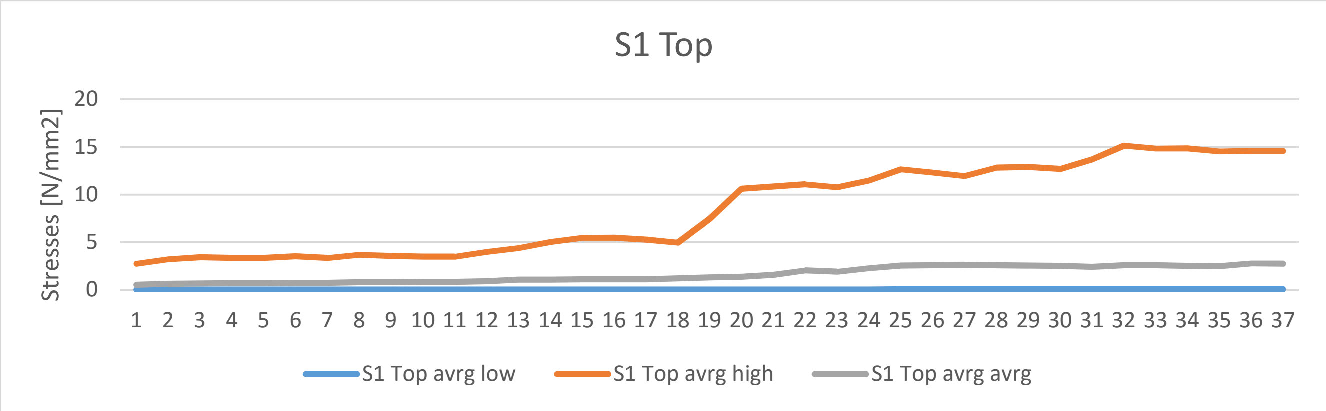
   Further projects of Studio RAP on paneled geometry involve Acoustic panels designed in combination with ARUP, double curved concrete facade panels for the Arnhem Central station together with UN Studio and an art installation out of hyperbolic foam panels cut with a robotic wire cutter. Unfortunately further information on these projects cannot released right now.

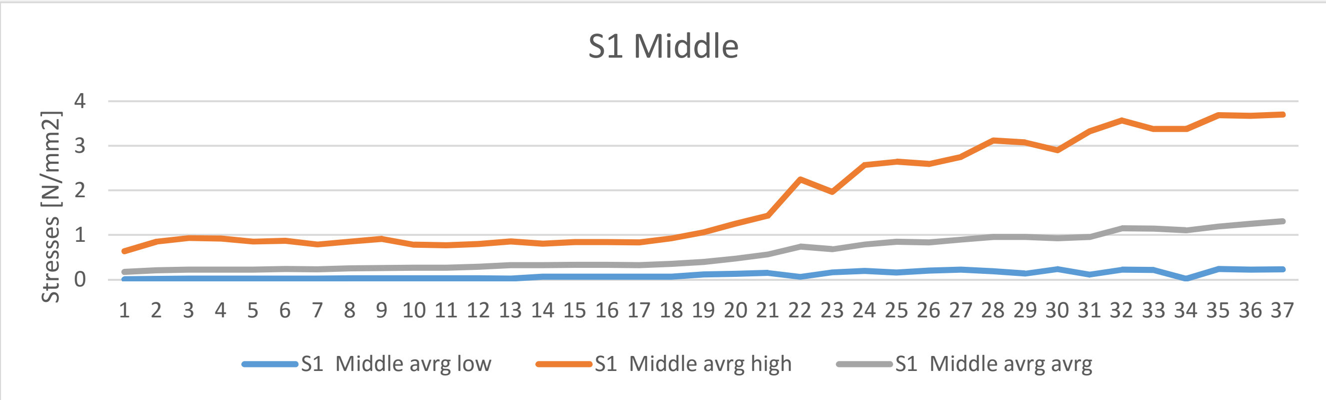
Appendix B: Tabulated results

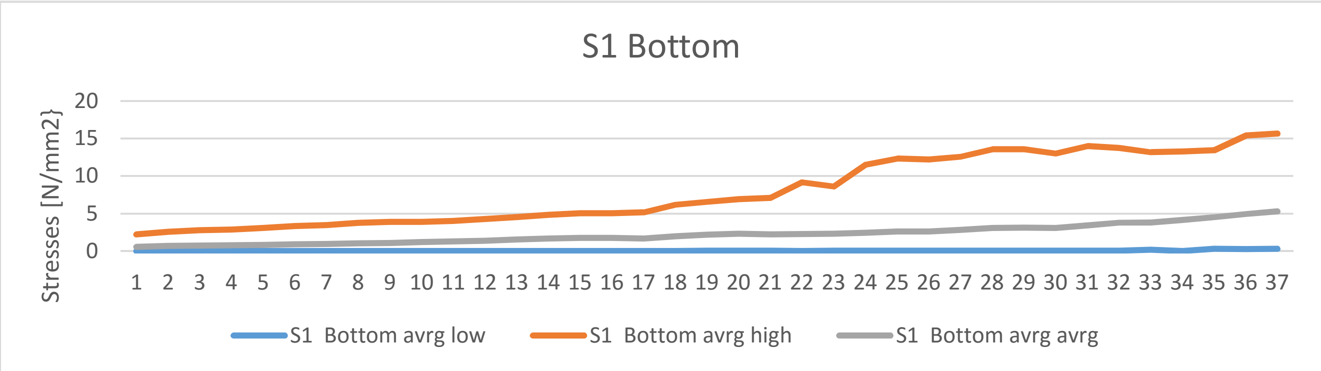
Pure Deconstruction complete results



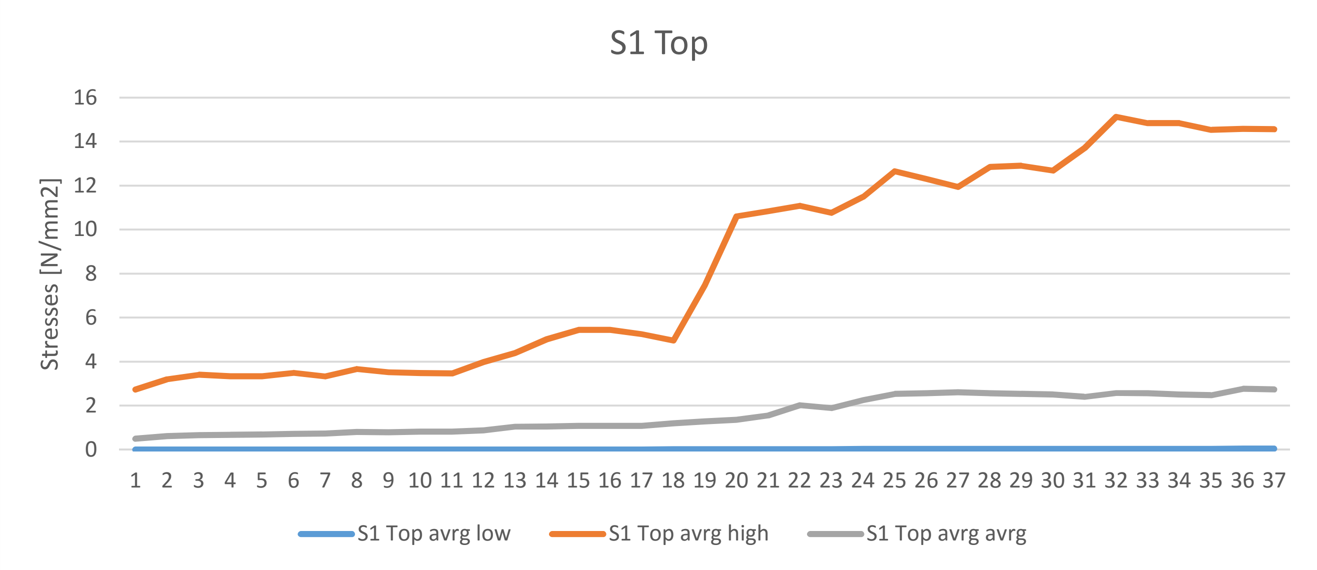
S1 Top, middle and bottom stresses

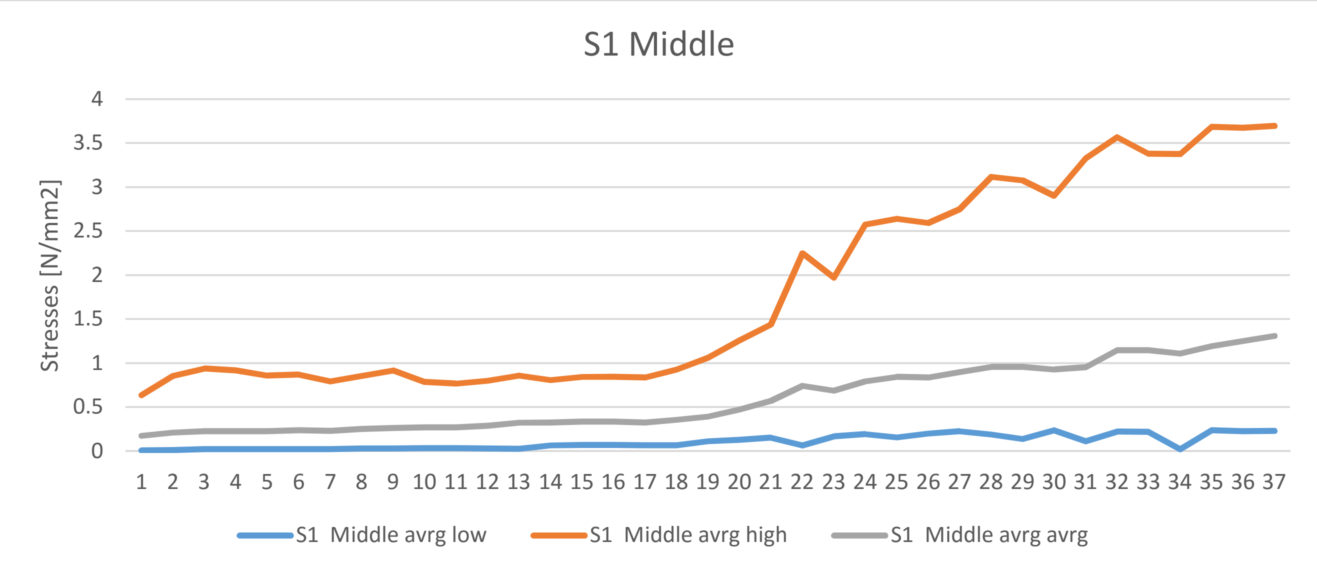


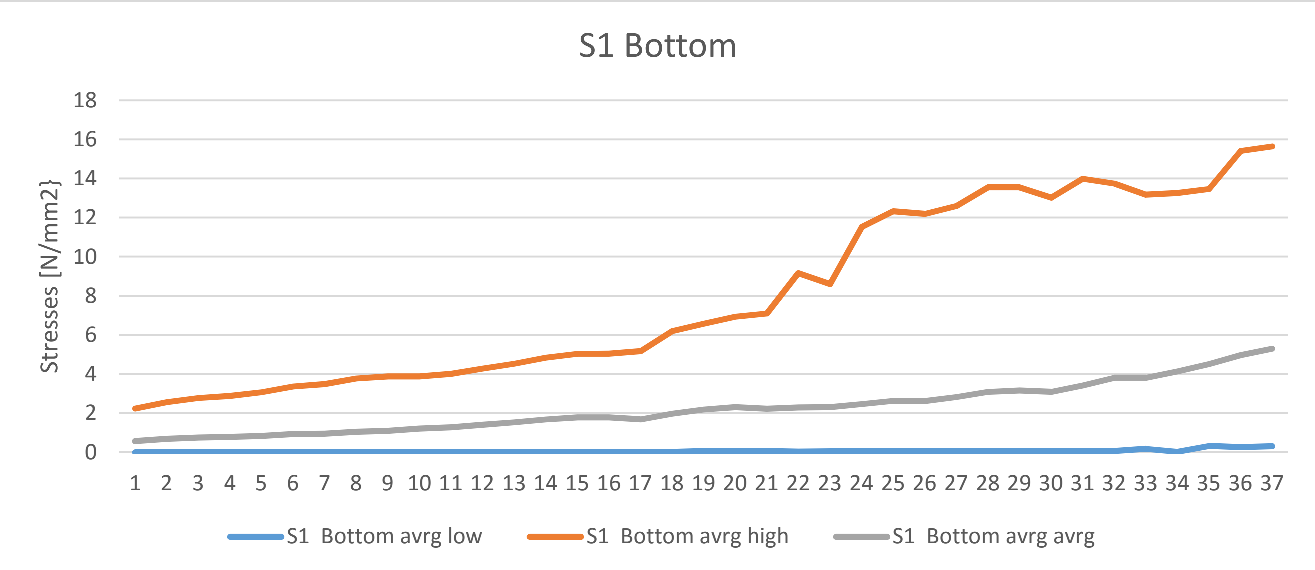




[S2 Top, middle and bottom stresses](#)







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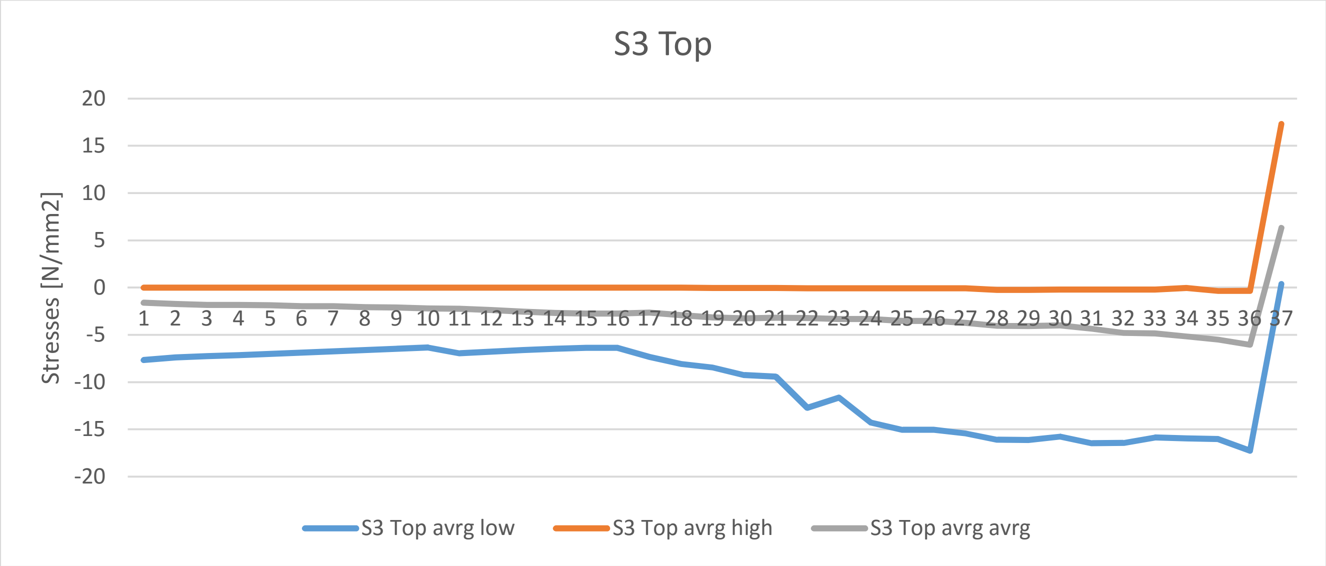

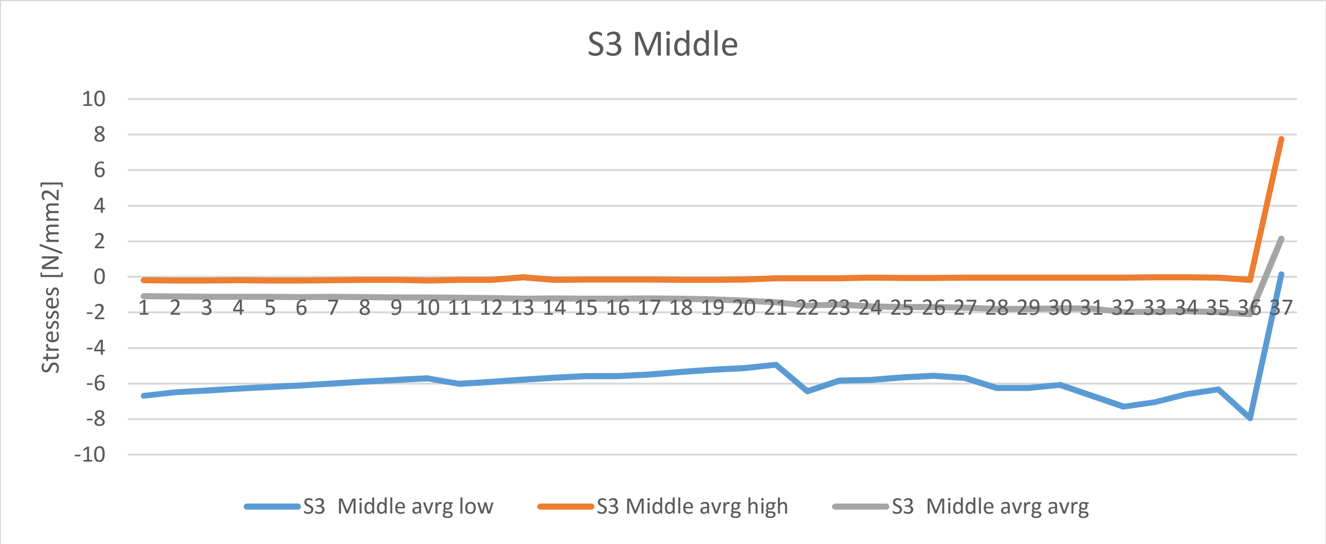

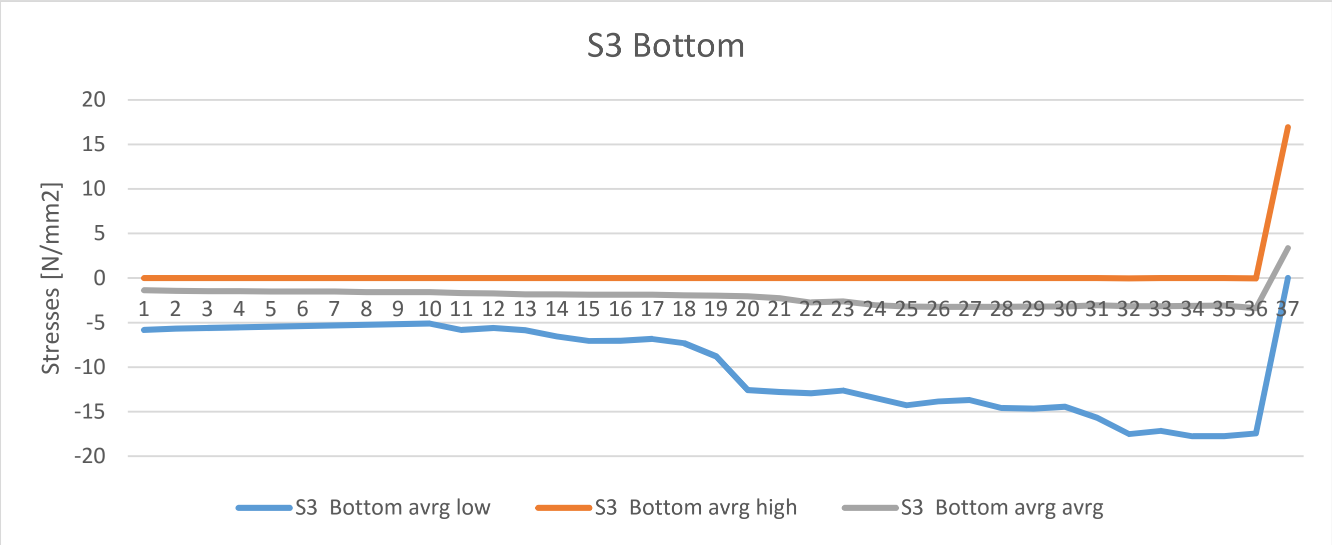

Preassembly configuration complete results

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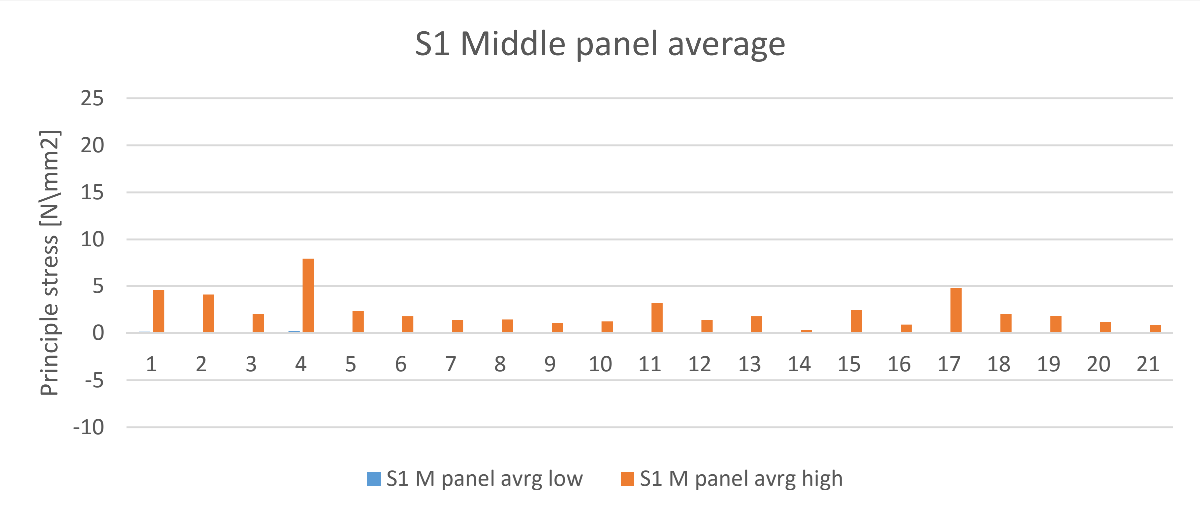

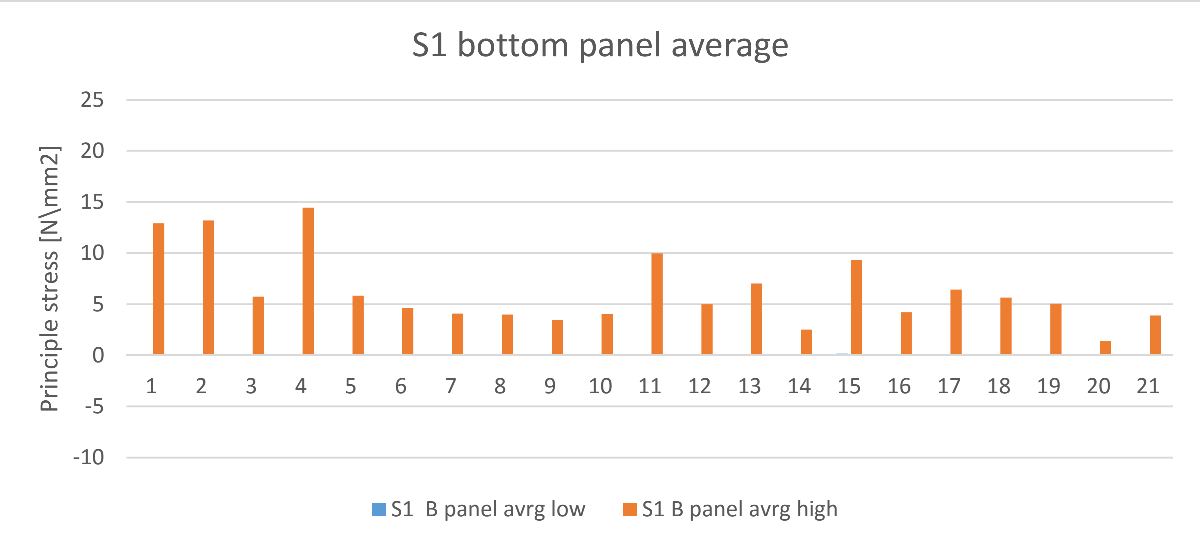

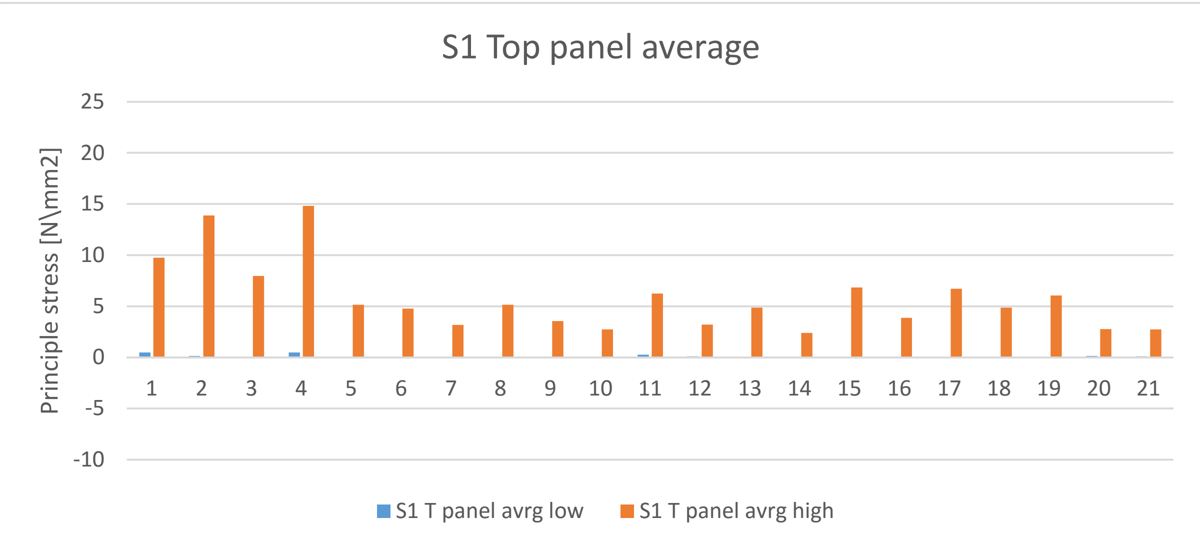

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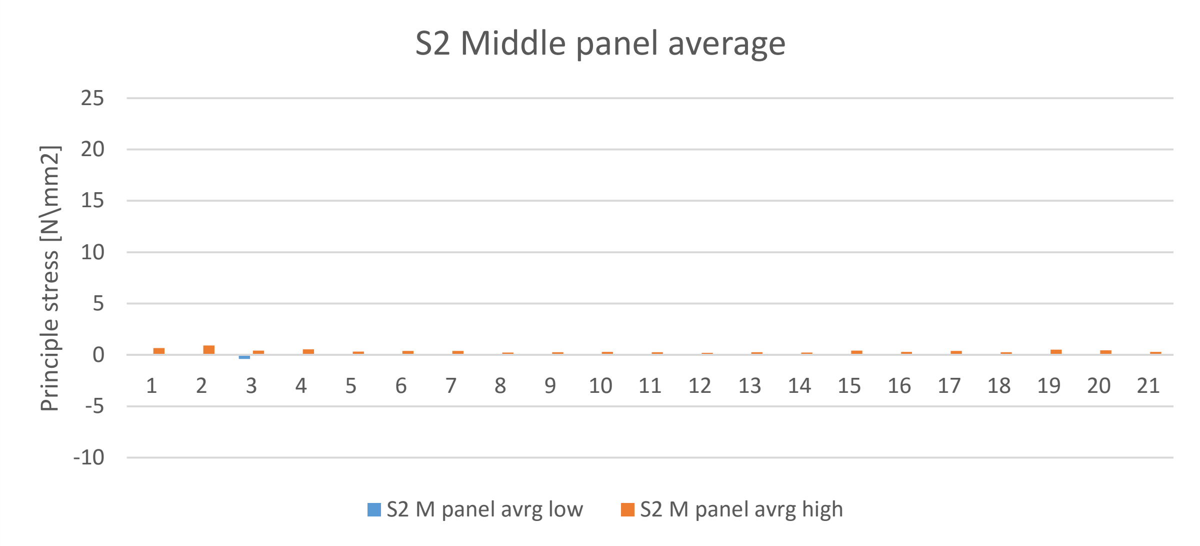

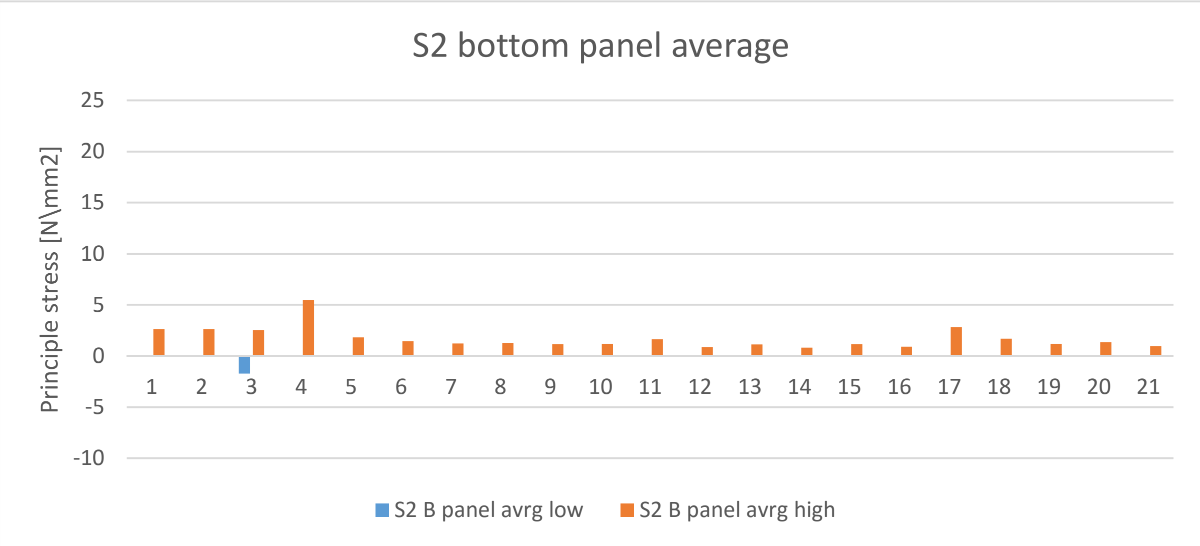

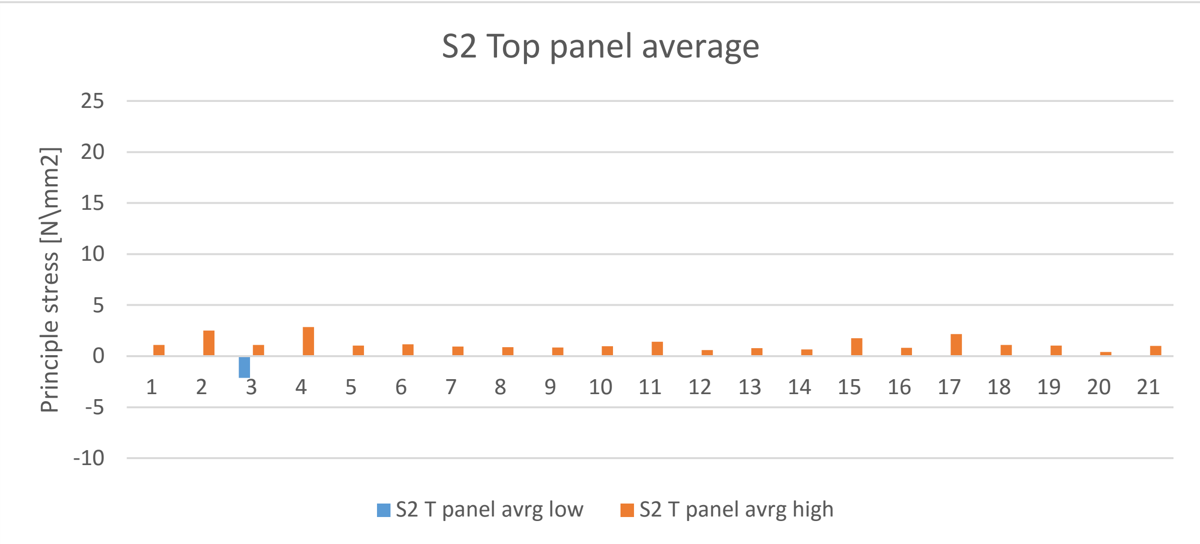

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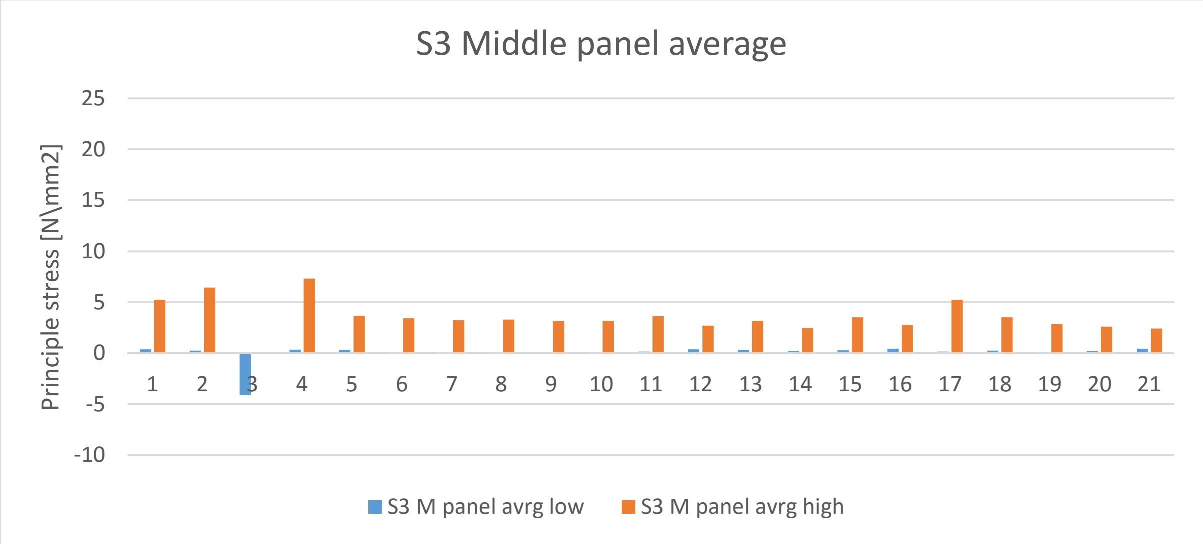
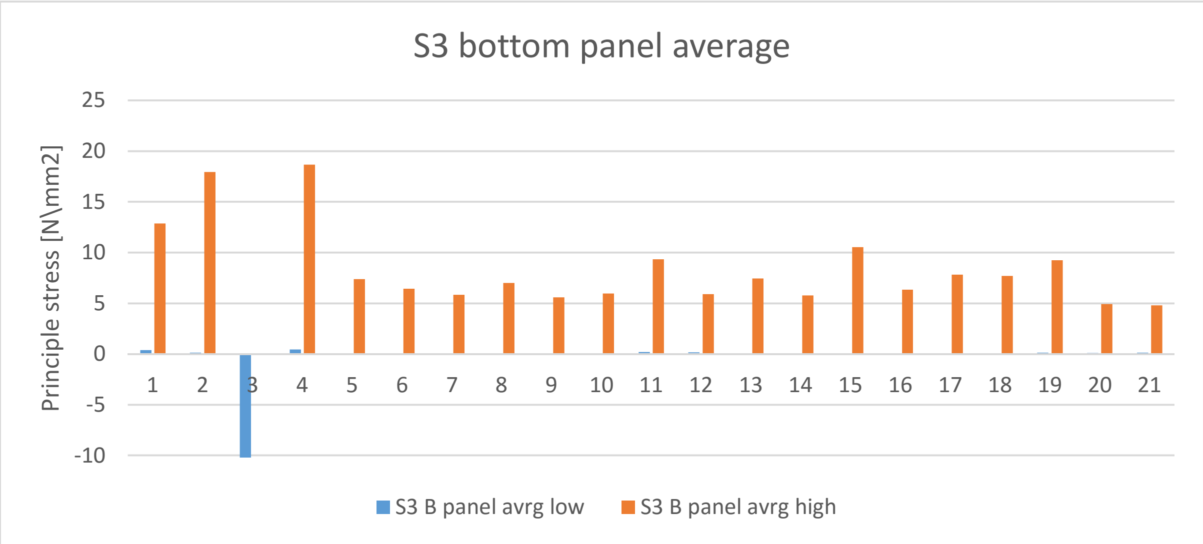
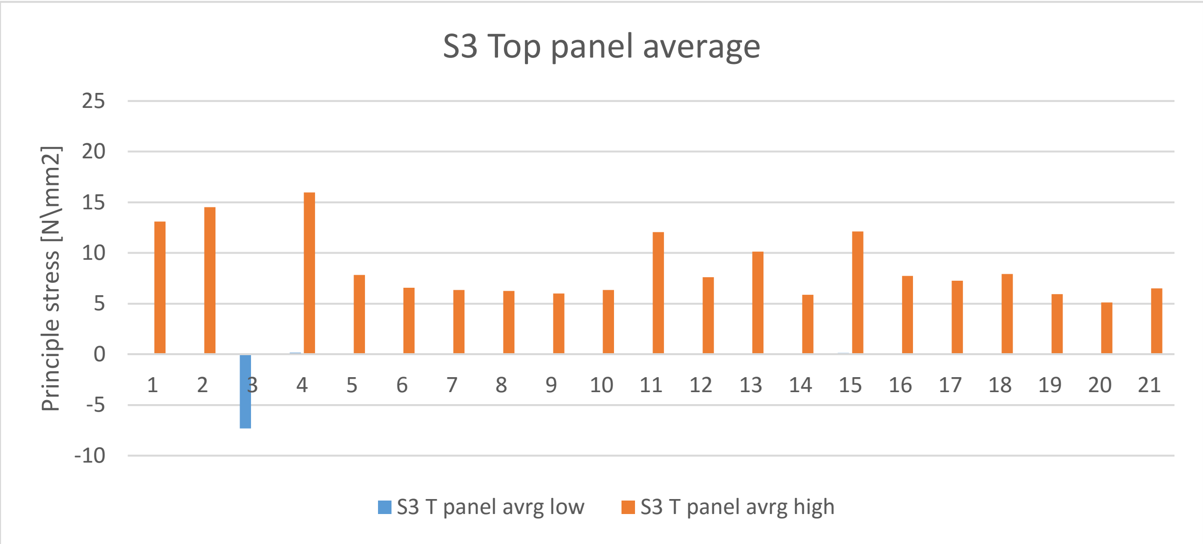
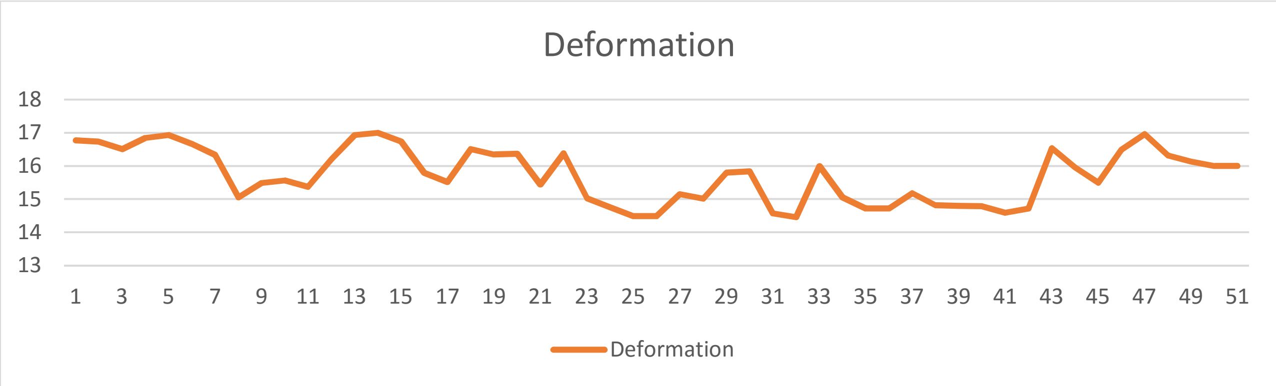






Preassembly 21 complete results



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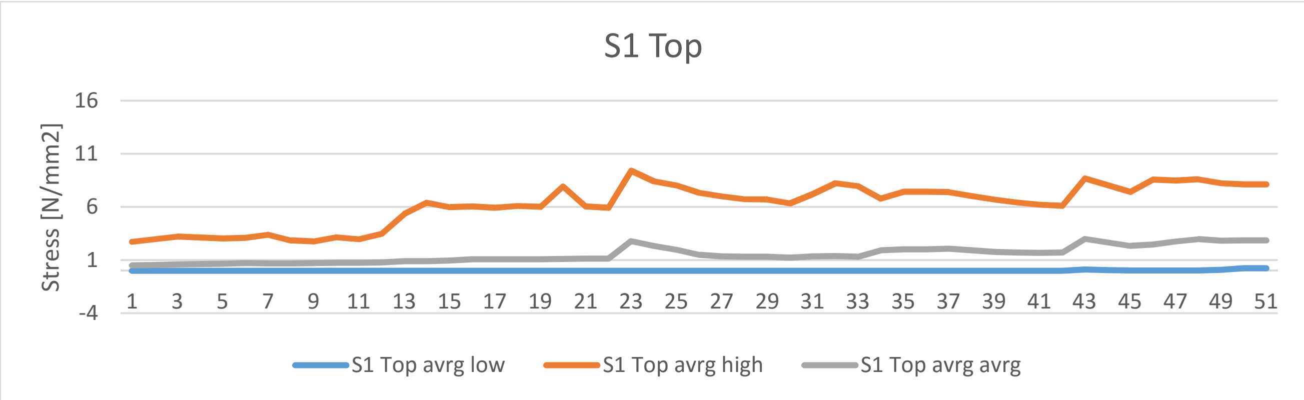

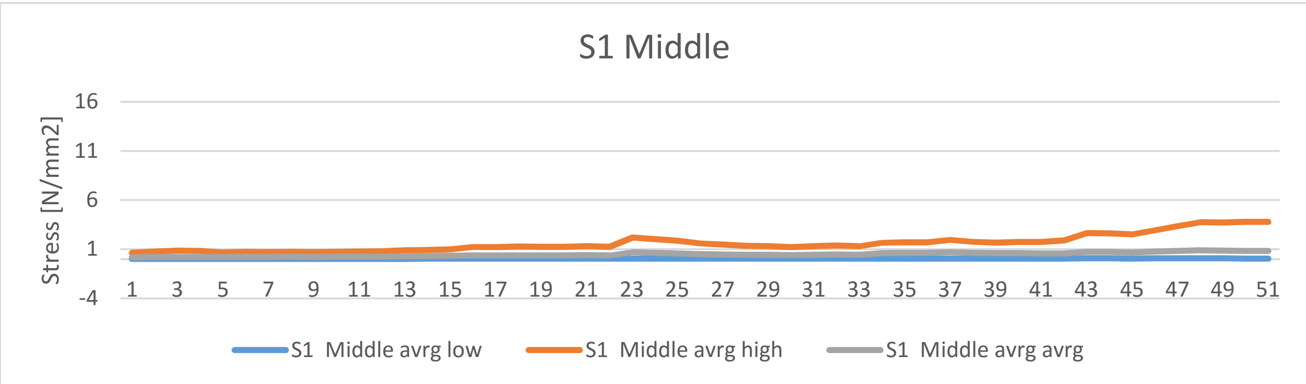

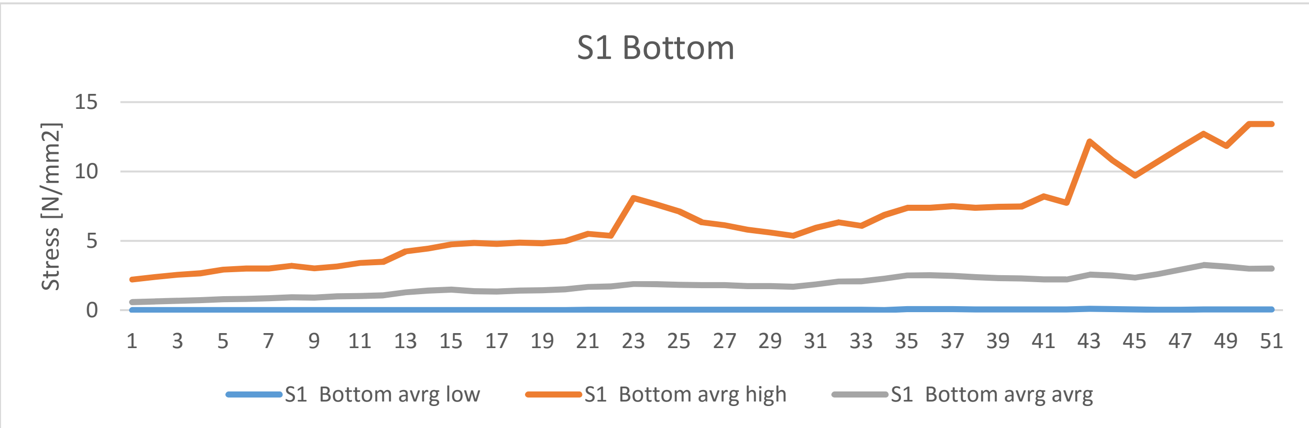

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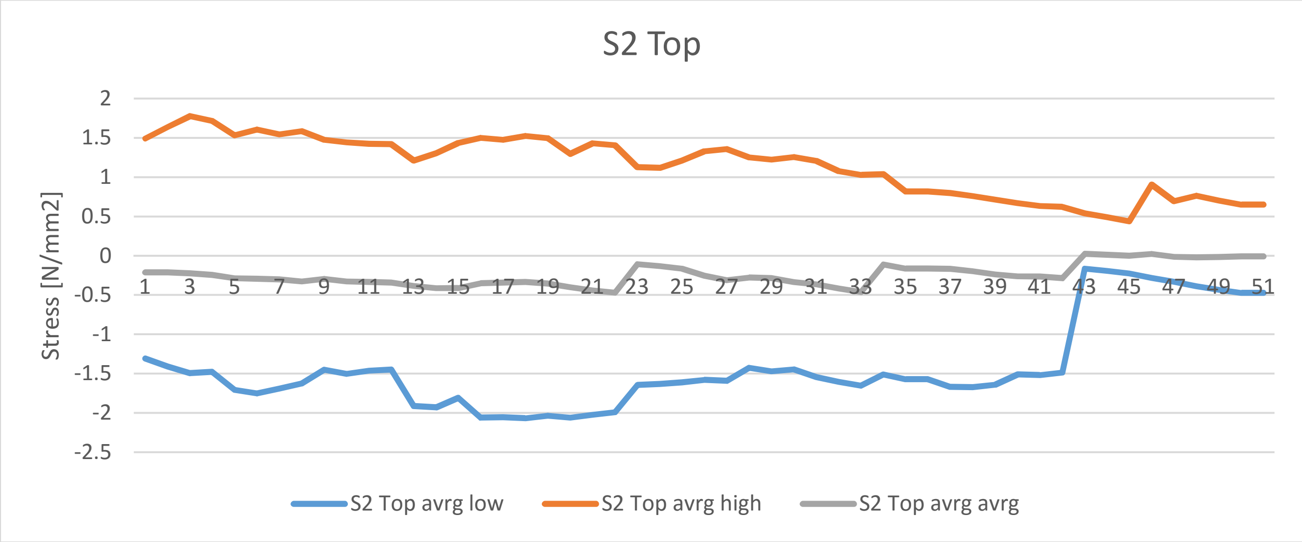

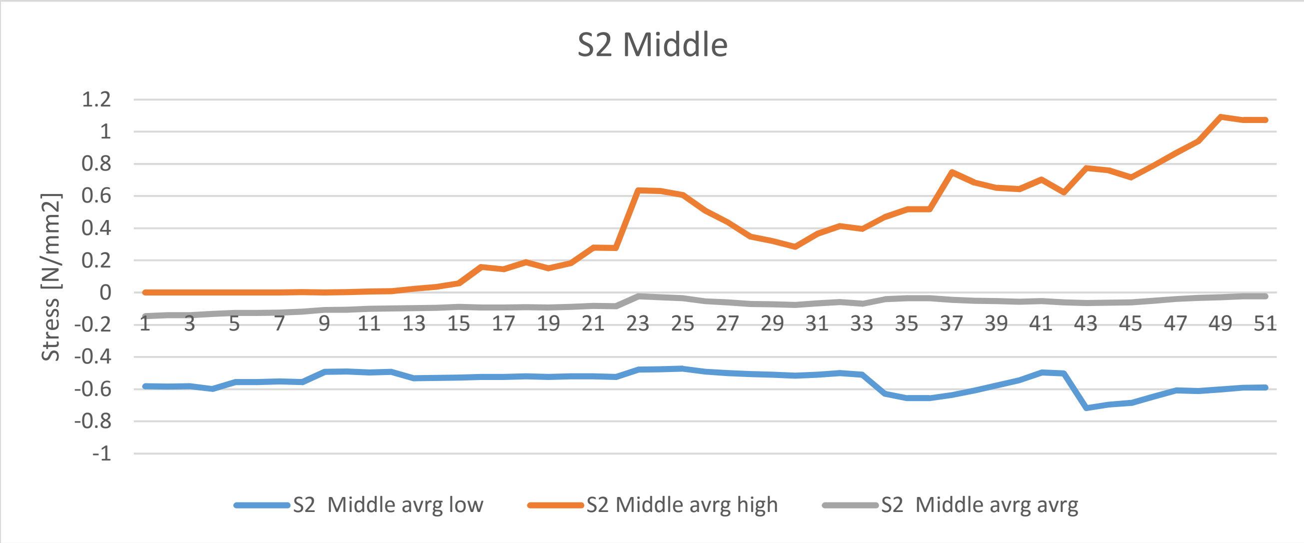

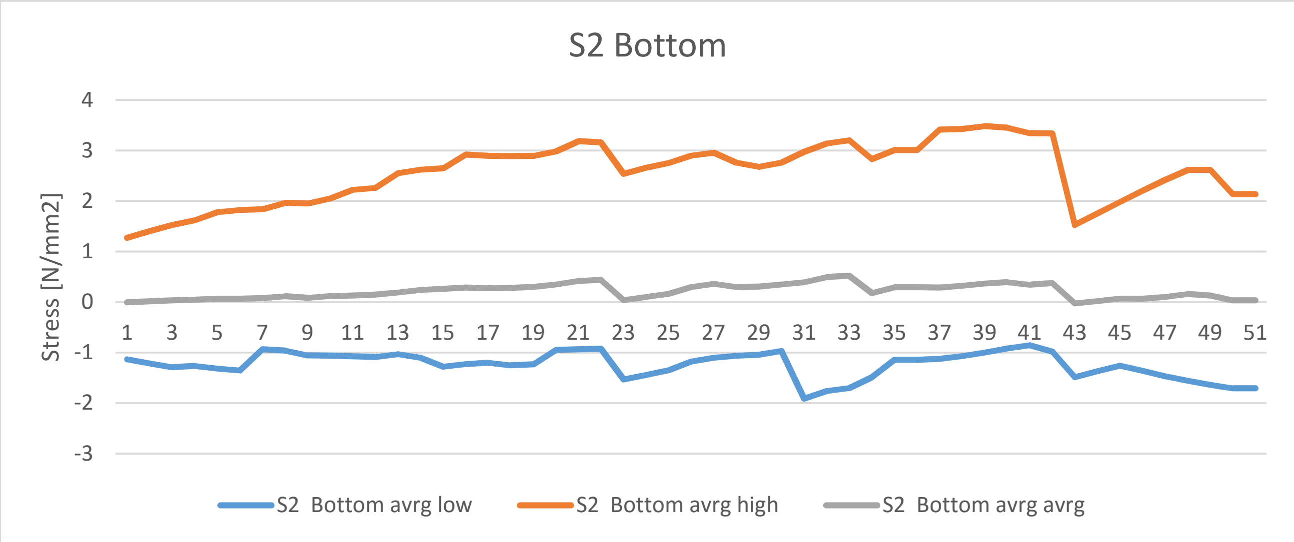

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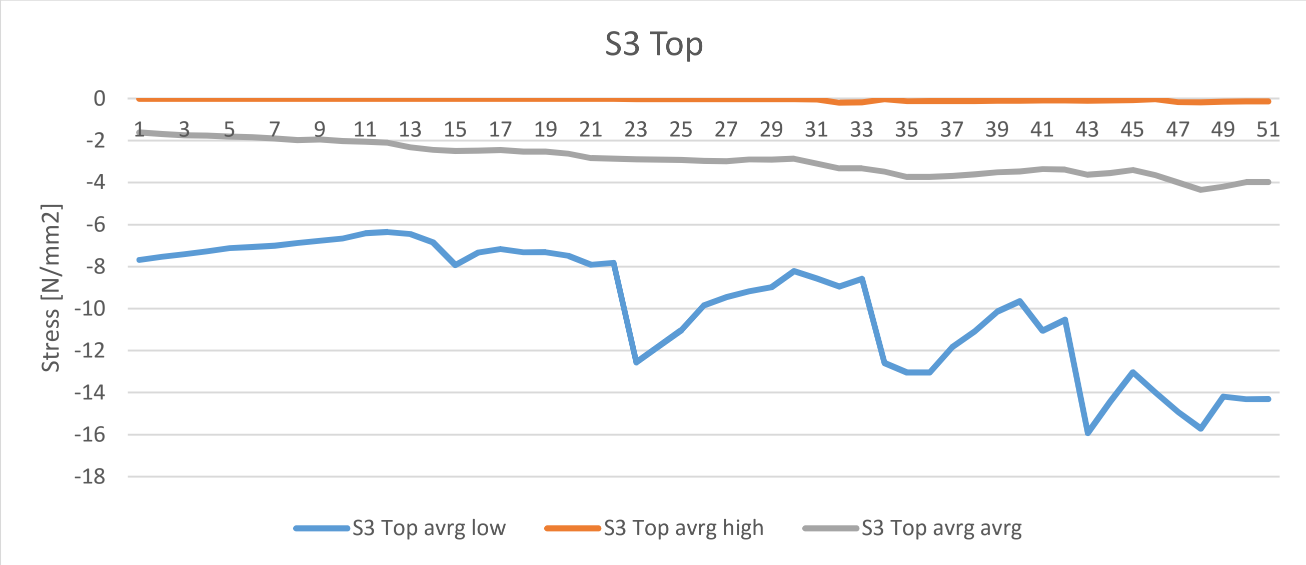
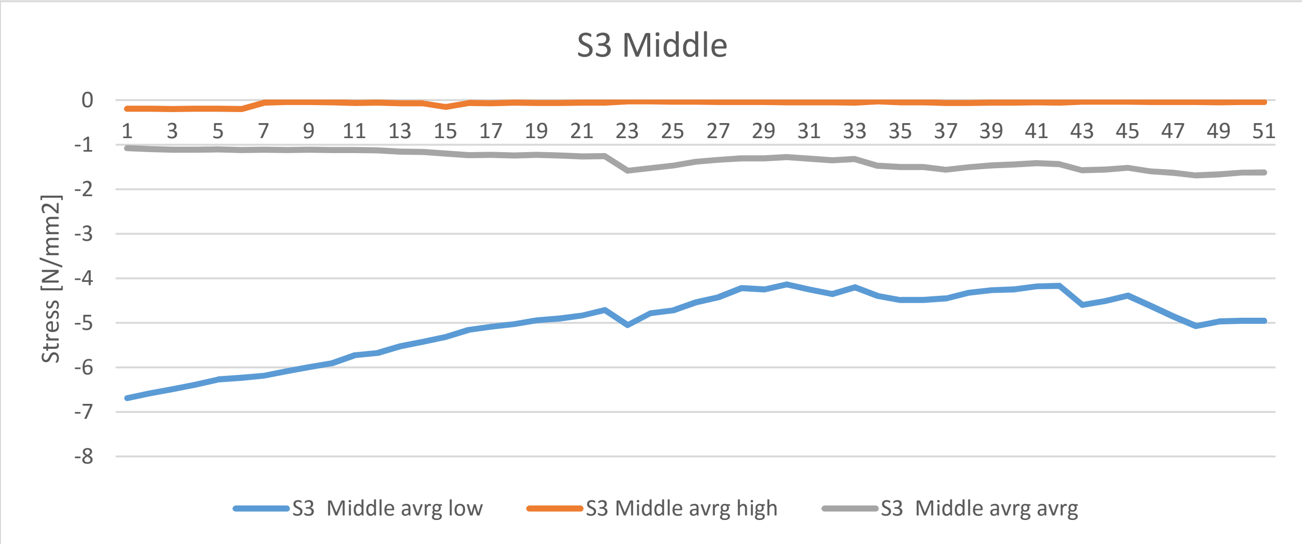
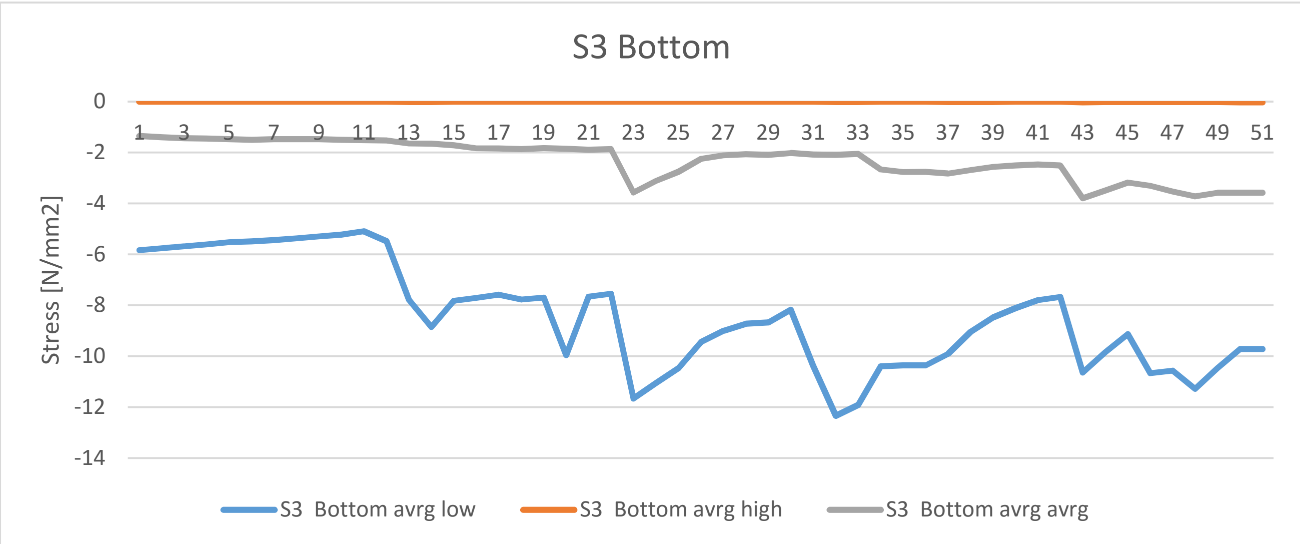
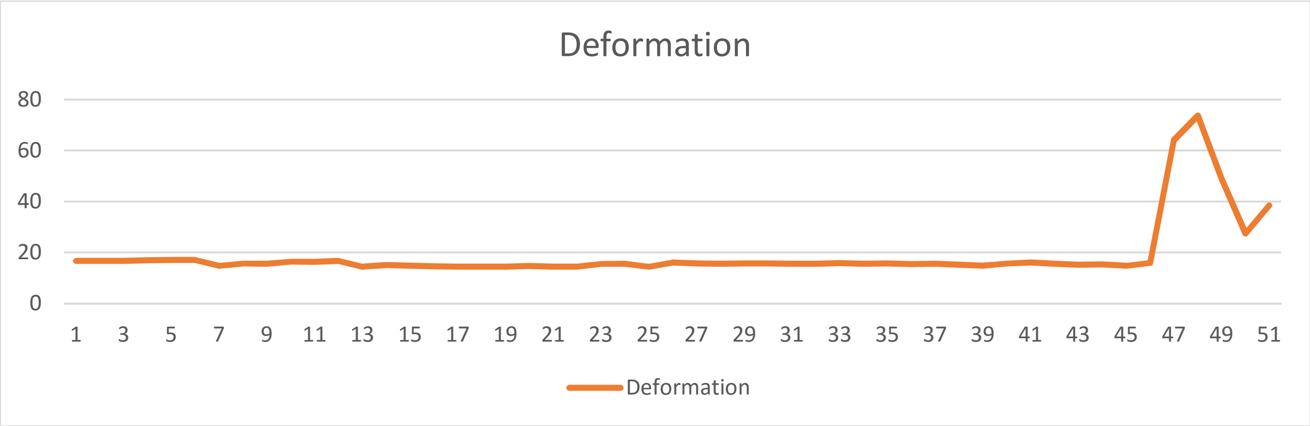






Preassembly 14 complete results



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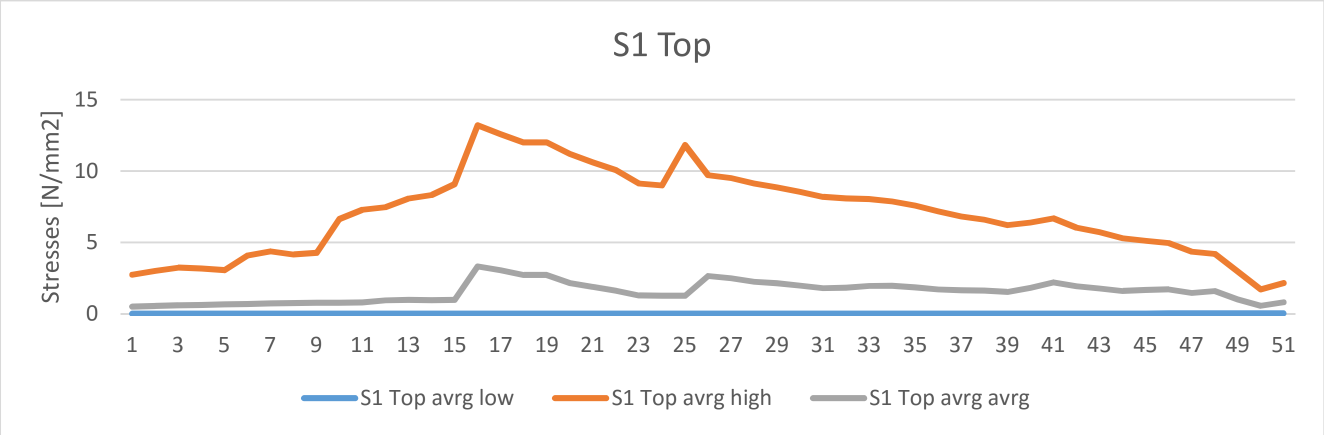

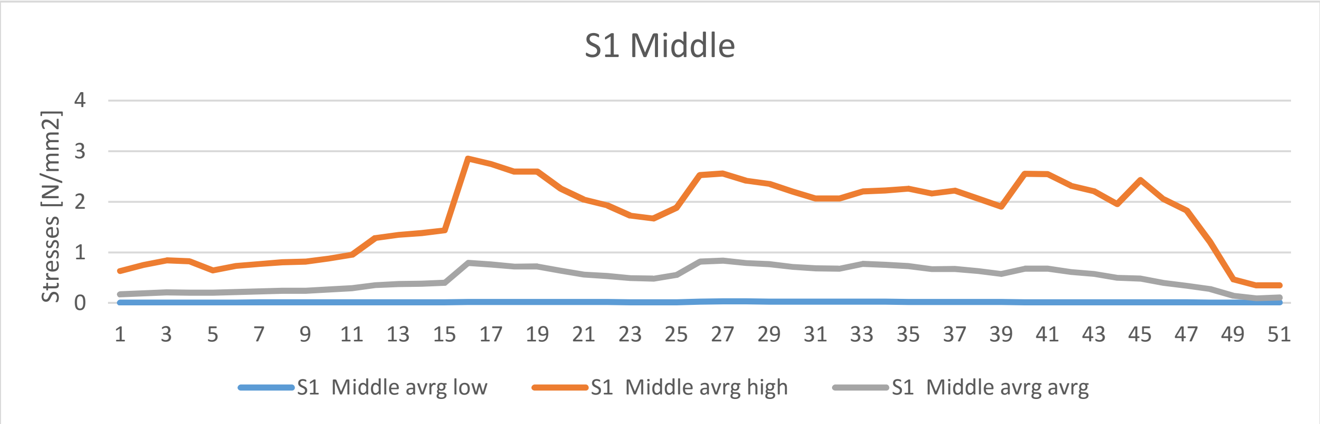

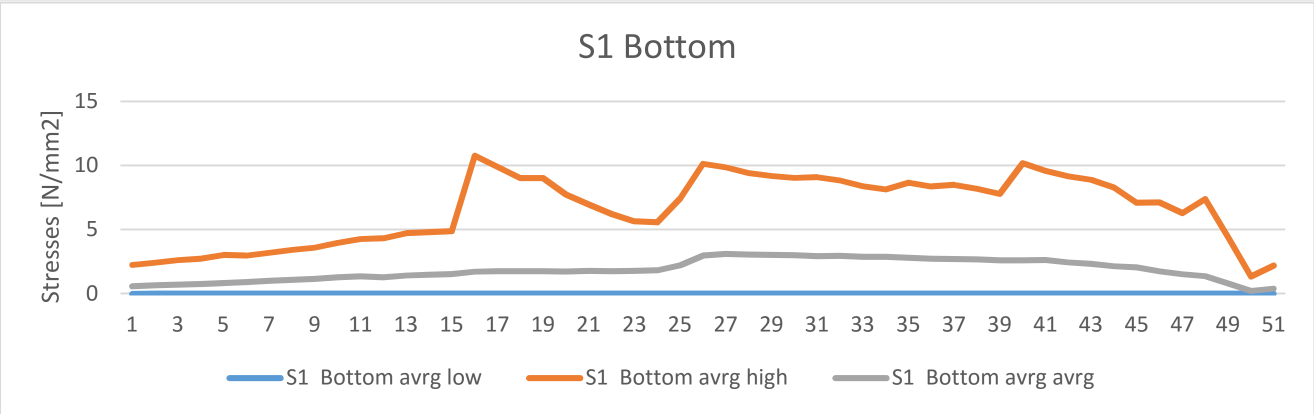

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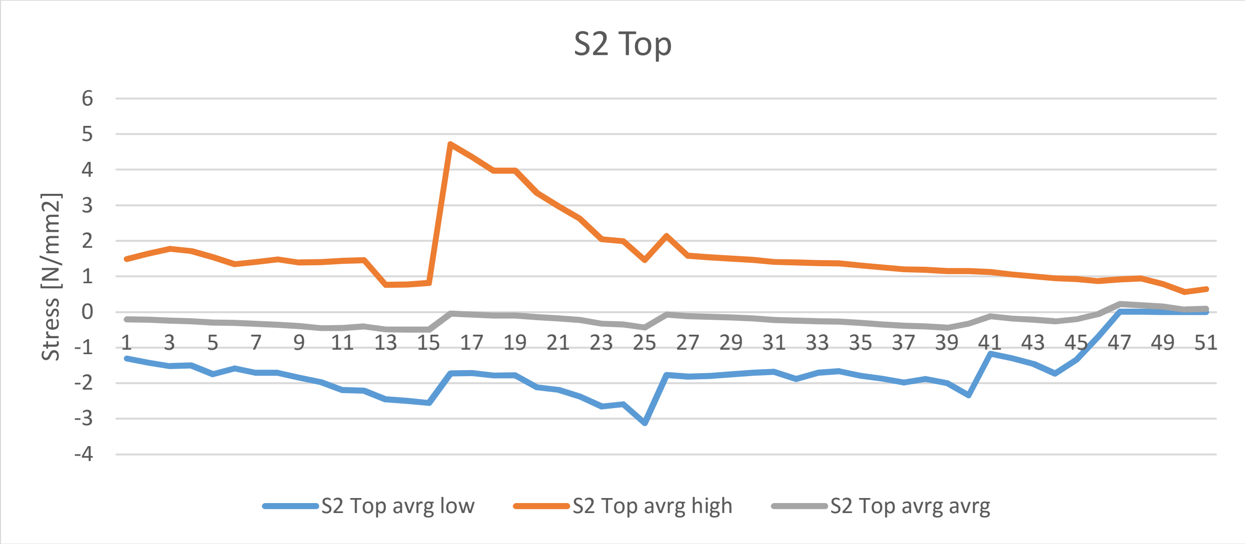

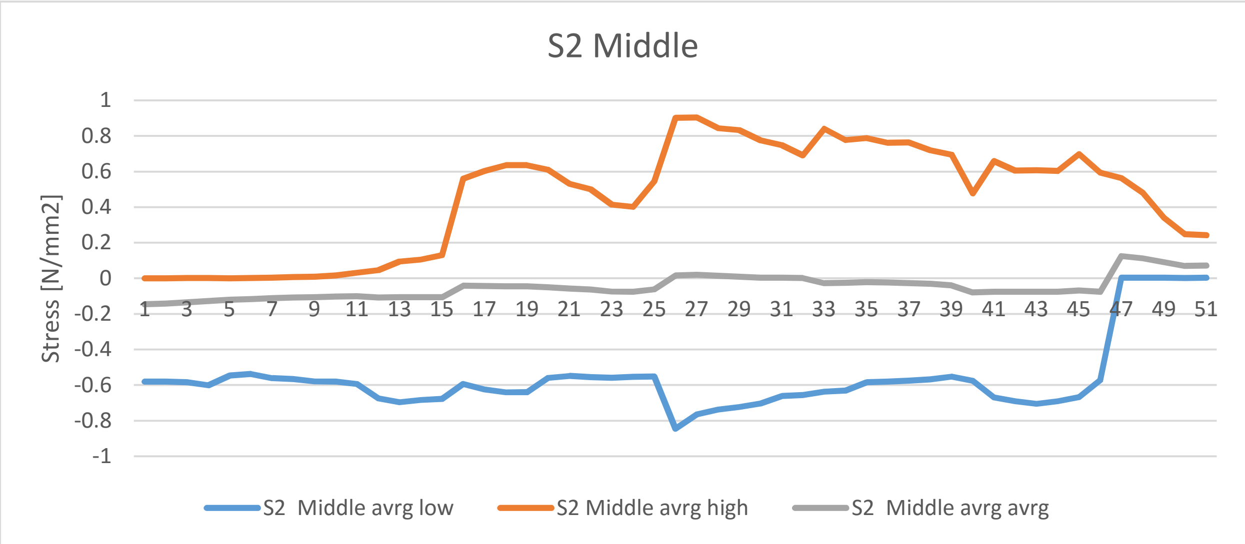

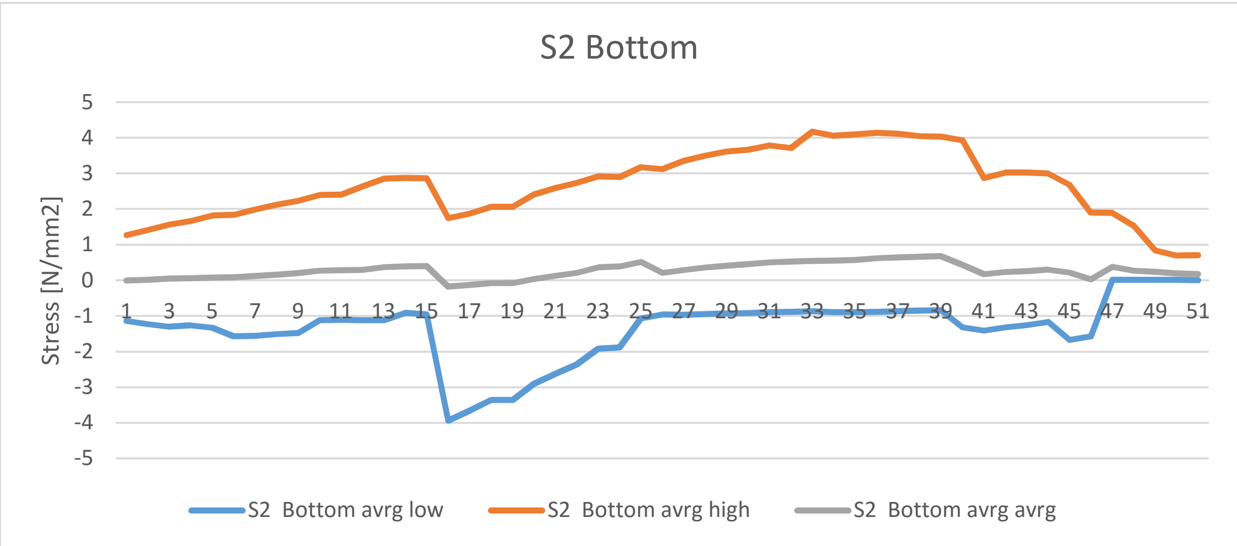

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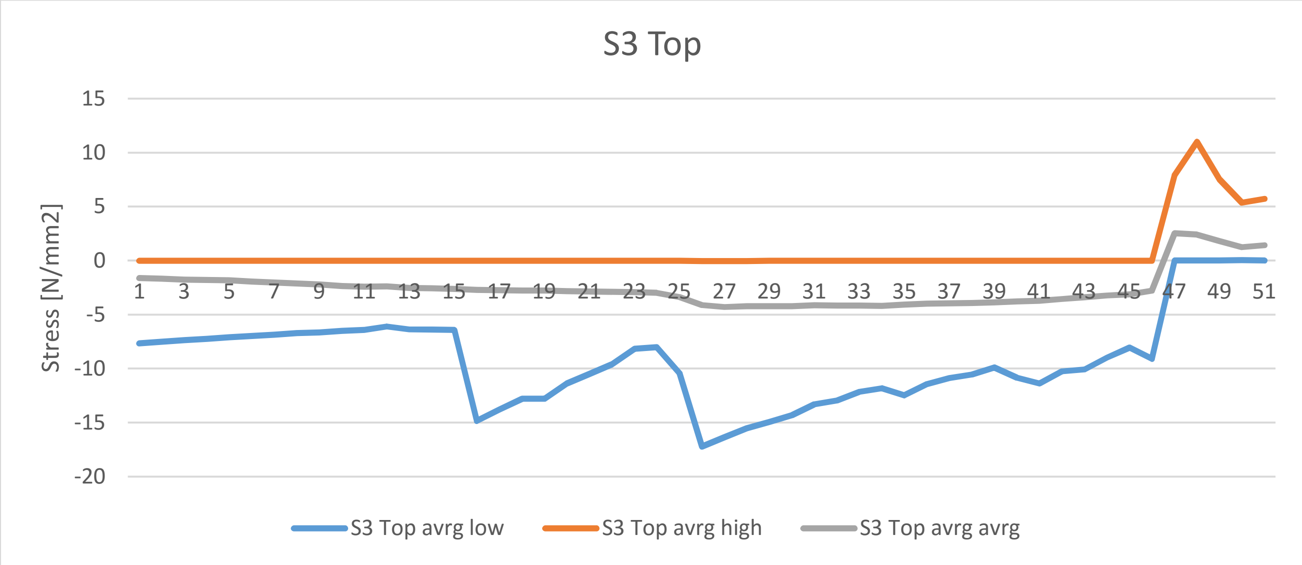
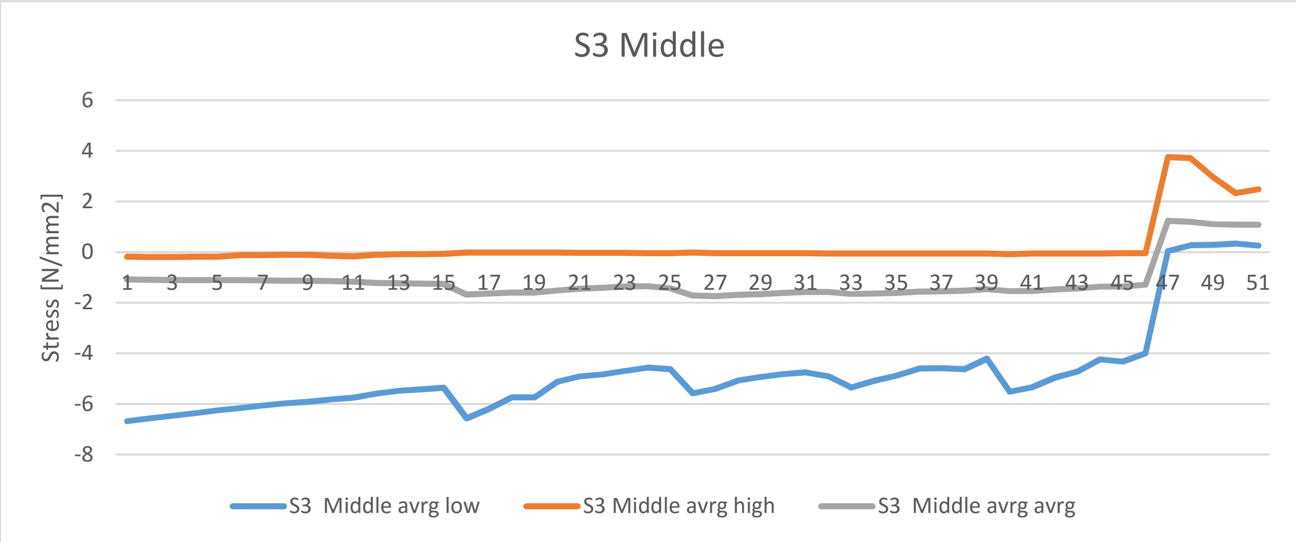
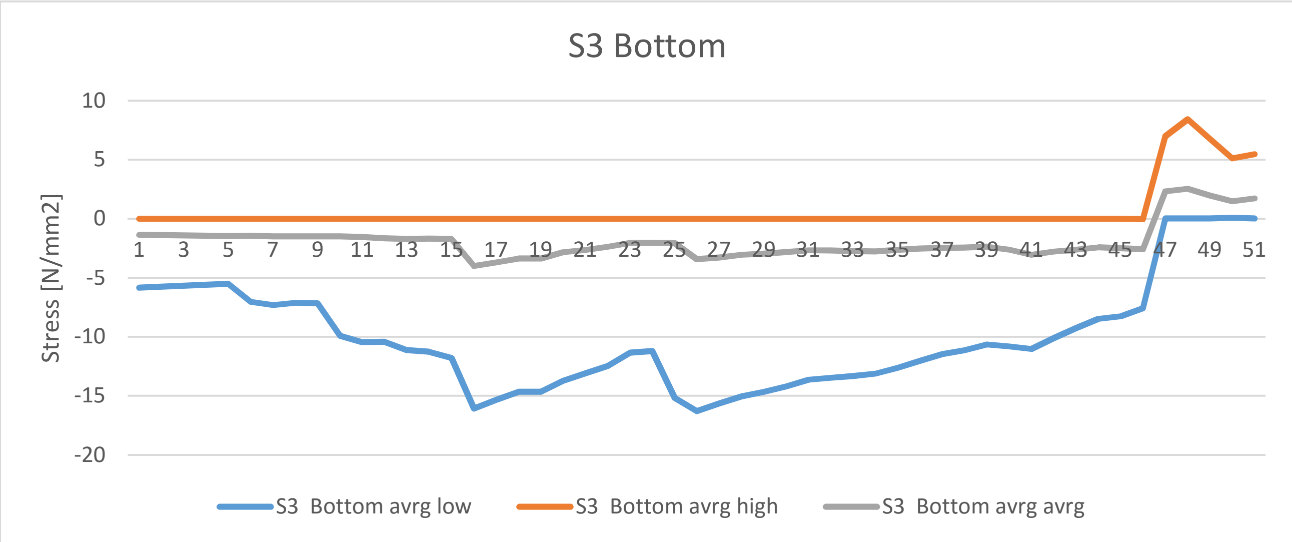
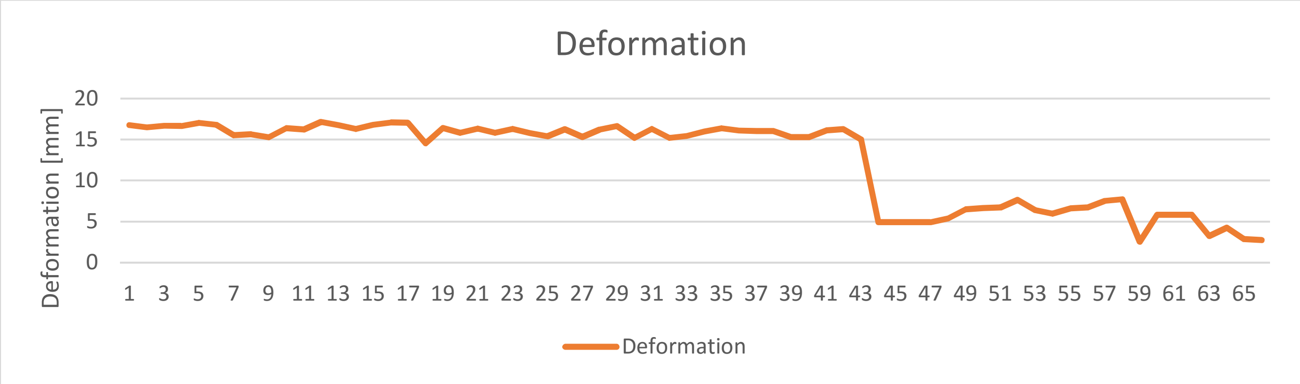


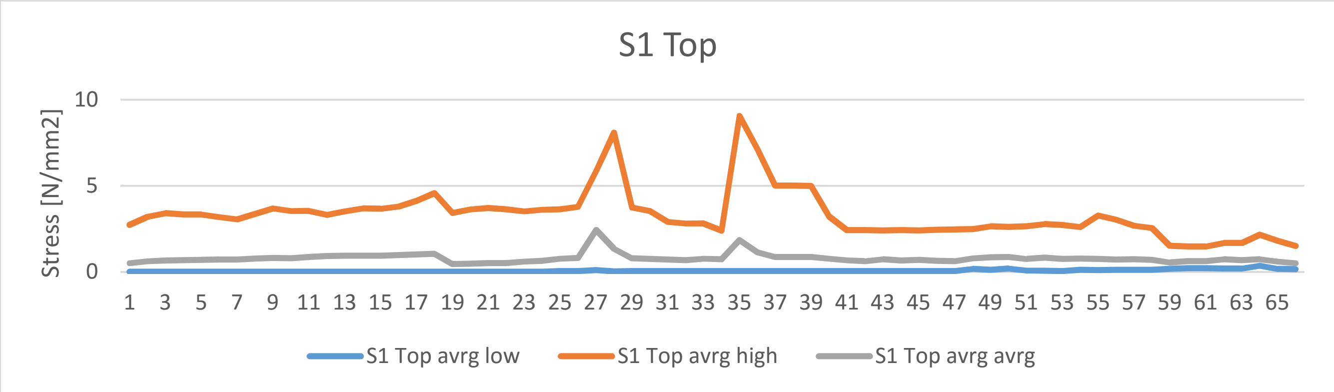


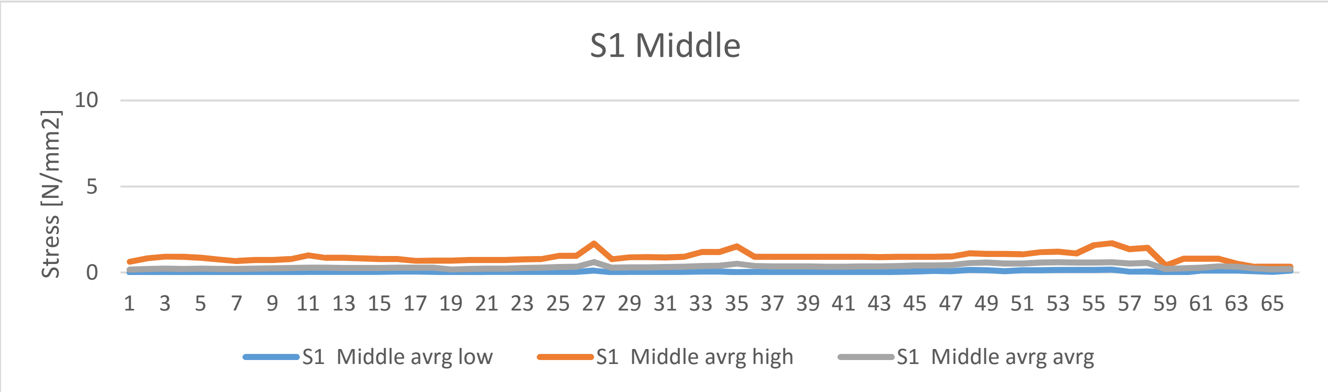


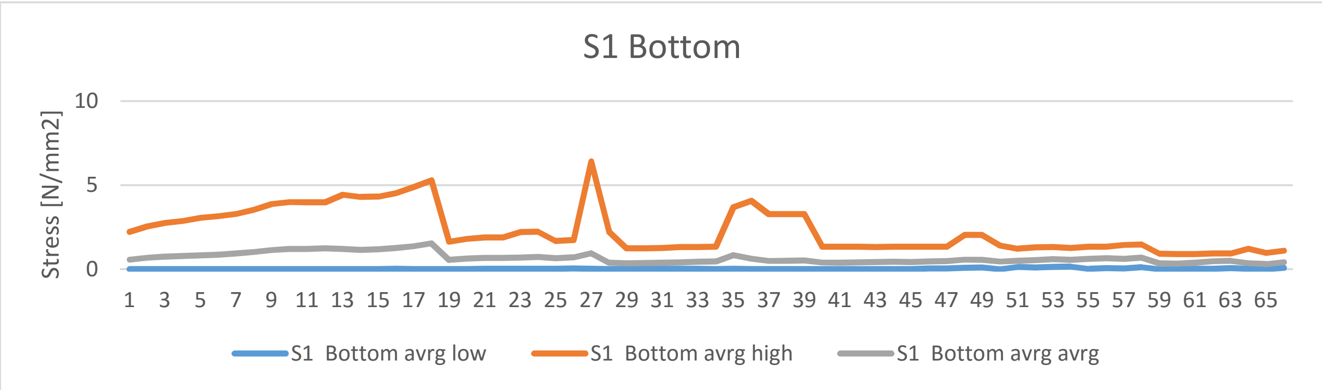
Automated support placement first run complete results



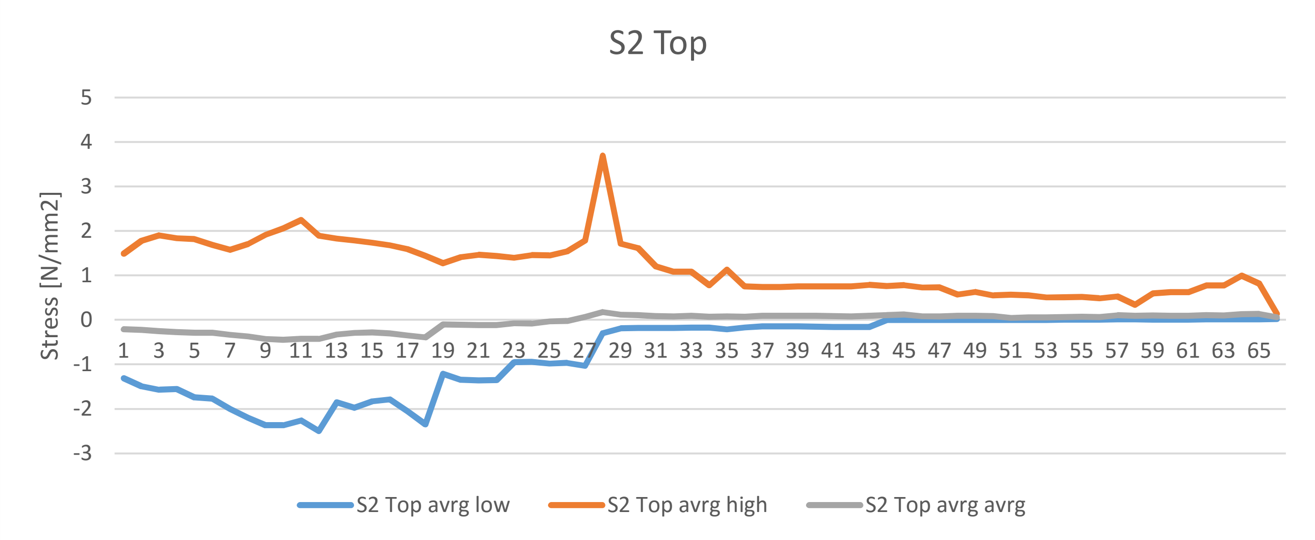
S1 Top, middle and bottom stresses

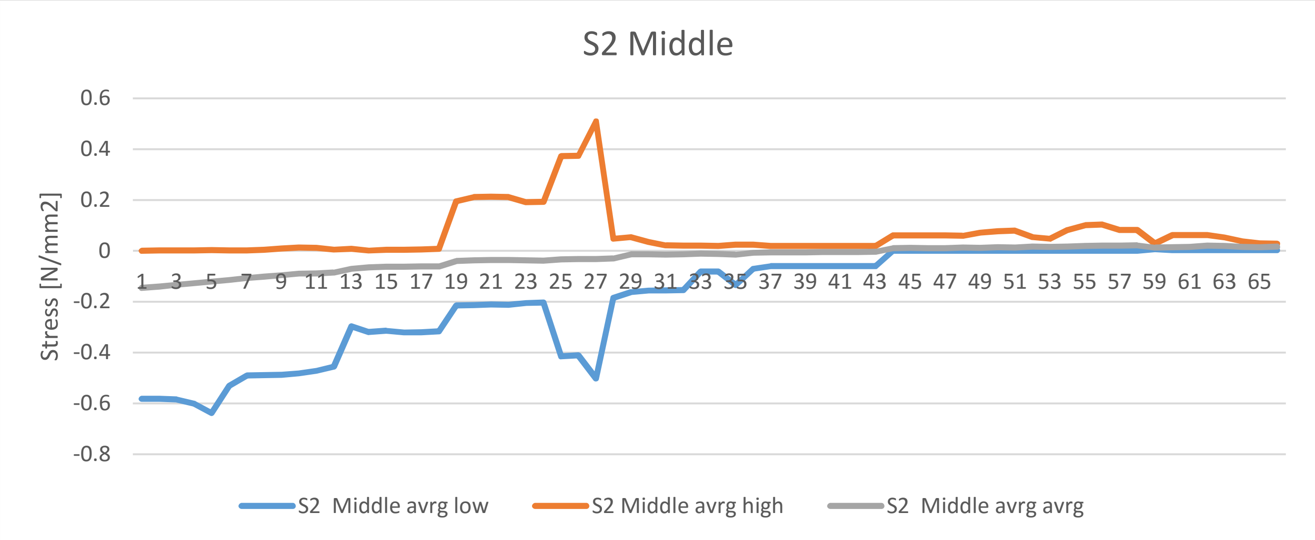


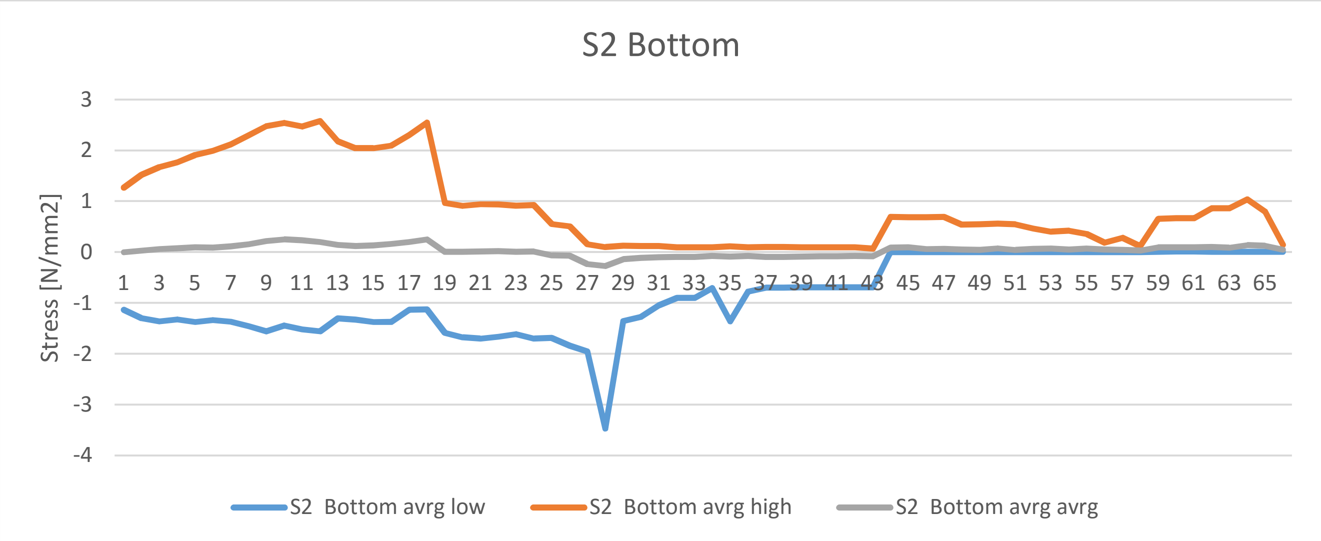




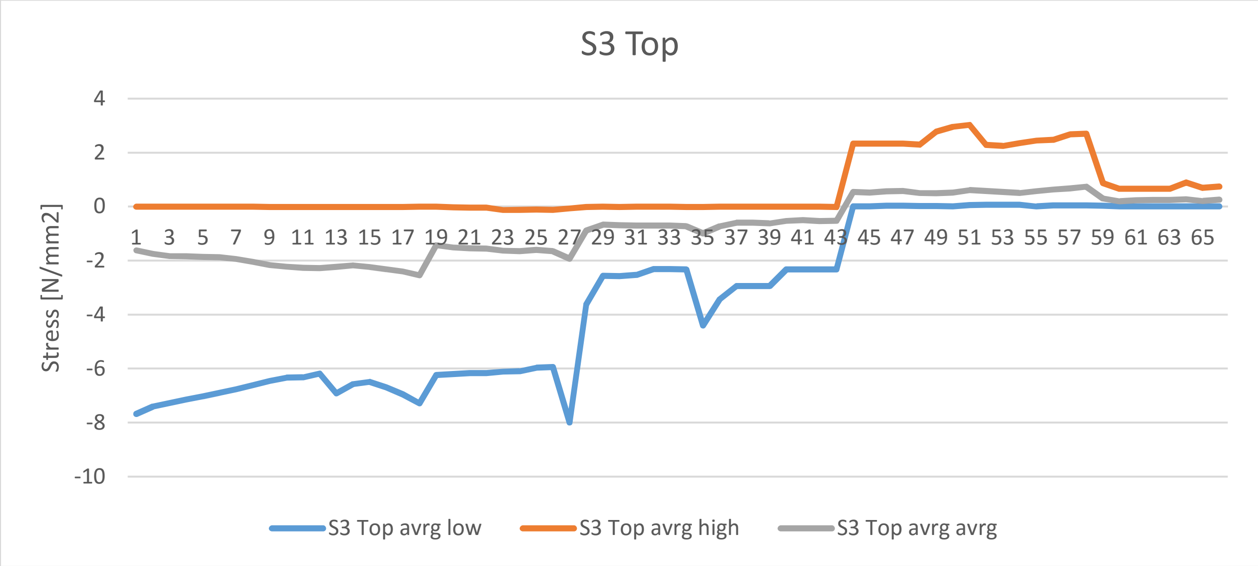
S2 Top, middle and bottom stresses

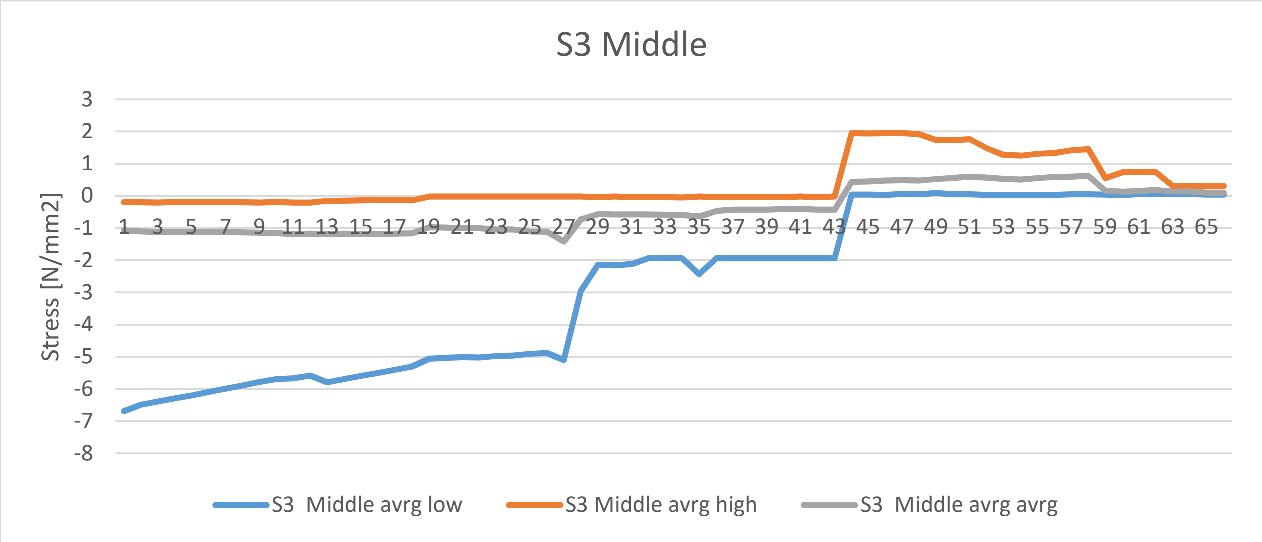


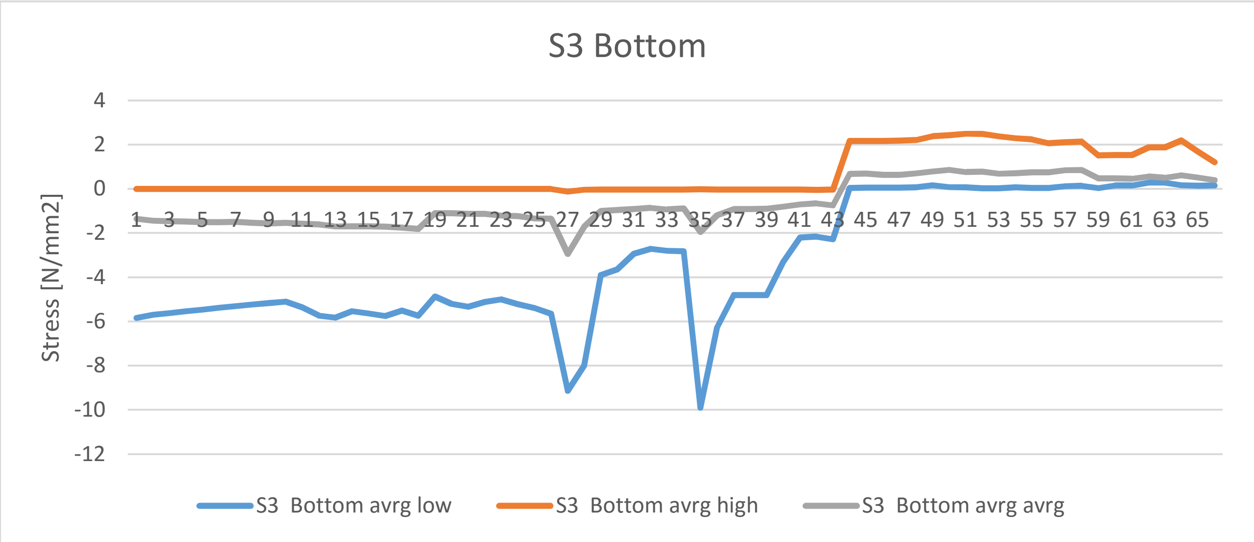




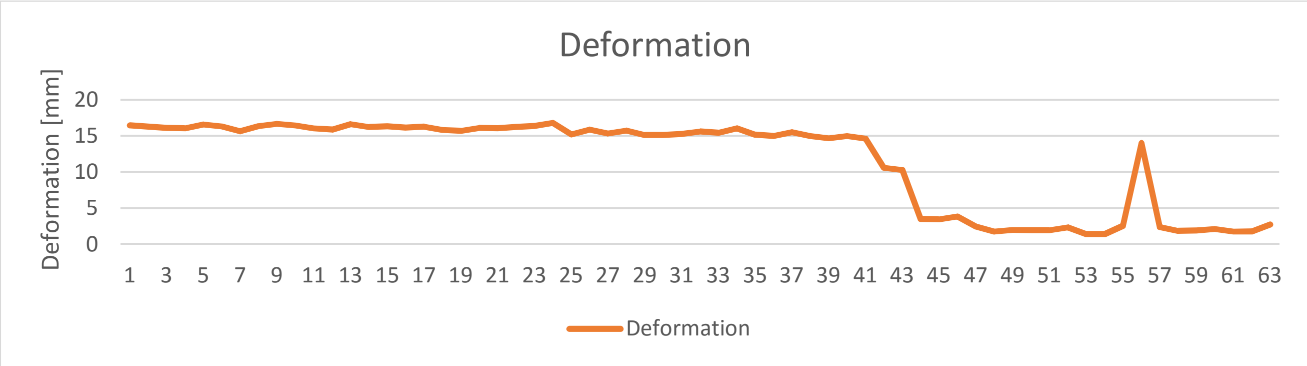
S3 Top, middle and bottom stresses







Automated support placement second run complete results



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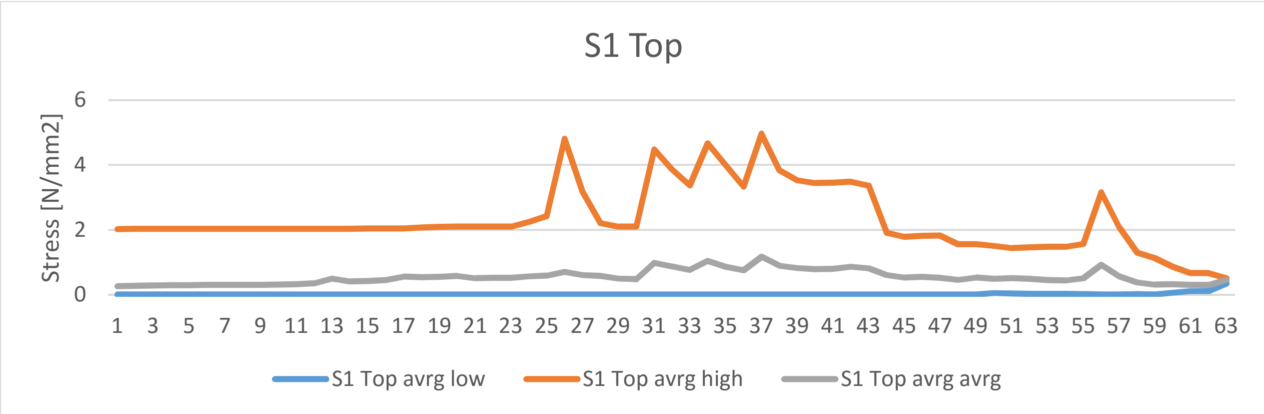
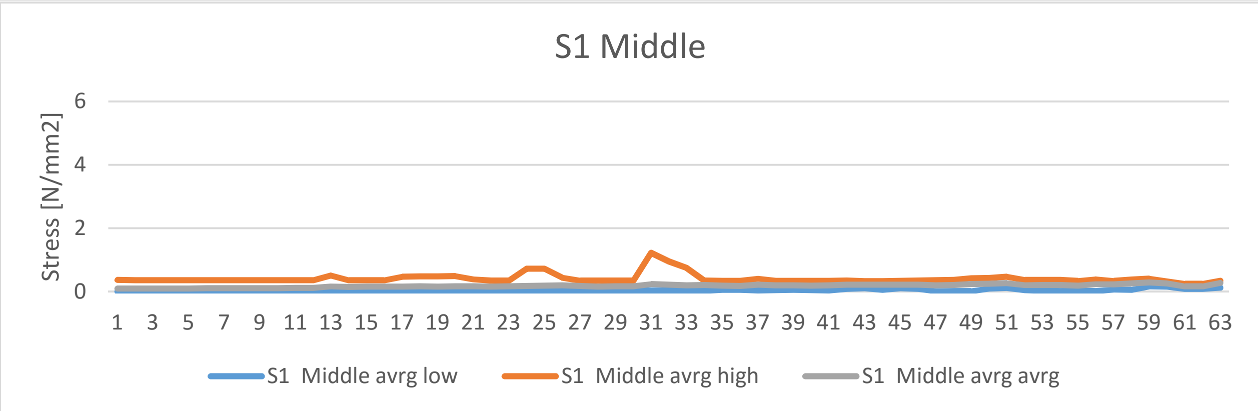
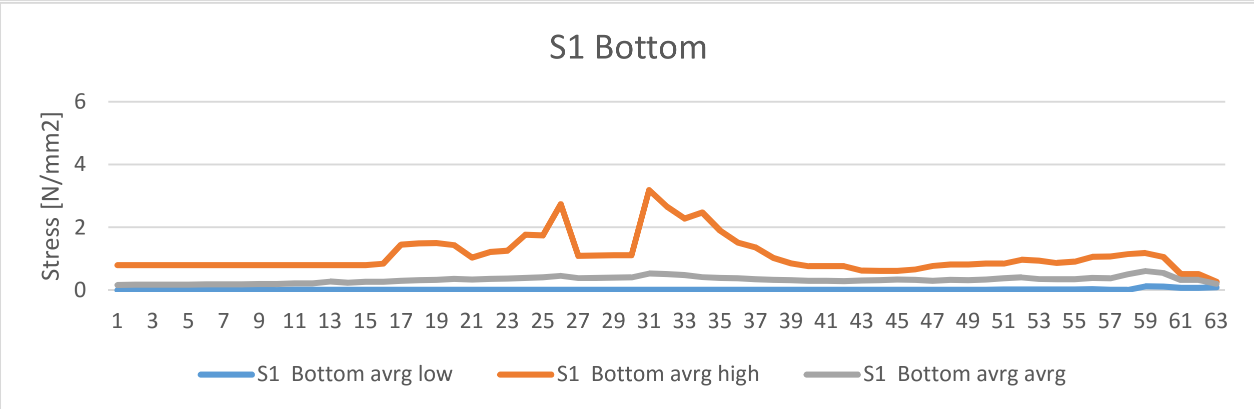
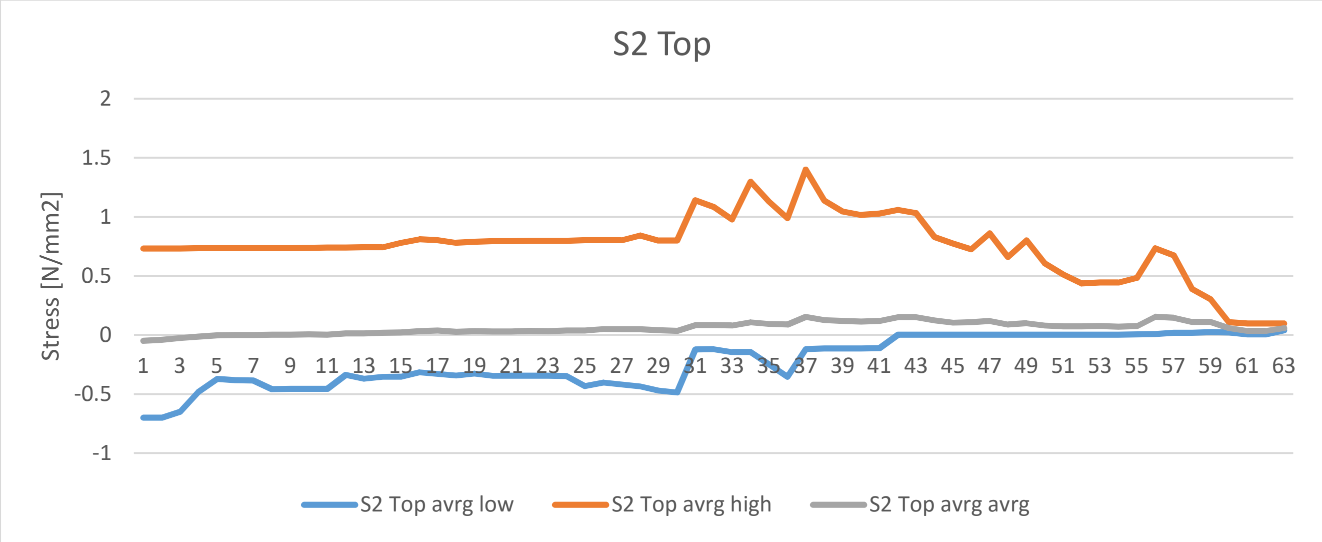
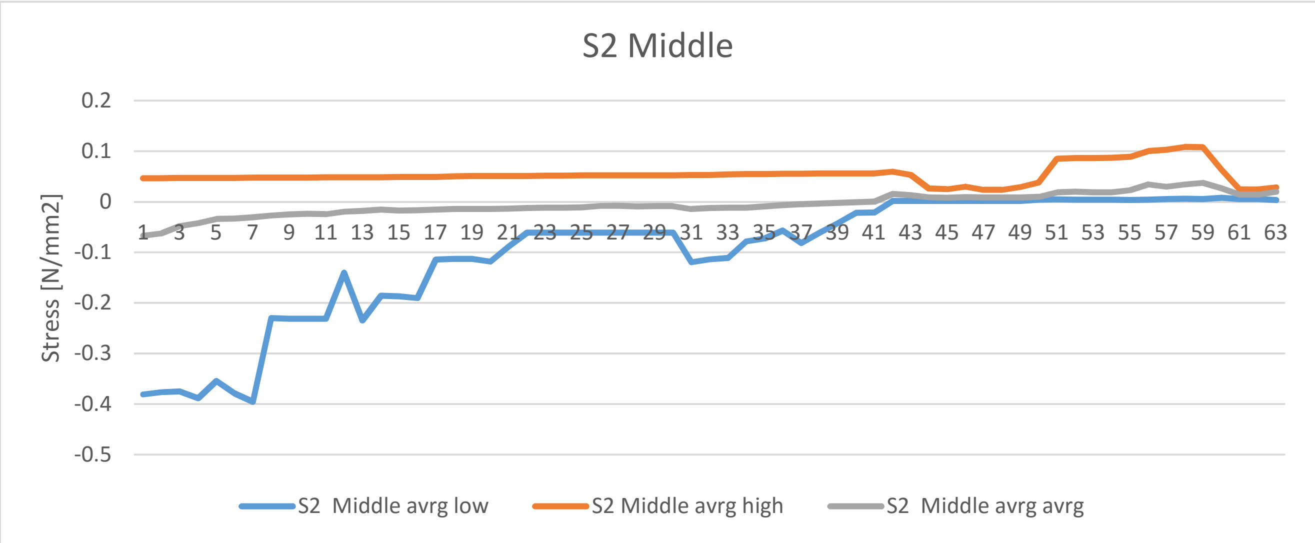


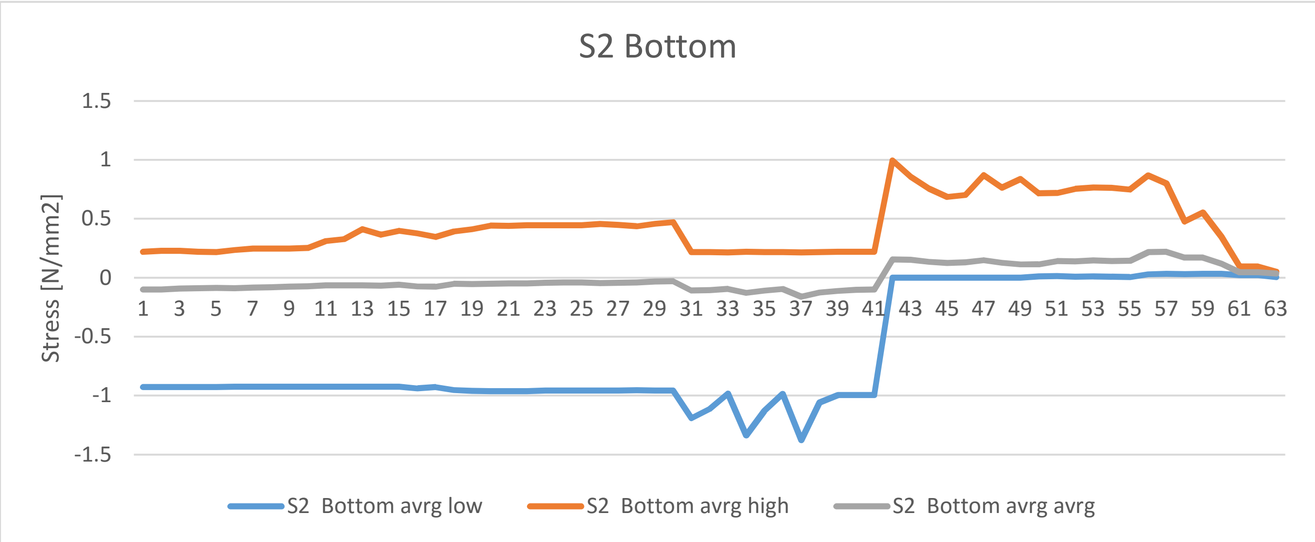




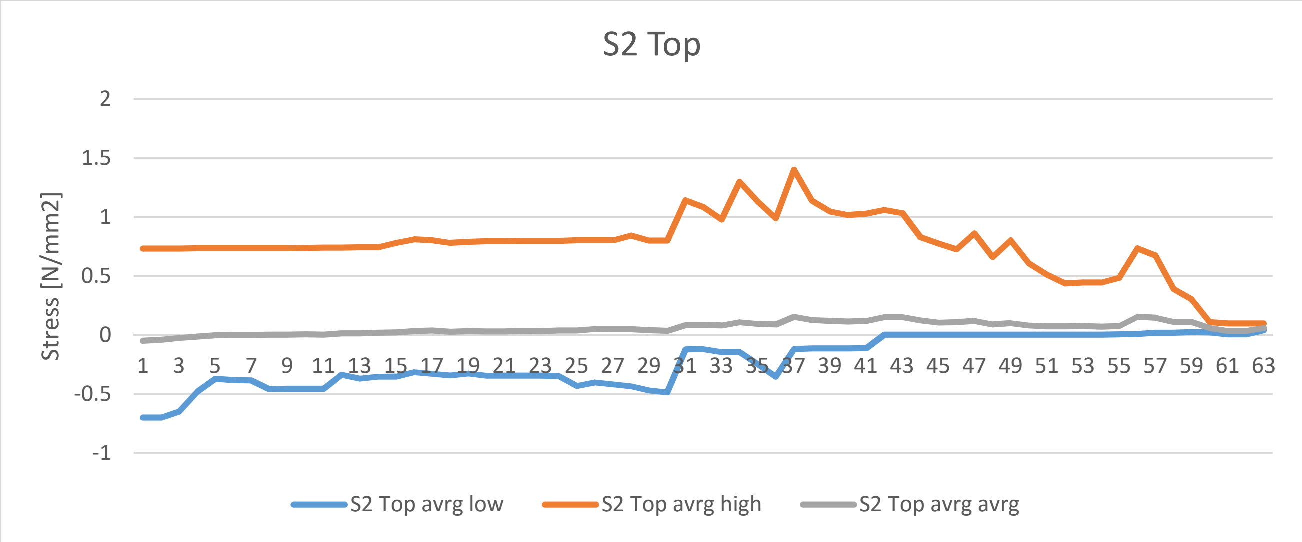
S2 Top, middle and bottom stresses

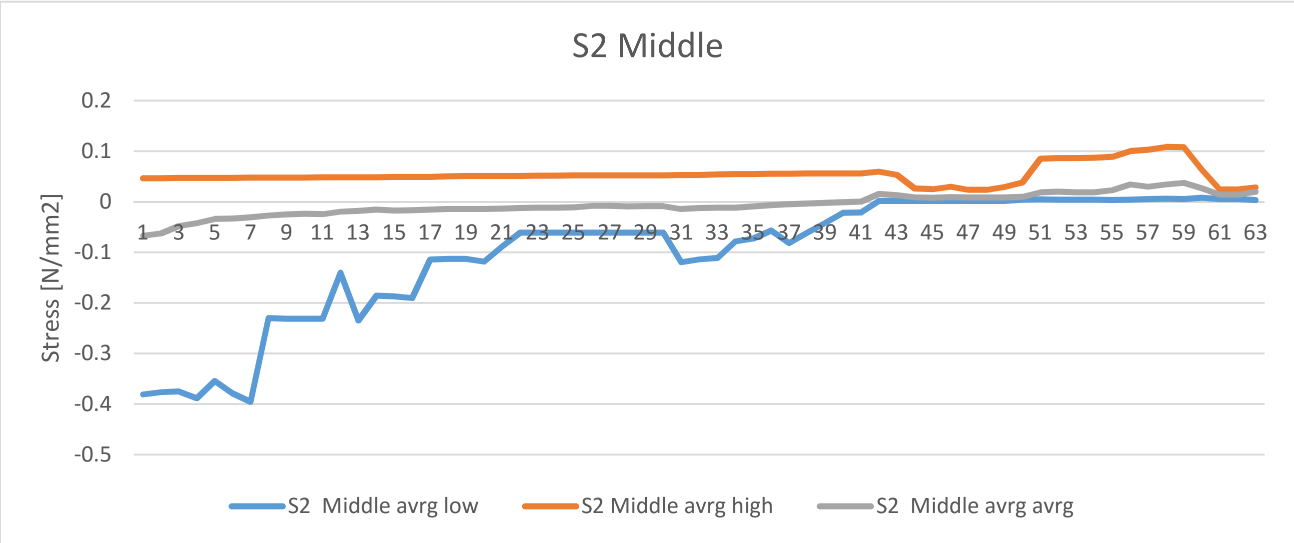


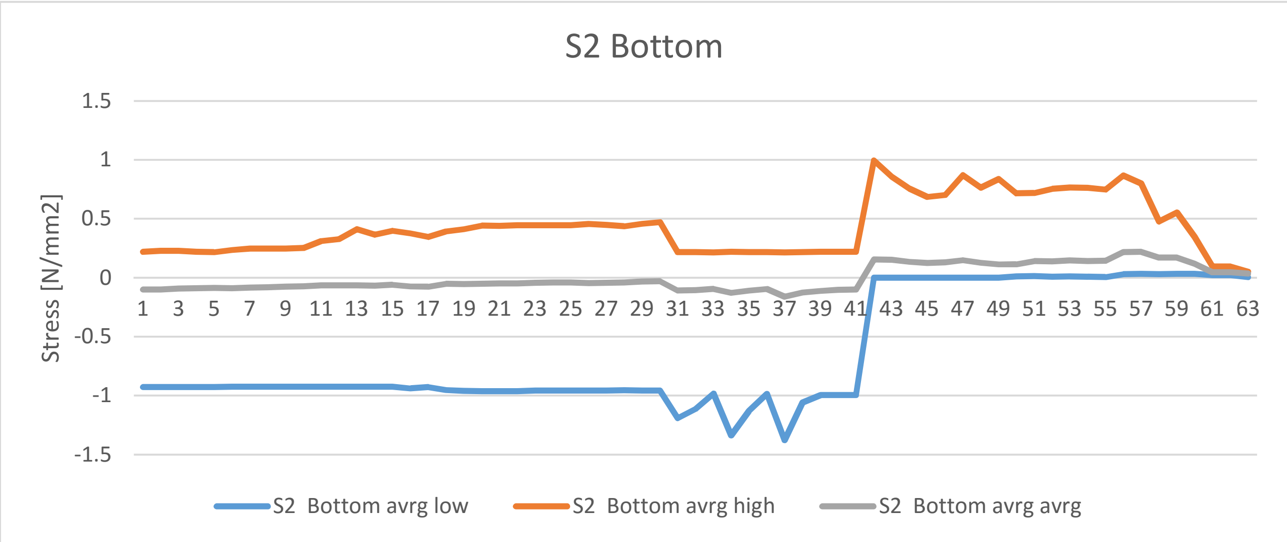




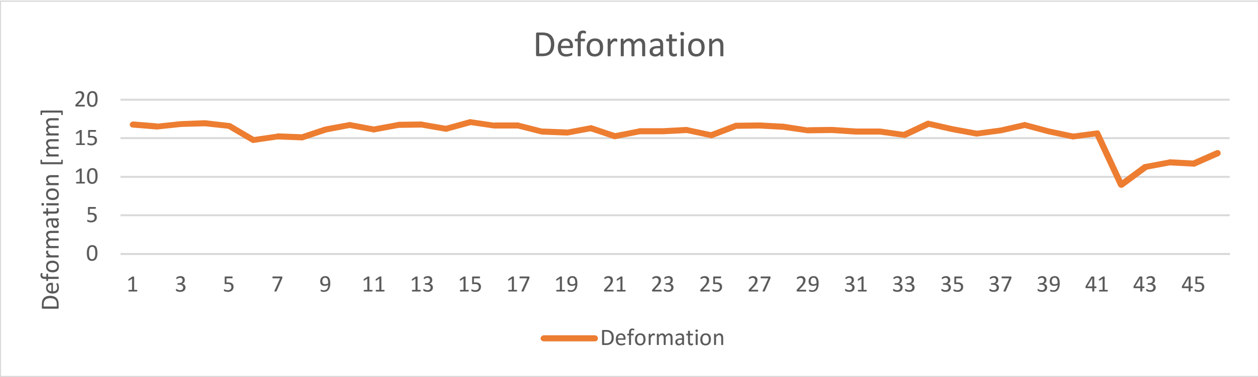
S3 Top, middle and bottom stresses



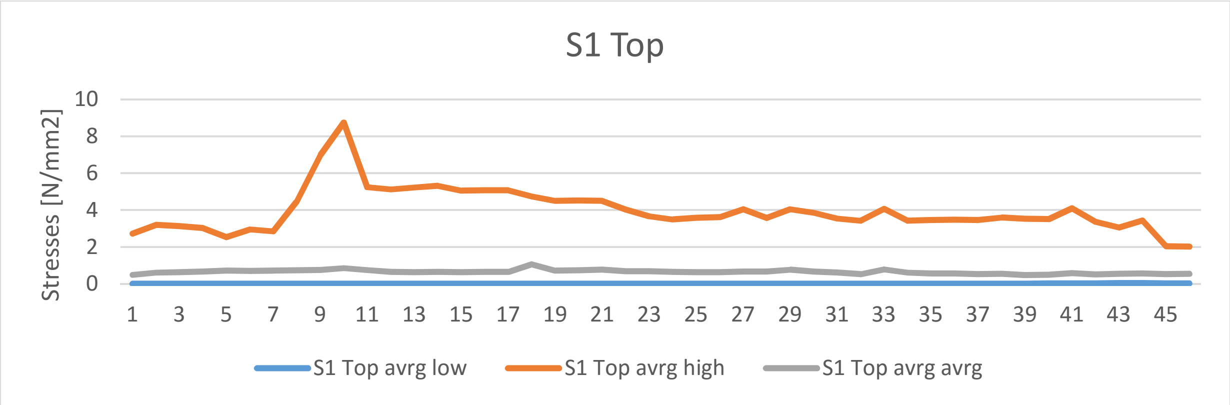


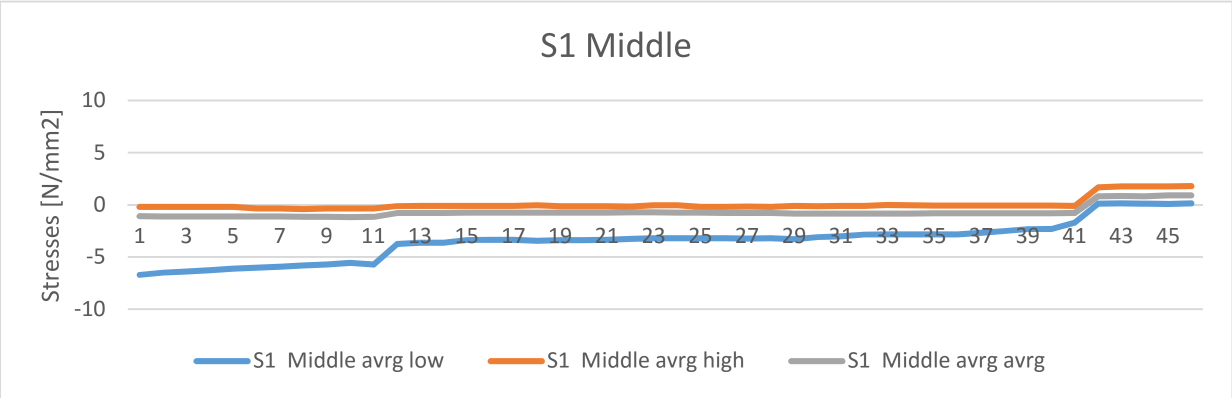


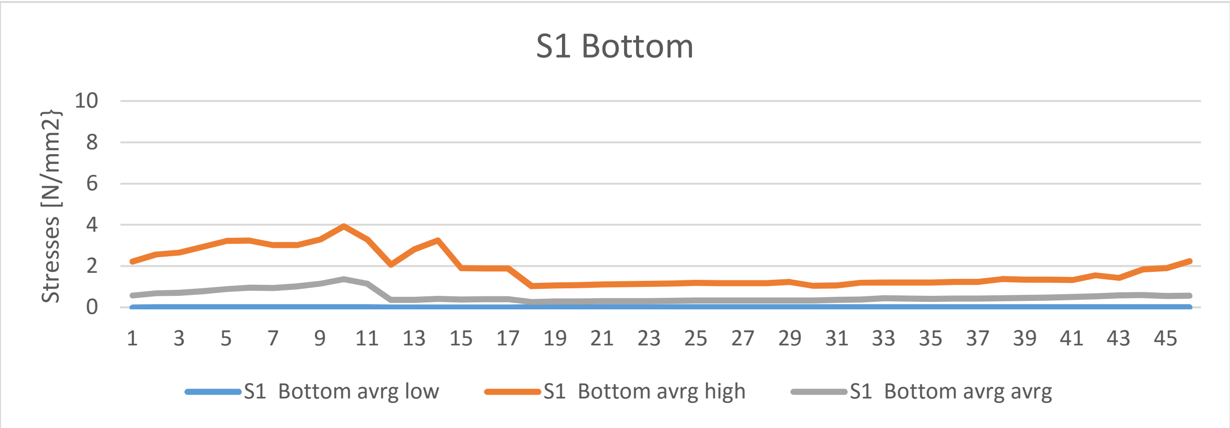
External combination complete results



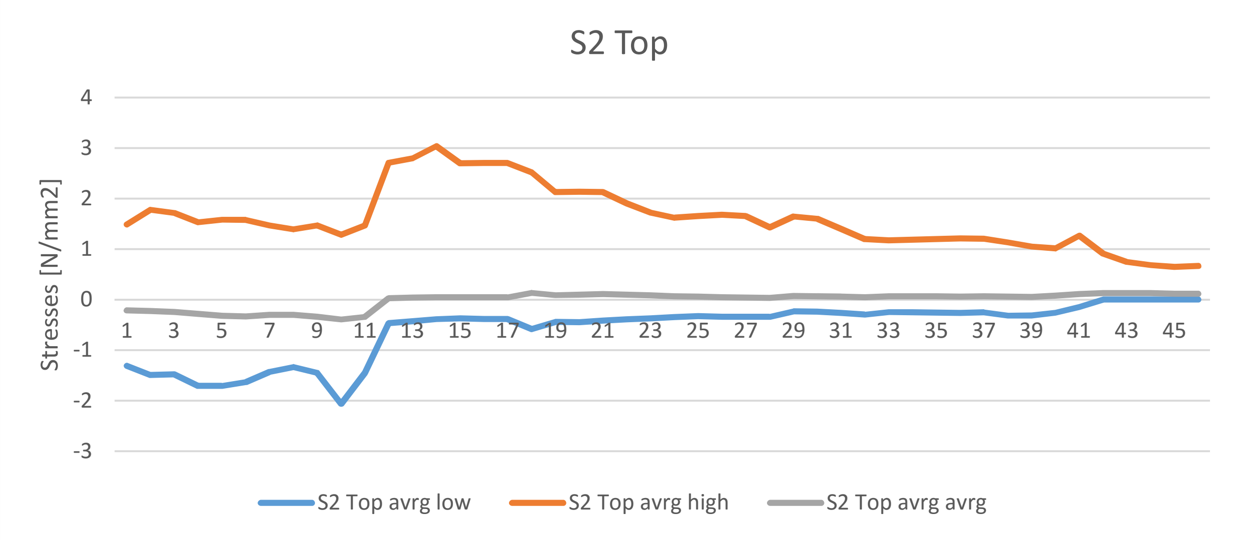
S1 Top, middle and bottom stresses

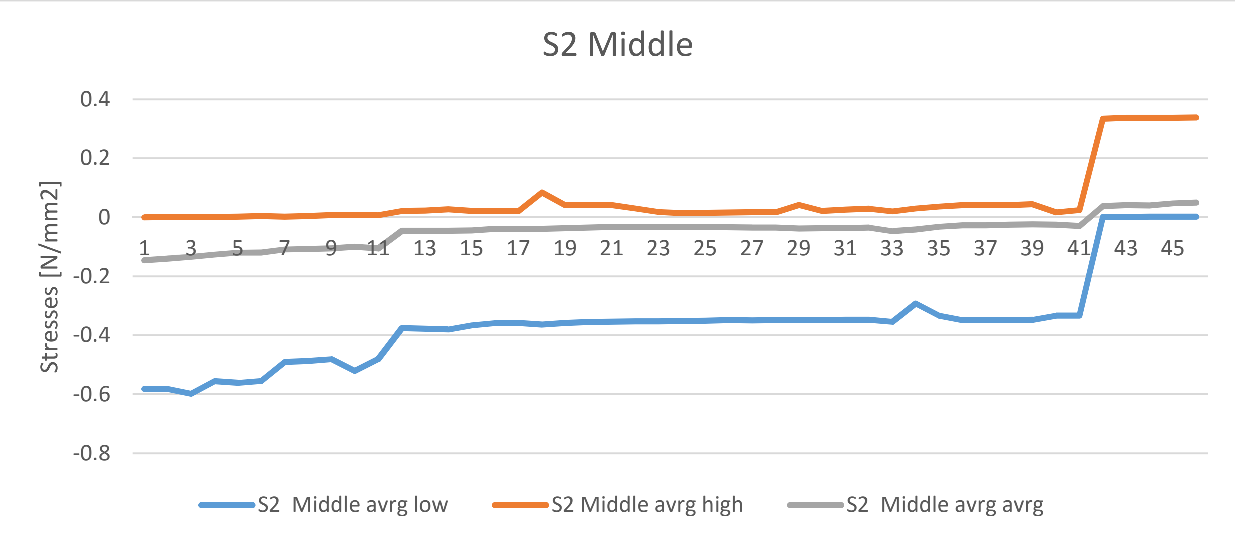


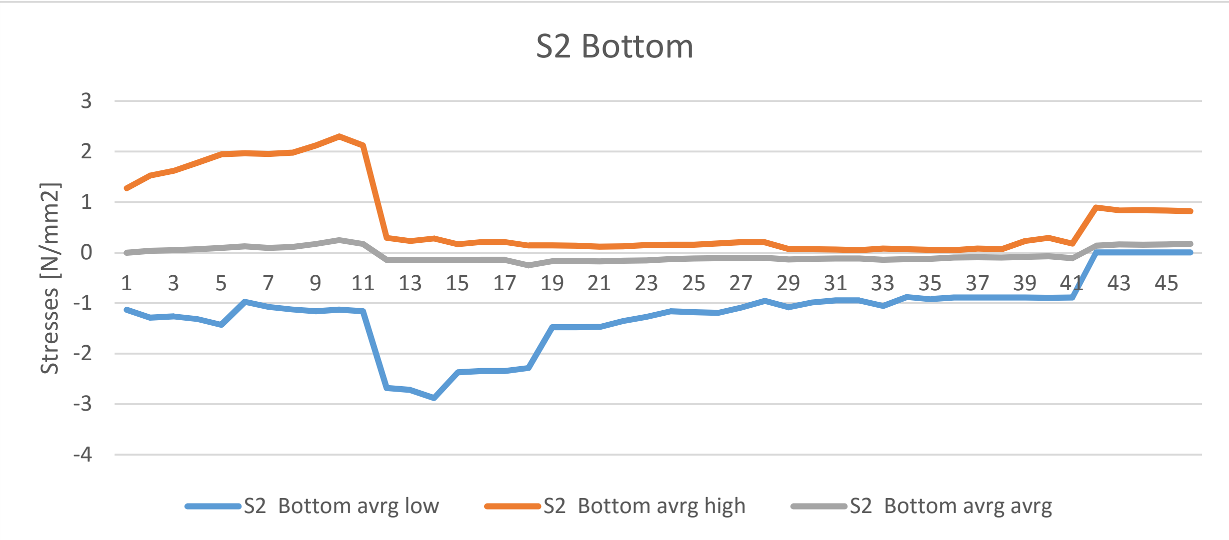




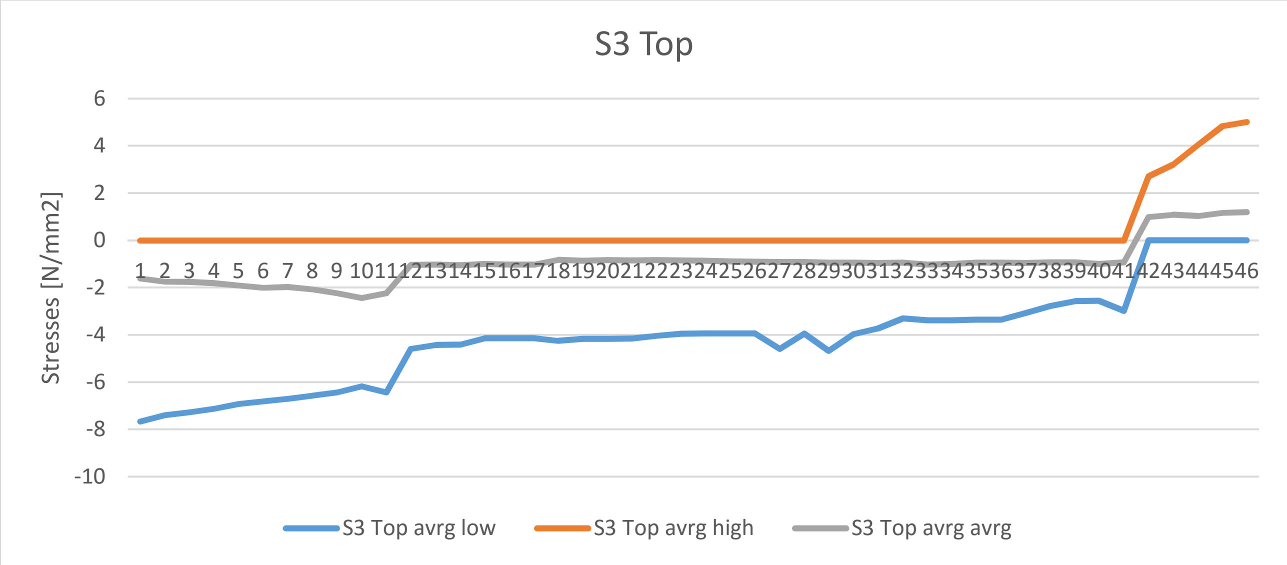
S2 Top, middle and bottom stresses

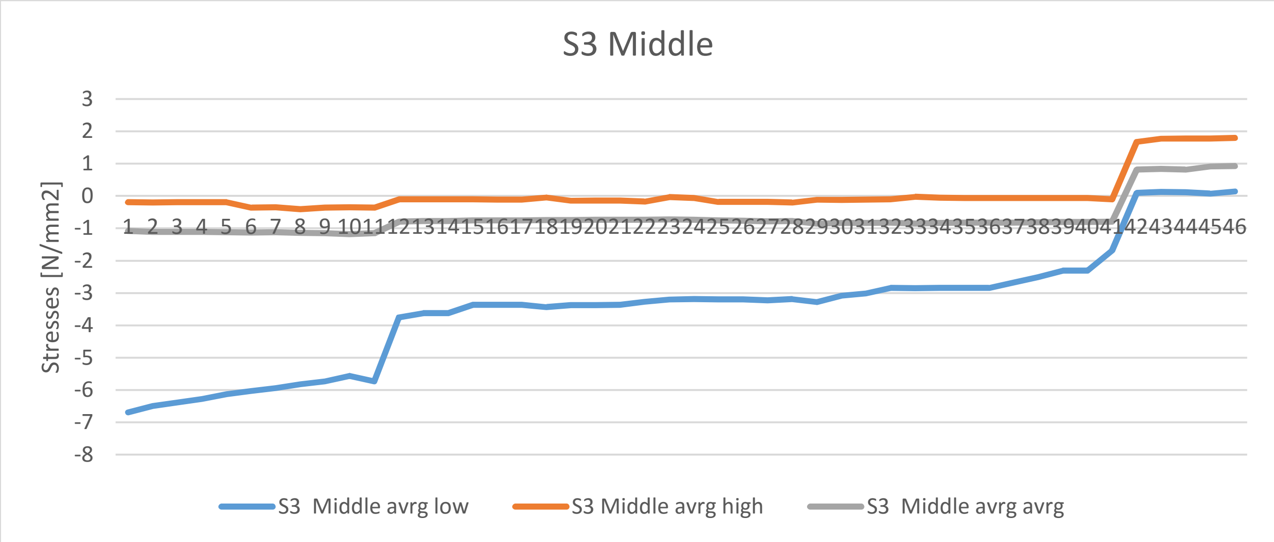


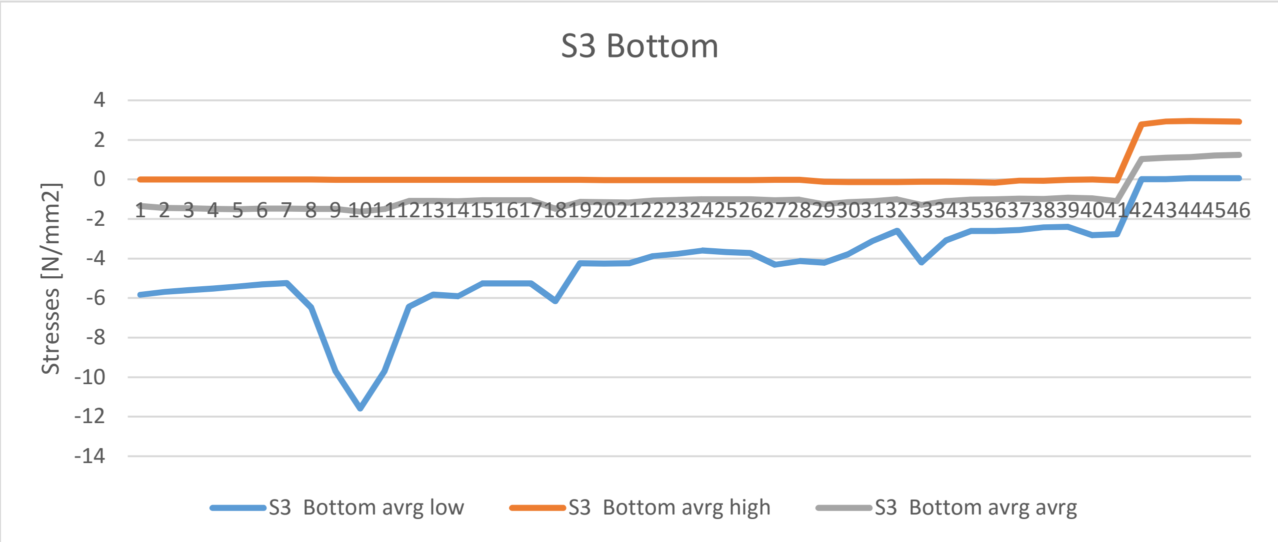




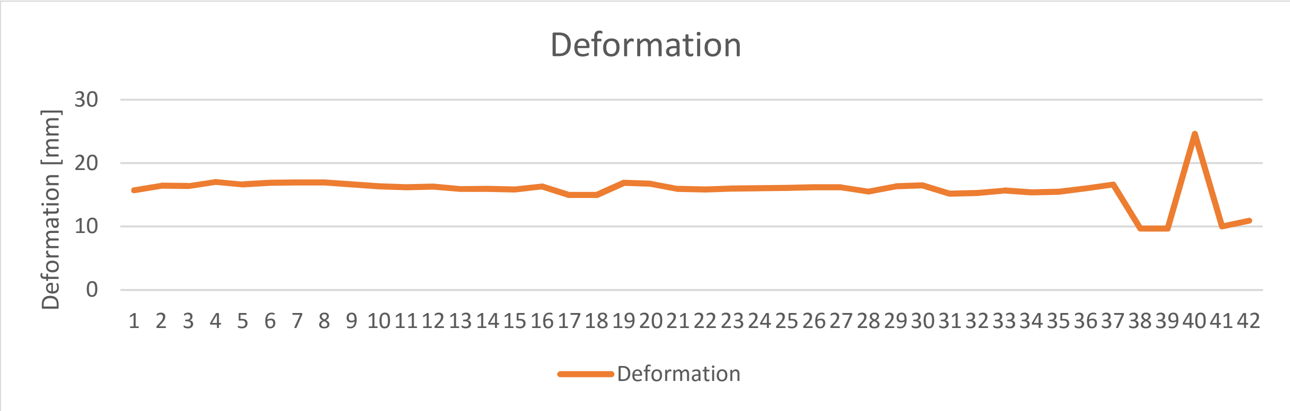
S3 Top, middle and bottom stresses



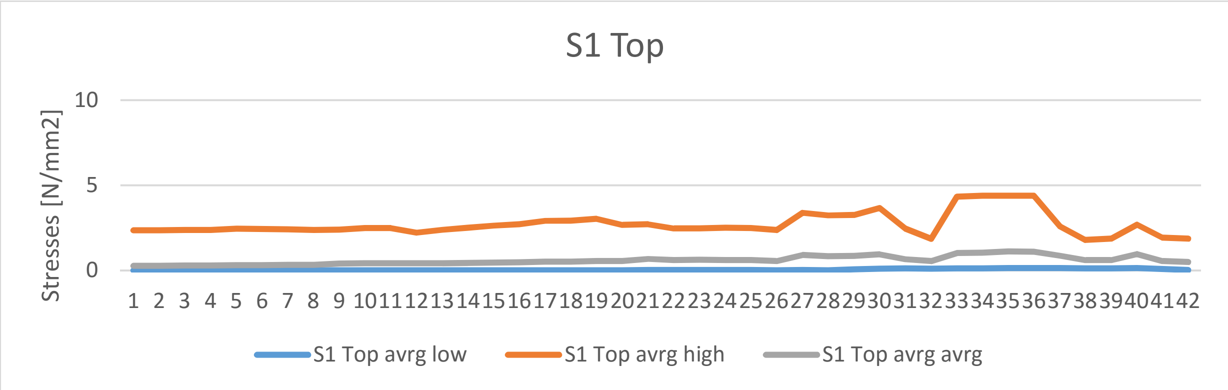


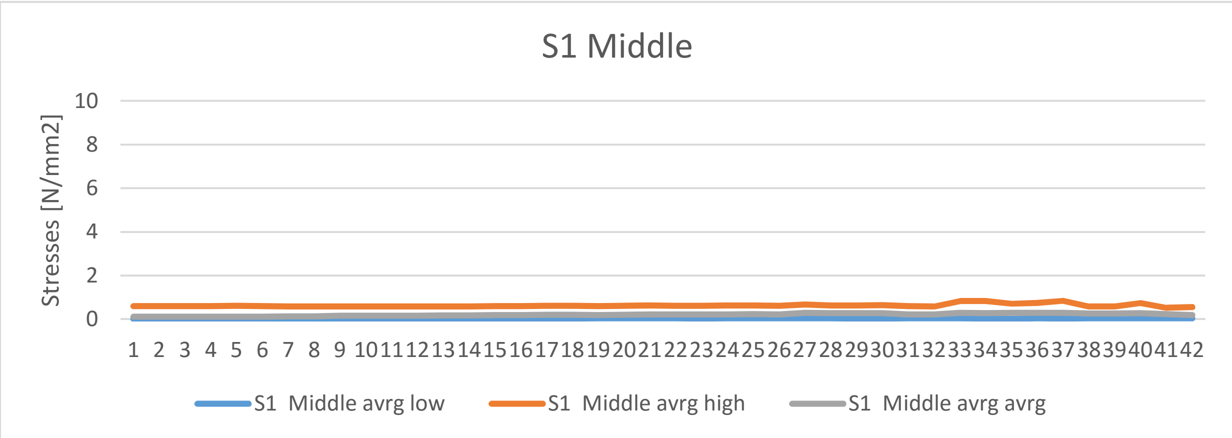


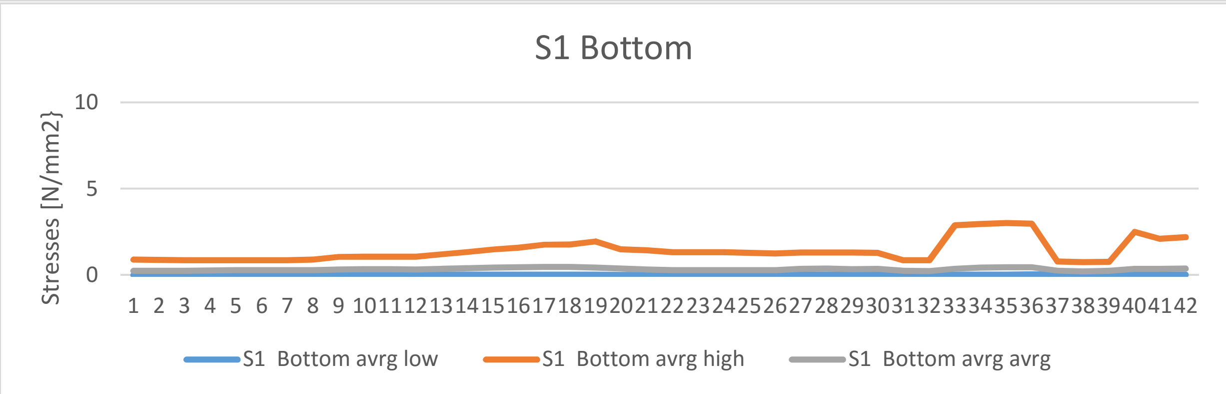
Internal combination complete results



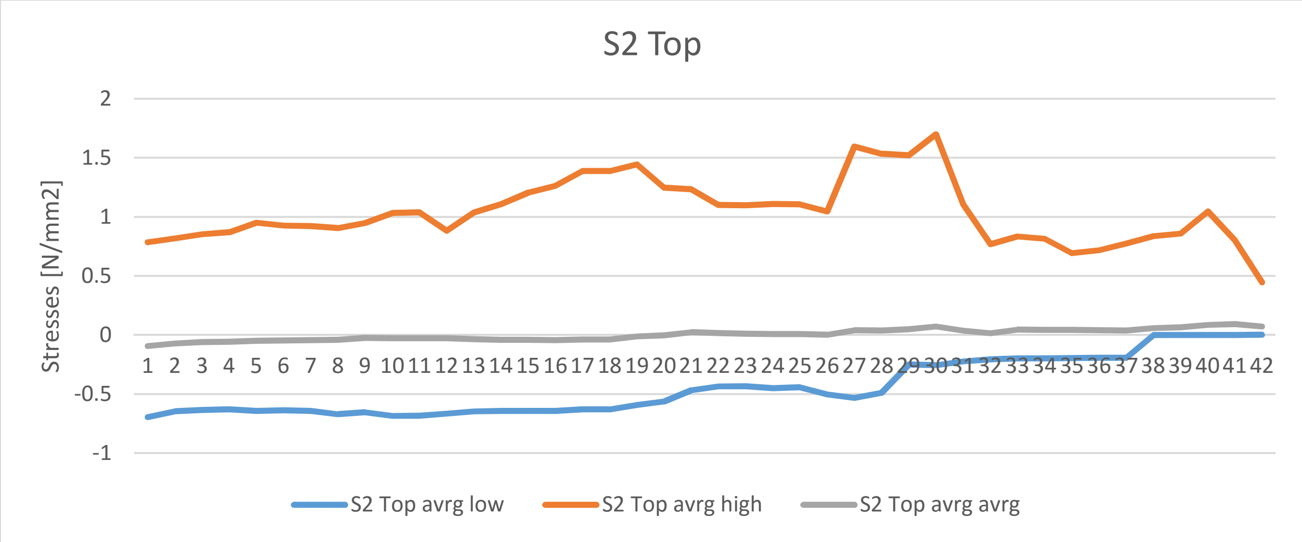
S1 Top, middle and bottom stresses

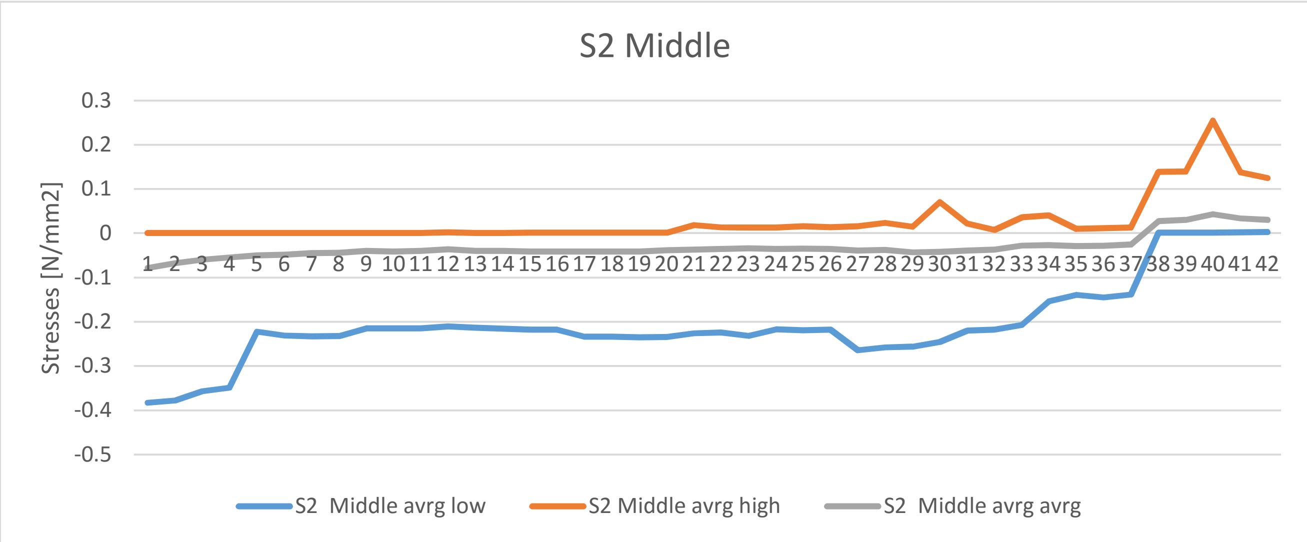


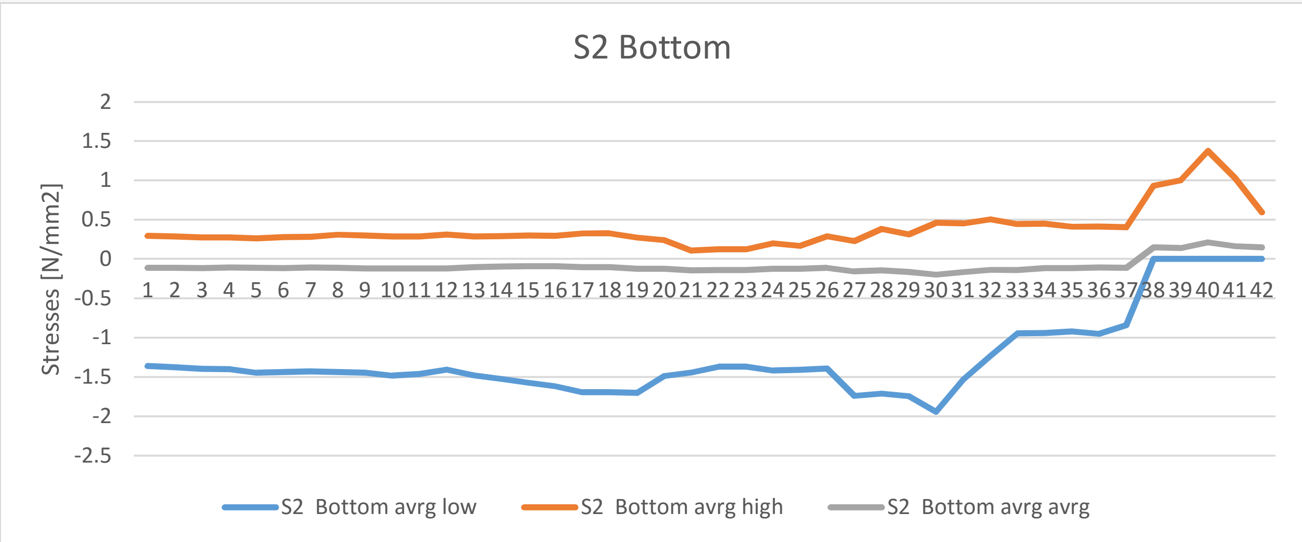




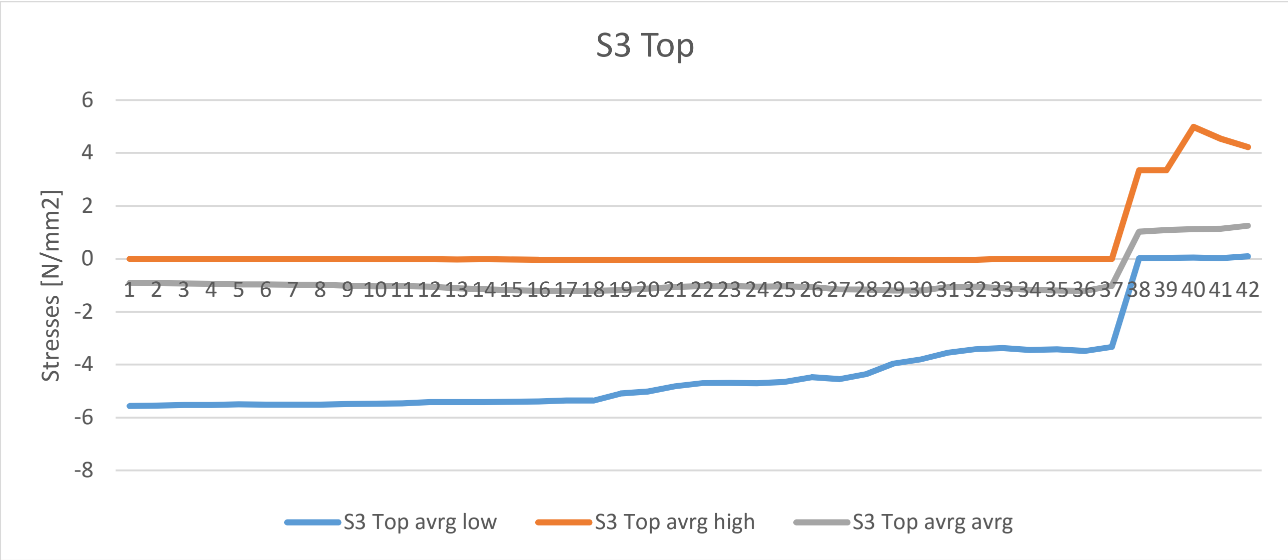
S2 Top, middle and bottom stresses

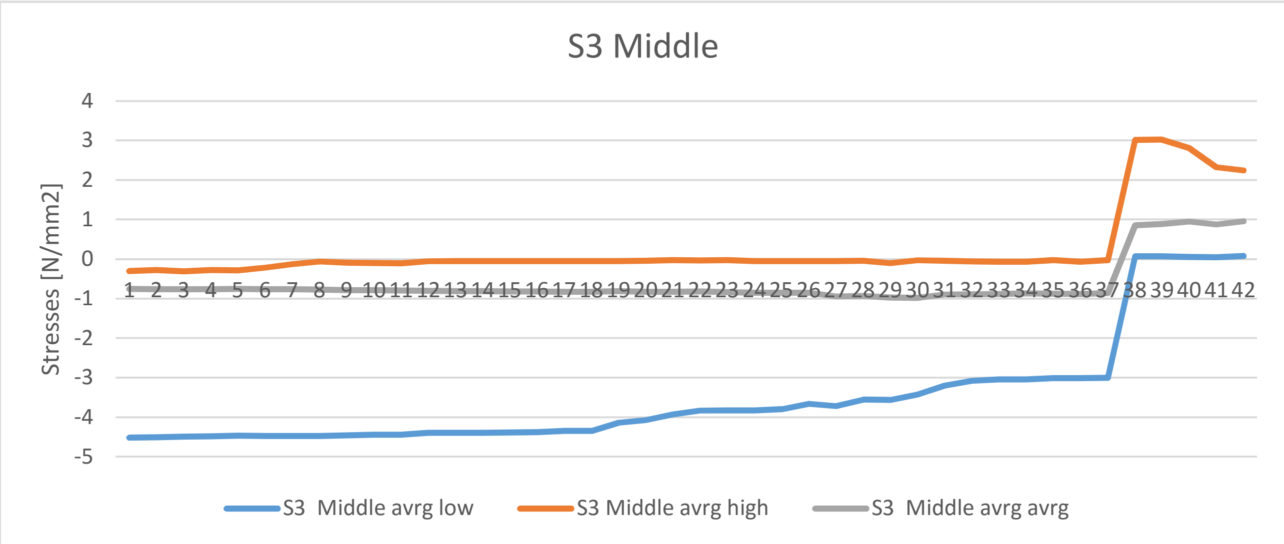


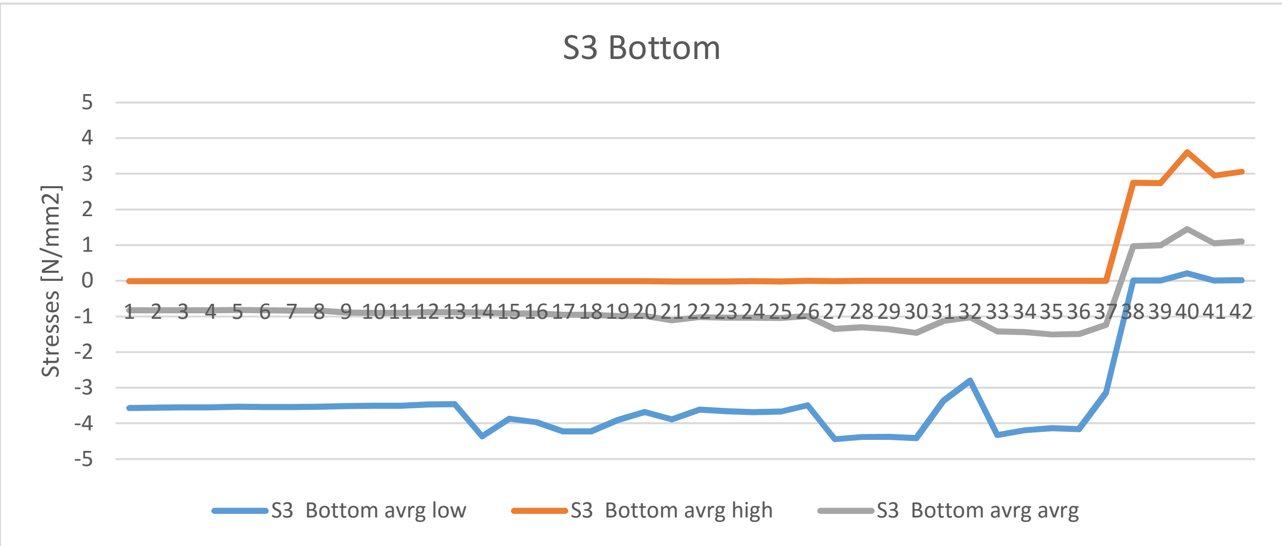




S3 Top, middle and bottom stresses







Appendix C: Construction method comparison

Method	Amount of manual labour	Supports	Amount of supports	Cost	Construction speed	Freeform	Amount of Waste material	Application to large span	Tolerance
Timber Formwork	Large, on-site	Scaffolding	Large	High	Low	Yes	High	Yes	High
Prefabrication (CNC-milling)	Average	Scaffolding	Large	High	Medium	Yes	High	Yes, Exponantial growth cost	High
Tile Vaulting	Large, on-site	Guiding wood or cardboard	Low	Low	Low	Yes	Medium	No, Exponantial growth labour	Low
Post-stessing (Utzon 40)	Average	Guiding wood or cardboard	Low	Low	Low	Yes	Low	No, Exponantial growth labour	Medium
Temp Post stressing (Lenin)	Average	installation gimmick	Very low	Unknown	High	No, Domes only	Low	Yes	High
Reusable Formwork (CNIT)	Large, on-site	Scaffolding	Medium	Medium	Low	No, Leaning arches only	Average	Yes	High
Pneumatic Formwork	Limited	Inflatable cushion	Low	Medium	High	No, Controllable pneumatic only	Low	Yes	Low
Pre-assembly	Average	Scaffolding	Low	Medium	Medium	Yes	Medium	Yes, Exponantial growth cost	High
3D printing	Limited	Scaffolding	Large	High	Low	Yes	High	Yes, Exponantial growth time	Medium

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