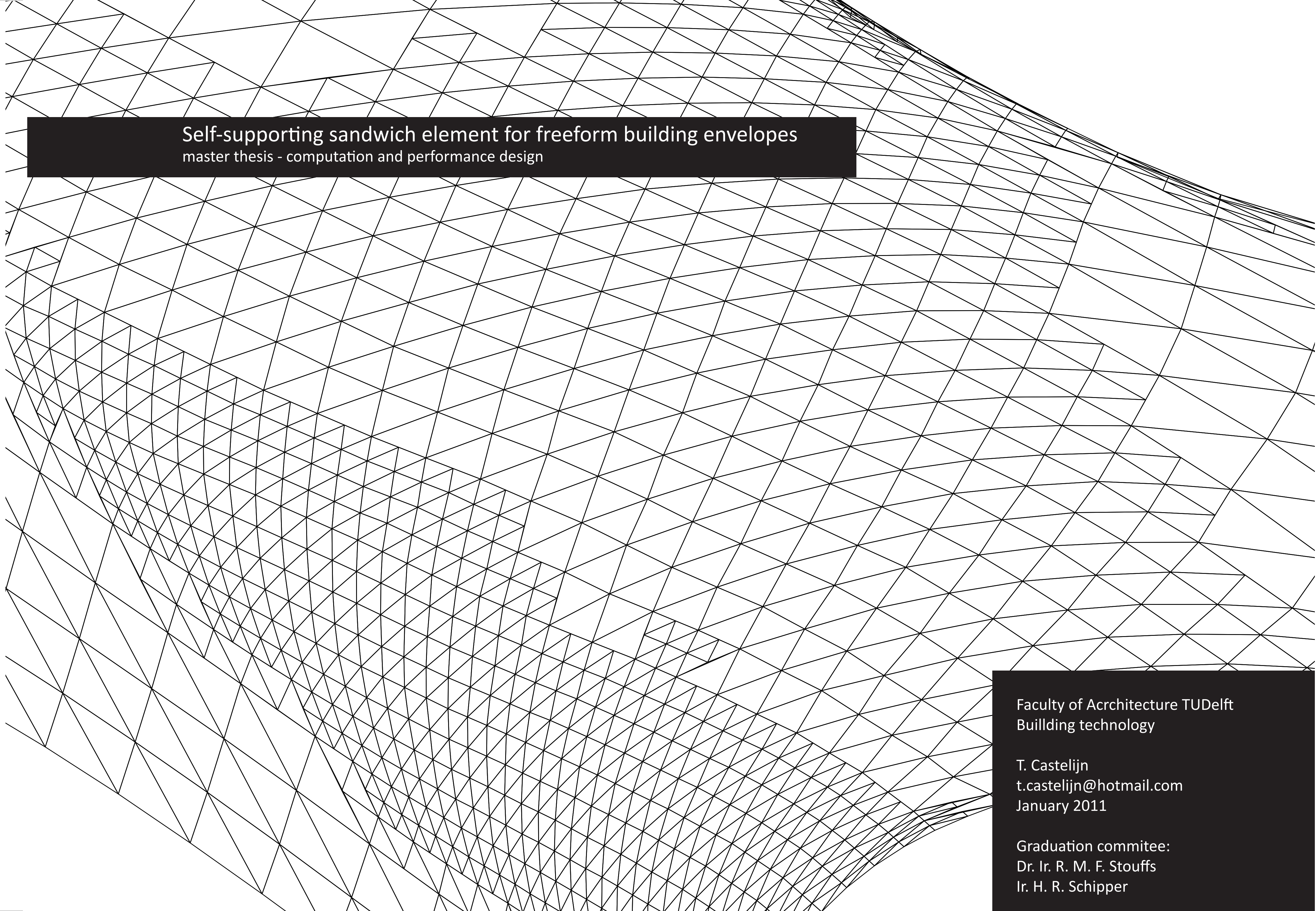

Self-supporting sandwich element for freeform building envelopes

master thesis - computation and performance design

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Preface

This report is intended to describe the graduation research for Computation and Performance design graduation lab at the Faculty of Architecture, TUDelft.

The choice for this subject is a personal interest in algorithmic modeling of geometry, the vast amount of possibilities with computer aided manufacturing and especially a combination of the two. In my opinion this combination will not only increase the possibilities in freeform architecture tremendously. It will open possibilities for many other types of architectural design as well. The scale level can vary from the biggest construction to the smallest detail. Every object that can be imagined by someone can be produced.
A part of this fascination is used as the subject for this report

I would like to thank my supervisors Dr. Ir. Rudi Stouffs and Ir. Roel Schipper for offering the possibility to do research on this particular subject, for their enthusiasm and guidance.

This research was started at Nedcam B.V. in Apeldoorn. Nedcam , specialized in CNC production, offered me the possibility to do the research at their company. I would like to thank everyone at Nedcam and Rene Homan and Erwin van Maaren in particular for sharing their technology and knowledge.
Special thanks to Walter Kohne from Inholland composites lab and Hans Struik from Brands Composiet. Processing of test productions, vacuum injection molding with glass fiber reinforced epoxy was done in the compositelab. Walters guidance and practical knowledge of composite processing made it possible to acquire usable results. Brands Composiet B.V. provided me with glass fabric and epoxy resin needed for making the physical models
Besides that I would like to thank Dr. Ir. Albert ten Busschen for sharing theoretical and practical knowledge on production aspects of composite processing.

Delft, January 17th 2011

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Summary

Introduction

Freeform architecture is becoming more common. 3D design software makes it possible to design freeform architectural surfaces. The combination of 3d models and Computer aided manufacturing makes mass production of customized building components possible. Automated production of custom components is an improvement in efficiency and accuracy compared to manual production. However, custom made building envelopes need multiple functional layers, for structural physical and esthetical quality. Each layer has to be constructed from customized building components. Besides that, each freeform design requires a different approach and production processes need to be reinvented over again.

If all functions of a building envelope could be fulfilled by a single building component, the production process would be much more efficient. In a sandwich element the multiple functional layers are combined in a single element. The core can be CNC shaped from foam and serve as both thermal insulation and an internal mold giving the element its shape. The face can be applied as a fiber reinforced composite providing in structural quality and waterproofing. Special interest goes to CNC wire-cutting of EPS foam, because of its low costs.

Research question

How can a universal and self-supporting sandwich element for freeform building envelopes be designed with regard to CNC wire-cutting?

Requirements

A building envelope must form a barrier for wind and water. The need for additional customized construction elements should be minimized in order to be efficient. Design aspects intrinsic to sandwich constructions from EPS/Epoxy, and the chosen production technique extend set the requirements for the design.

Design aspects

Arnhem OV terminal is chosen as a design context in order to frame the unlimited possibilities of freeform architecture. Yet the characteristics of this freeform reference surface in particular are considered representative for freeform building envelopes in general.

Physical aspects related to building practice are considered. These aspects concern water tightness, thermal insulation and thermal warp. The water resistance of epoxy together with a watertight seal joining the elements provides with a sufficient barrier to water. Thermal insulation of 4,0 W/m2K is provided, given the thermal conductivity of EPS of λ =0,04, which is sufficient with thickness > 160mm.

Thermal Expansion of a 14000mm segment is 28mm at a 60° temperature difference representing a range from -10 to 50° C.

Theory on structural behavior (Allen, 1969): shows possibilities of structural spans from 10 to 14m with a construction thickness of 400-700mm. In building design the dominant failure types of sandwich constructions are exceeding of maximum deformation, exceeding shear stress limits of the core material and exceeding critical value for wrinkling of face stress.

The face thickness is predefined at 4mm and the core thickness resulted from the structural design aspects at 450mm. With these dimensional properties the critical stress value for face wrinkling is 48N/mm2. An optimum cost ratio between the amount of core and face materials is found to give an impractically low value for face thickness concerning production aspects and robustness.

Production aspects that are considered are related to efficiency and accuracy. The most efficient and accurate use of CNC wire cutting technique is to minimize the manual operations in the process. The freedom of shapes is limited to shapes described by two paths. The CNC wire-cutting machine is assumed to move exactly according to the machine instructions, yet there are some aspects that might influence the accuracy. Unequal speed of the spindles can result in irregular width of the melting slot. Application of the sandwich faces with the vacuum injection technique might result in deformations or inaccurate produced surfaces.
Production tests showed that the effect of the unequal spindle speed is negligible and the effects of the deformation under vacuum pressure are as well, when the vacuum pressure is - 0,35 relative to atmospheric pressure.

Design
The reference surface is divided in triangular elements based on support grid. Triangular prismatic elements are best suitable in the geometric limits of the production process. The elements are combined to triangular segments spanning 14m. The subdivision density is refined when the maximum distance to the reference surface exceeds a specified threshold in an iterative process improving the approximation of the reference surface. The refined elements have similar shape parameters as the initial elements.
Connections between the elements need to perform in structurally by transferring forces between adjacent elements and physically by closing the joint for water and air infiltration. Structural connections are made with steel inserts that transfer tensile and compressive face stresses and shear stress. These fixture components are placed according to a CNC machined reference, ensuring their position is correct. Finite element analyses on the structural inserts show peak stresses occurring at the connections. The peak values do not exceed critical values for normal stress in the face.
Connections to the structure are designed to take on size changes due to thermal expansion. Besides that shear and normal stresses concentrate near the support. Additional construction elements are added for improving stress distribution and preventing stress peaks to exceed the limits.

Conclusions/evaluation
The design meets the stated requirements for structural and physical performance. The CNC cutting of the element can be done efficiently. The application of the face is the bottleneck in production efficiency, but the efficiency is regained at the building site because the prefabricated construction can be put together without measuring. The system can be used for other freeform surfaces as well, making it universal applicable.

1. Introduction

Freeform architecture has become increasingly popular with the development of computer technology and 3 dimensional digital design tools. Though digital design tools are completely incorporated in today's way of making architecture, the digital design has to be manually translated to a composition of conventional building products.
A solution can be found in Computer Numerical Controlled (CNC) production processes, in which machining of materials is controlled by digital data from virtual 3D models. CNC-milling machines or 3d printers can be used to manufacture a series of custom shaped elements. This is called mass-customization. In the context of freeform architecture, these elements can be the prefabricated non-repetitive components of a freeform façade. Prefabricating freeform facades eliminates the need for costly tailor-made solutions, that are only applied once. In combination with algorithmic modeling to generate the machining data, digital production is a powerful tool for constructing freeform architecture.
Realization of freeform architecture is often done by designing complex custom solutions for each specific project. For instance with custom manufactured building components, complex intermediate structures between the main structure and facade building envelope or cladding panels. (Schodek, 2004). An example is Frank O. Gehry's design for the Guggenheim museum, where a really expensive degree of complexity was necessary to construct and to support its non-standard shapes. The use of multiple functional layers that have to follow a certain shape makes freeform architecture complex and therefore expensive. All layers have to be shaped separately in according to the design of the building envelope. A facade system of prefabricated sandwich elements with functional aspects as strength, stiffness, thermal insulation and sealing internally solved, could make freeform construction more efficient.

1.1. Relevance

1.1.1. Reference projects

A couple of reference projects have been looked at in order to give insight in the field of research.

Sound barrier ONL

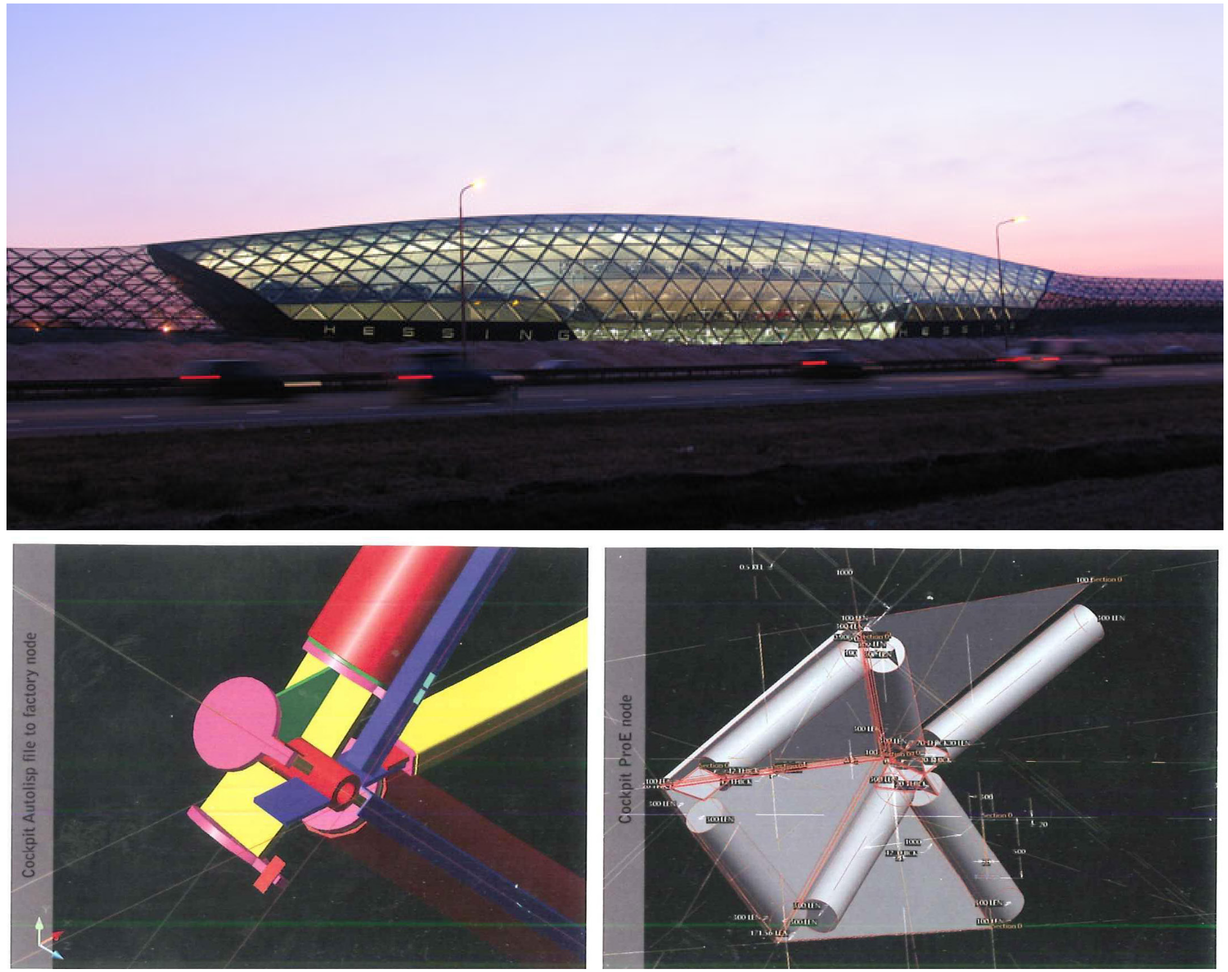


Figure 1.1 - sound barrier(Kas Oosterhuis: Architect)

The beams are CNC cut to the right length. The nodes are manual welded together in a CNC mould, controlling the angles between parts. The use of the 3d model for digital referencing is an important aspect. It replaces the need for extensive manual measuring. Besides that, it is far more accurate than can be achieved by manual measuring. An important aspect is the uniformity of the construction, all the beams are produced in the same production process, the nodes as well.

Guggenheim bilbao - Frank O. Gehry

Freeform façade constructed from titanium cladding on a steel structure. Design evolved from 3 dimensional sketch models in paper. Which were digitalized by 3d scanning.

Figure 1.2 - guggenheim bilbao - Frank O. Gehry

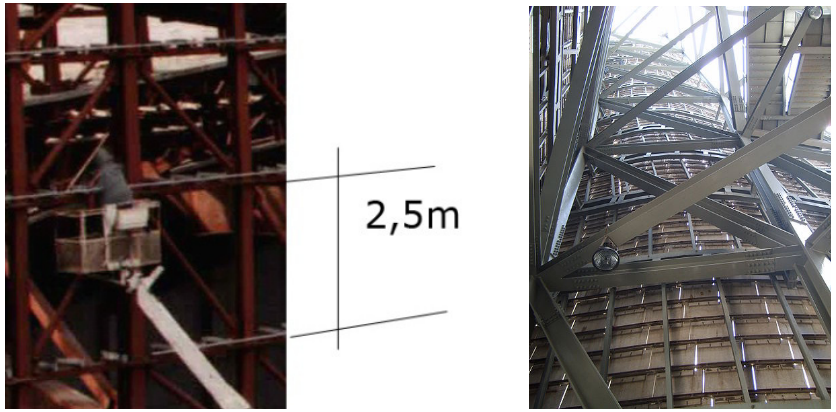


Figure 1.3 - guggenheim - secondary construction

Esthetical skin constructed from titanium plates overlapping like scales, plates are not deformed but small enough to suggest it concerns a curved surface. There is no particular relation between interior space and exterior shape, resulting in large unused spaces between interior and exterior. Large steel structures manually put to position and bolted together, lot of customized parts. Subcontractors worked in same main reference model as designers, forming an integral design process.

Heydar Aliyev cultural centre - Zaha Hadid

High complexity of custom 3D space frame forms load bearing structure. Additional functional layers (steel roof panels, insulation, spacers, cladding, interior cladding) are built from customized parts as well.

Figure 1.4 - spaceframe heydar Aliyev cultural centre

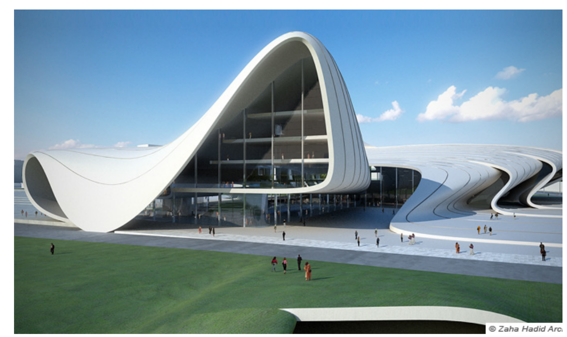


Figure 1.5 - Heydar Aliyev Cultural Centre - Hadid

Giant whale jaw - Maurice Nio

Bus station in Hoofddorp. Sculptural design from CNC milled EPS and a 6mm thick glass fibre reinforced polyester face. Roof is a 50m unsupported span. Solution is very specific for this design. Function of the building is serving as a rain shelter, interior space is in outside air as well.

Figure 1.6 - Giant whale Jaw

Figure 1.7 - milling of EPS blocks

EPS blocks were CNC milled and put together on site. EPS was covered in protective film to prevent styrene released in hardening process of polyester to solve the EPS. Face is applied in manual lamination process, using slurry of resin and fibres.

Protospace 4.0 hyperbody

Fragment of a prototype for a pavilion; protospace 4.0. CNC cut EPS elements covered in 1-2mm thick layer of polyurethane. Wooden inserts have been manually crafted to provide in structural connections.

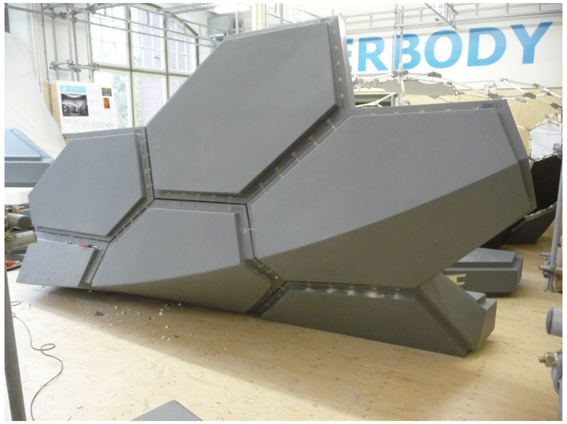


Figure 1.8 - mockup Protospace 4.0 Hyerbody

Figure 1.9 - poduction process of connections

Structural and physical aspects were not taken into account. Strength and Production aspects are no taken into account, leading to ineffecient production technique with many manual operations.

1.1.2. Freeform building envelopes

There are several types of façade systems that can be used. Schodek refers to them as:

- Integral envelope (load bearing facade
- Cladding / custom shaped load bearing structure
- Cladding / secondary (and tertiary) structure
- Self-suporting facade / main load bearing structure

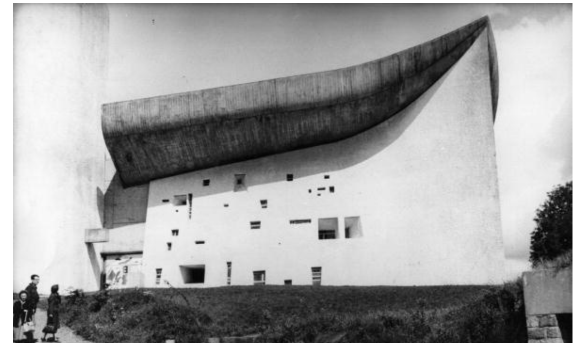


Figure 1.10 - Chapelle de Ronchamps - le corbusier

Integral envelope. (load bearing facade)
The integral system is where the façade is a freeform, mostly monolithic structure that has a load bearing function. Examples are freeform poured in situ concrete as la chapelle de Ronchamps by le Corbusier (Figure 1.10). Also component systems like masonry constructions can be considered integral systems. The main characteristic of the integral system is that both the form work for concrete and the outline for the masonry have to be created by hand. CNC milled foam can be used to make digitally prefabricate the form work.


Figure 1.11 - BMW pavilion - Bernhard Franken

Cladding, load bearing structure follows envelope's geometry
The primary supporting structure can be shaped according to the buildings envelope so that the cladding or façade elements can be directly mounted to it. In this case both the primary load bearing structure as well as the façade system have to be custom made. Bernhard frankens Bubble is an example (Figure 1.11)The inner space can follow the contours of the outer envelope if desirable.

Cladding, secondary structure, main load bearing structure
A secondary structure is often used as an intermediate structure between a standard load bearing structure and relatively flexible or bendable cladding material. The gugenheim bilbao has a relatively large and complex secondary structure (Figure 1.12). The outer cladding is often only used to form the visible envelope and an inner façade acts as a physical barrier for wind and rain. The inner façade and the load bearing structure do not necessarily follow the geometry of the building envelope.

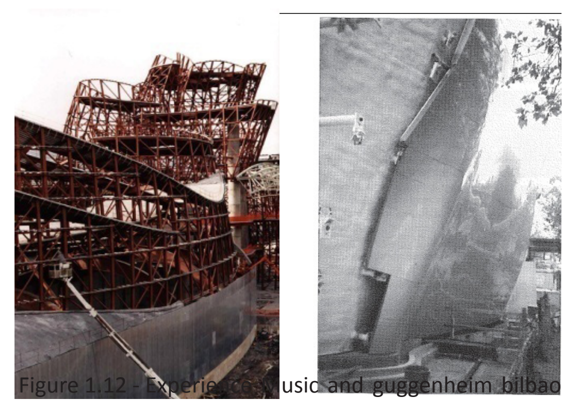


Figure 1.12 - Experience music and guggenheim bilbao
Frank O. Gehry

Self-supporting façade with standard load bearing structure (limited need for secondary structure)
Self-supporting façade systems consist of elements with enough strength and stiffness themselves and can be carried by a small number of supports. There is an intermediate structure needed between the main load bearing structure and the façade, but it can be less dense then when it would need to support the cladding. The façade can be applied both as merely an outer cladding with no physical qualities and as a complete façade. An expample is the Experience music building by Gehry (Figure 1.12)

Conclusion
The first type, the integral load bearing façade is a general solution for constructing unique architectural forms. The uniqueness of the solution requires a project specific approach and the process has to be completely redone for each project. The single used form work needed for concrete poured in situ or the unique set of coordinates needed to outline masonry walls in combination with labour intensive construction of non-standard surfaces have to be done for each specific project. The process cannot be digitally controlled, though digital models can be used for extracting coordinate points.

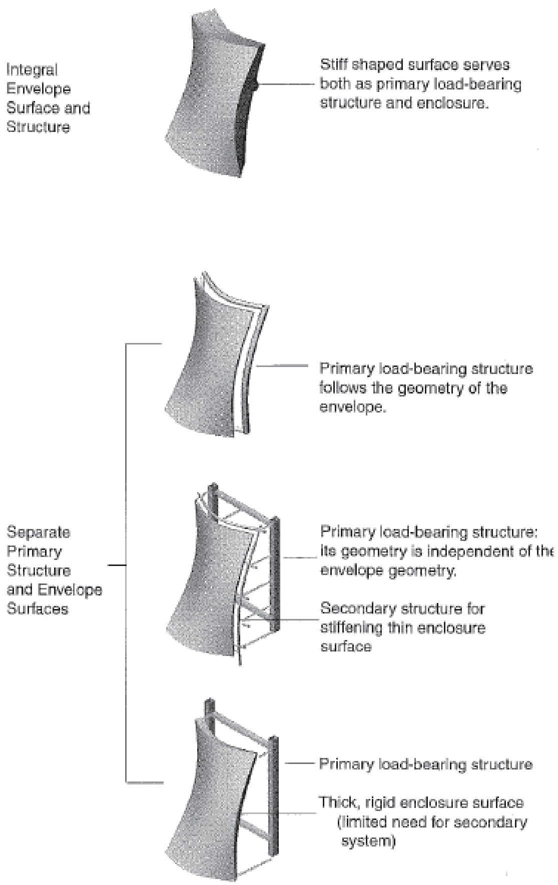


Figure 1.13 - Types of freeform building envelopes

The second type, the primary load bearing structure following the building's envelope, is a good solution when the primary construction allows it to be specifically designed according to the buildings shape. Usually this is only the case for specific applications or single storey buildings, like the BMW pavilion. Specific design of a load bearing structure can be highly expansive, but is not uncommon in for instance railway stations or airport terminals. Used for an integral roof/façade system. The process is suitable for CAM production methods.
The third type with a secondary intermediate structure is very usable for a semi standard building, with a standard primary structure and a non-standard façade. The secondary structure can carry an integral façade, or just a cladding with an inner wall added from the inside. In the first case the secondary structure is visible in the buildings' interior. In the second case the secondary structure is integrated in the façade and it is not required for the inner wall to follow the envelopes shape. The secondary structure can be produced with CAM techniques, but it is an additional step in making a freeform façade and an increase of complexity.

1.1.3. Conclusions

Production of multiple functional layers, that all have to be custom produced, is what makes freeform building envelopes expensive. Combining the layers in a single CNC produced element avoids the need for producing multiple freeform layers. Besides that, solutions for freeform architecture are often applied only once, because they are designed for one building in particular.
A sandwich element with a CNC shaped core as an internal mould and a fibre reinforced composite face can provide in functionality and be produced in any shape. Theoretically it can provide in a functional façade for any freeform design.
Uniformity of the products as in ONL's sound barrier makes the CNC production process more efficient. Products that are based on similar shape parameters, which may vary for each unit, can be produced in the same production process.

1.1.4. CNC fabrication techniques

There are three main principles in CNC-machining: additive, subtractive and deformation. Additive techniques, like 3d-printing or stereo lithography, are generally very slow and costly. In 3d printing and stereo lithography, the complete product must be drawn by a 3 dimensional path, stacking layers of 2d prints on top of each other. The techniques are generally used in rapid prototyping or single production runs of high complexity. Casting is an additive process as well. It is more efficient than the other two processes, but for a series of custom elements a custom mould is needed for each element, leading to excessive material use. Using a variable mould is more efficient in material use, but elements can only be cast one at a time.
Deformation is used for simplest shapes. Known techniques are bending of beams or tubes to form custom construction elements. Bending of flat plates into single curved or double curved surfaces is done to create freeform cladding for instance. Variety of materials is usable as long as they allow plastic deformation. For instance metals or heated thermoplastics or glass can be used. Low degree of freedom in shape, only suitable for isotropic materials.
Subtractive techniques have a wide range of possibilities; Cutting, sawing and milling of both 2d- and 3d-shapes. Subtractive techniques are based on the principle of carving the product out of a solid block of material. Achievable complexity is dependent on the specific process, varying from simple 2d laser cut plates to complex 3d shapes, milled by a 5 axis milling machine.

CNC shaped Sandwich element

A sandwich element usually consists of multiple layers, from which the outer layers are strong, rigid material and have relatively small thickness compared to the core. The core consists of flexural material.
The choice for shaping the core of the sandwich element is based on the generally applied low density insulating materials i.e. foam. Low density implies that the material is easy to shape.

			complexity of shapes	surface quality	processing speed	costs	efficiency (waste of material)
subtractive	milling	foam	+	-/+	++	++	-/+
		wood/metal/polymers	+	+	-	-	-/+
	hot wire cutting		-/+	-/+	++	++	-/+
additive	3d-printing		++	+	- -	- -	++
	stereolithography/SLS		++	++	- -	- -	++
	molding	lost mold	+	+/++	+/++ (1)	+	- -
		reusable mold	+	++	- -	-/+	+
deforming	bending		- -	-/+	++	-/+	++
	exploform		=	-/+	++	-/+	++

Figure 1.15 - table comparisson CNC production techniques

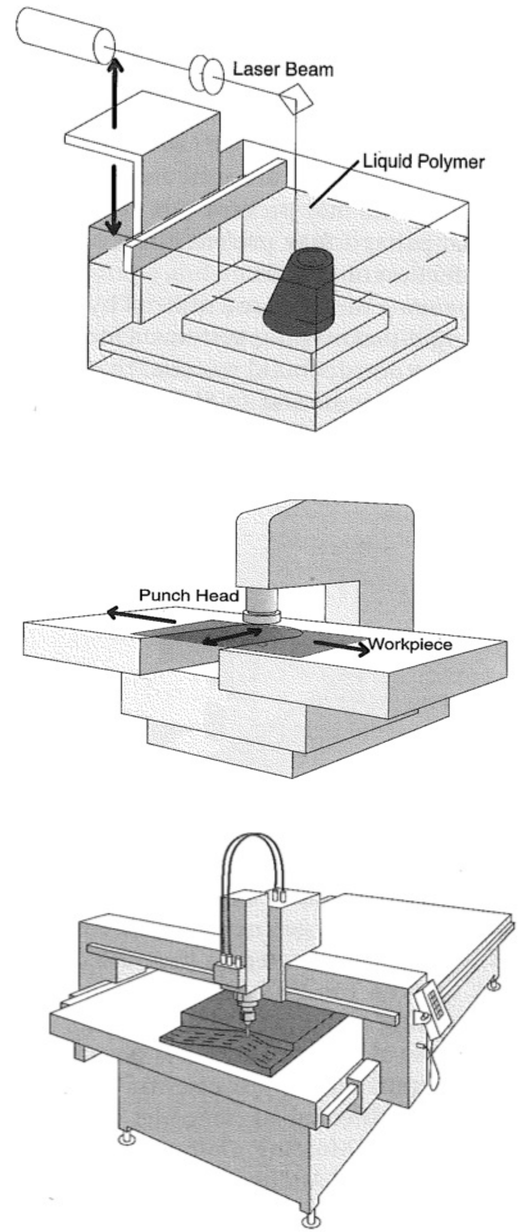


Figure 1.14 - a. Stereolithography, b. CNC bending, c. 3-axis milling

Earlier research on CNC-milled façade elements has shown difficulties in producing curved profiled edges and also pointed out CNC-milling is a slow process (Castelijn, 2010). CNC wire cutting is a good alternative in terms of efficiency, because it works along a one-dimensional line while the mill has to shape a two dimensional surface.Despite the limited freedom in shape that is achievable with the CNC wire cutting process it is the most simple and cheap CNC process. Besides that the most Suitable material, EPS, is cheap, light weight and has thermal insulating qualities.

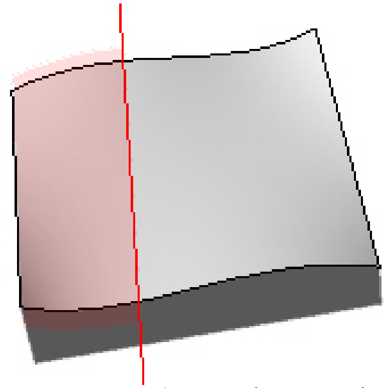


Figure 1.16 - CNC wire cutting, one dimensional path

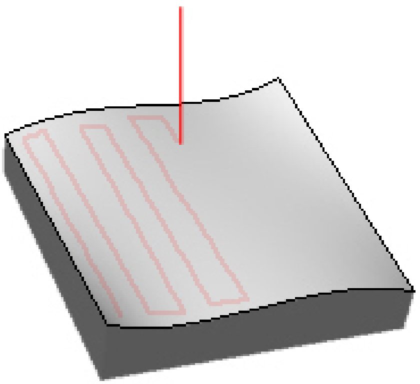


Figure 1.17 - CNC milling 3 dimensional path

Figure 1.18 - OV Terminal Arnhem (www.arup.com)

1.1.5. Composite processing techniques

The face of the sandwich elements have to follow the shape of the internal mould. Fibre reinforced composites have the ability to be applied in a flexible state, which means the face can follow the form of the relatively weak core. When hardened, the face will be rigid enough to provide in structural strength and stiffness.
Common techniques to process composites are by manual lamination, spraying, or vacuum injection.

Vacuum injection moulding

Vacuum injection moulding is a technique where a mould is pre-laminated with dry glass fabric. The glass fabric is then covered PE foil which is sealed airtight with mouldable tacky tape. Two tubes are placed. One is connected to a vacuum pump and one to a resin supply. Low viscosity resin is then pulled through the glass fabric under vacuum pressure.

Spraying of composite

Spraying of fibre-reinforced composites is done with a nozzle. A continuous feed of glass fibre is near nozzle. The glass fibre is chopped up and directly fed into the resin spray. The resin and fibre mixture hits the mould in a thick multidirectional layer of resin and bits of fibre. The fibres are flattened by hand with a paint roller.
The technique does not require preparation of fibre mats and needed production facilities are simple. It is assumed not possible to control the thickness and therefore difficult to construct accurate models.

Hand lamination

Hand lamination is done by placing impregnated glass fibre mats onto the mould. Resin of high viscosity is needed to ensure the glass fabric sticks to the mould. The resin distribution and the thickness are assumed to be less controllable than in the vacuum injection technique. Besides that, lamination of an EPS foam element on all sides at once is considered to cause difficulties for the lower side of the work piece.

1.1.6. Design context

In order to have a realistic design context within architectural design, the OV Terminal of Arnhem is chosen as a reference project. The research context is narrowed to the design for a system of CNC fabricated sandwich elements for this project. Though the research narrows to one reference surface, the irregularity within this surface represents numerous possible geometrical shapes in freeform architectural design. Expected is that solutions for this specific geometrical context can be applied on other reference surfaces as well.
The choice for this specific project is based on Nedcams involvement in the construction of freeform roof cladding for the OV Terminal. The emphasizes relevance for Nedcam to cooperate in this research and makes it possible to make use of available material as technical drawings and digital 3d models.

1.2. Conclusions/ frame of reference

From the previous section conclusions are drawn to form a frame of reference:

- A universal system that can be reused for different building designs, avoids the need to reinvent construction for freeform envelopes.
- Sandwich element is a building product closest to the integral façade. A sandwich element has the potential of combining structural, physical and esthetic functionality in one element, that can be produced with CNC production techniques.
- Production of custom elements is expensive. Efficiency within production process is a major aspect in the design process.
- CNC wire cutting is a cost efficient production technique for the core compared to other CNC production techniques.
- Material choice based on production techniques. EPS is common material for wire cutting process, because of its low costs. Choice for epoxy based on possibility to combine with EPS.

Conclusions from this section formed the starting point for this research. The main goal is constructing a sandwich element from EPS and epoxy for the freeform building envelope of The OV terminal Arnhem. The product design will be based on the production technique in order to benefit its efficiency.

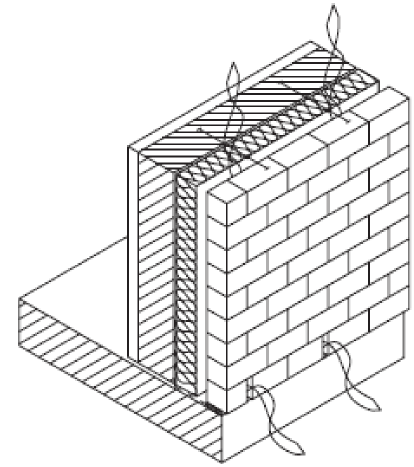


Figure 1.19 - functional layers of a facade

1.3. Definition of the problem and research question

Facades with multiple functional layers cannot be applied for complex freeform shapes without customizing all the elements of different layers. Mostly this results in complex secondary and tertiary constructions with custom cladding. Sandwich elements as an integrated system can offer a solution for this problem, but restrictions in form and implementation of more complex components require a lot of manual operations. Limits within production process concerning geometry, material use and tolerances have to be taken into account.

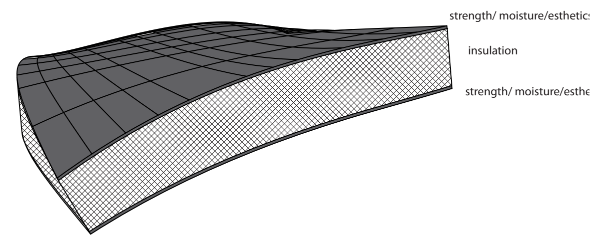


Figure 1.20 - combining functional layers in one sandwich element

Research question

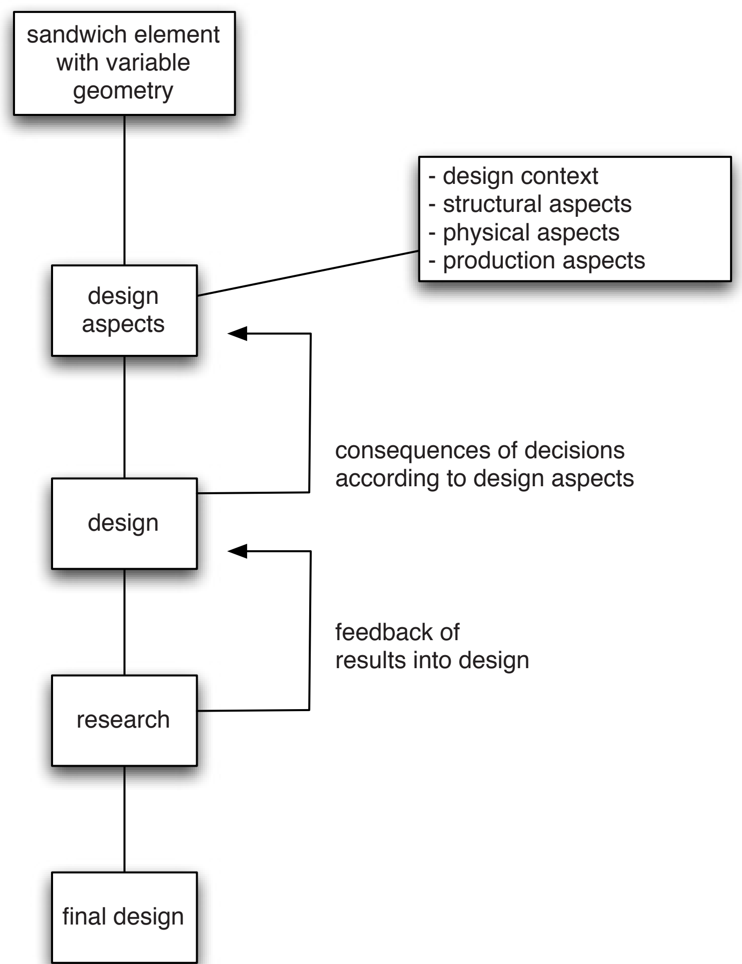
How can a structural sandwich element with custom geometry be designed for production with CNC-hotwire technique?

subjects:

- What are the basic requirements for the sandwich elements?
- What are design intrinsic problems?
- What are physical design aspects?
- What are structural design aspects?
- What are design aspects in relation to production?
- How can the aspects be implemented in the product design?
- Does the design meet the requirements?

1.1. Research strategy

Design aspects that have to be considered are described in the first part of the report. Subjects are physical and structural behavior of sandwich elements, geometrical context of the OV Terminal Arnhem and possibilities or limitations of production techniques. These are the design intrinsic problems.
The design is made within the frame of possibilities from the design aspects. The technical research is done to compare options and verify the chosen solutions. The results from the research are used as feedback for decisions in the design process. The design aspects might be extended as a consequence of new insights based on the design process.



2. Design aspects

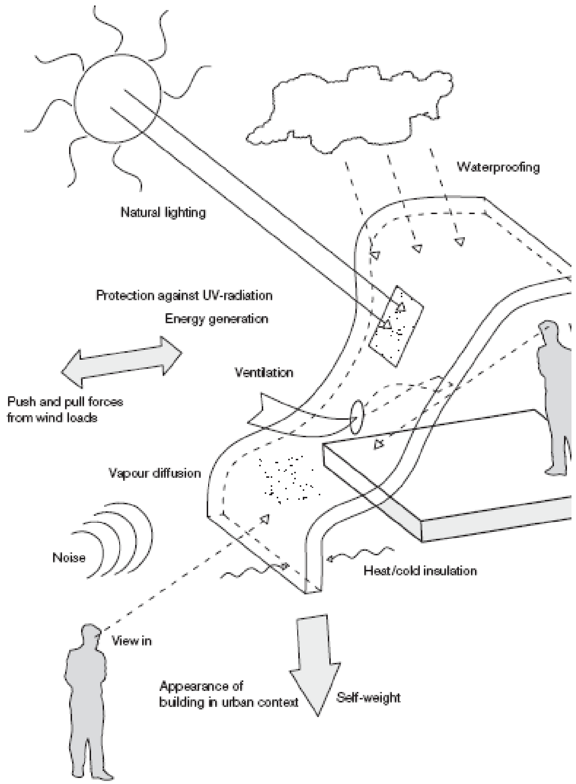


Figure 2.21 - functions of a facade (Knaack, 2006)

2.1. Introduction

In this section the design aspects of a building envelope are discussed. For any building envelope there are basic requirements concerning functionality and safety, which is described below.

2.1.1. Basic requirements

Requirements for a building envelope in general are stated in the image below (Knaack).
This research is mainly focusing on structural and physical aspects, which can result in a functional building envelope. Apart from that, problems implicit to the design based on the design context and consequences of the variation in shape and chosen production technique will extend the requirements

Requirements for building the freeform building envelope:

- Strength and stiffness, spans to 10m in order to avoid additional load bearing structures.
- Wind- and waterproofing
- (Architectural appearance/aesthetics)

Apart from the basic requirements that concern any building envelope, there are additional aspects that have to be taken into account. These aspects concern structural and physical properties of sandwich constructions in EPS and Epoxy. The limitations of the production technique and the demands derived from the design context.
Together, the basic requirements and the aspects described in this section, form set of requirements, where the final design has to comply to.

2.2. Design context

2.2.1. Arnhem OV Terminal

The design context is chosen to restrict the scope of research. The terminology ‘freeform architectural surfaces’ covers any shape configuration possible. The design of a universal system for freeform architectural surfaces would need an infinite amount of shape configurations to be considered and thus cannot be completed.

Figure 2.22 - OV Terminal Arnhem - UN Studio (source Arup)

Project description

The main function of the OV terminal is housing a combined Train and bus station. Besides that office space is added for serving functions offices. The main aspect of the design in the context of this research is the roof. The roof of 3800m2 consists of two parts: one high part housing the Terminal main hall, one low part housing some supporting functional spaces. The high part of the roof has a tunnel shape orientated with the open side to the square in front of the station. Considering the plan of the floor directly situated underneath the roof structure, it is visible that the lower part of the roof can be supported on the interior walls forming the office spaces. The higher part however has no construction elements in the inside space, except for project specific elements twist and back twist. Walls confining the interior space carry the rest of the loads.
In the initial design the roof consists of a structural concrete shell, with thermal insulation and waterproof foil applied on top. The construction is covered with concrete panels defining the shape and appearance. The panels exactly follow the reference surface and are cast in custom-made foam molds.

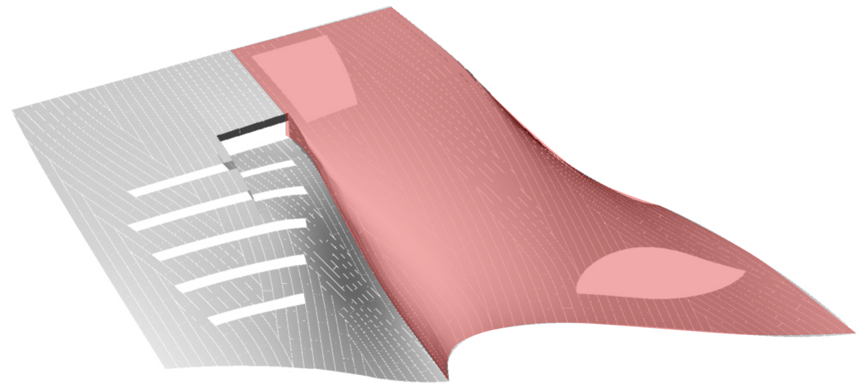


Figure 2.23 - The roof of the OV terminal is used as a reference surface throughout the rest of this research.

Spatial planning OV Terminal

The spatial planning of the OV terminal Arnhem is partially determining the possibilities in supporting the structure. Considering the plan of the floor directly situated underneath the roof structure, it is visible that the lower part of the roof can be supported on the interior walls. The higher part however has no construction elements in the inside space, except for project specific elements twist and back twist. Walls confining the interior space carry the rest of the loads.

2.2.2. Curvature analysis Arnhem

A curvature analysis is done to get an idea of the reference surfaces curvature values. Surface curvature can be expressed in curvature κ or radius *r.* In this analysis the radius is used because it is easier in comprehension and for calculation purposes. The surfaces curvature is easier measured when the relation between radius and scale compared to the reference surface is clear.

In the case of OV Terminal Arnhem, the roof will be segmented in either curved segments exactly following the reference surface, or flat faces approximating the reference surface. When the curvature radius is large in relation to the roof segments, the segments will appear almost flat. CNC machining of elements that are almost flat is very inefficient in relation to the visual effects. The obtained curvature in an element might be too small to be noticed.

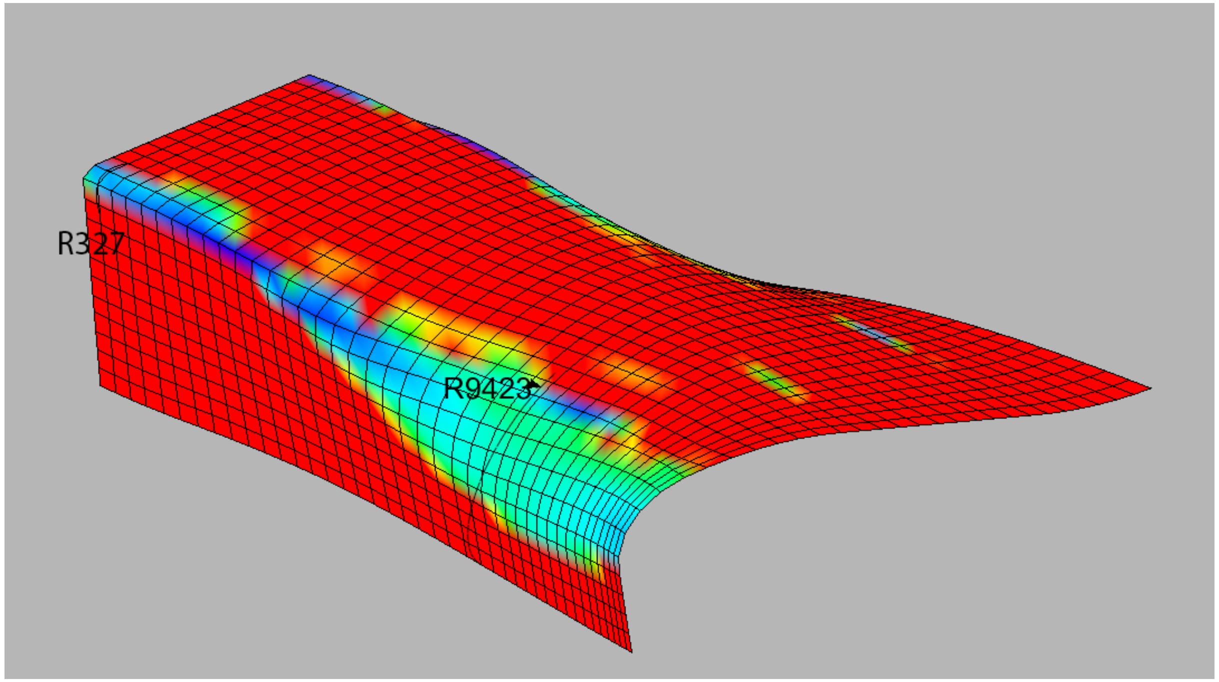


Figure 2.24 - curvature analisys, range blue - red represents curvatures from resp. 327mm to 20000mm in radius

Curvature analysis above shows highly curved areas in the roofs surface. The lower and upper boundaries for the gradient represent radii of 327mm and 20000mm. The red areas all have larger curvature radii than 20000mm. At this curvature radius an element of 3000mm in length would diverge only 56mm from the reference surface, which is a 1:53 ratio. In the green region, radius 9500mm, the distance is 119mm which is a 1:25 ratio. The ratios are calculated with the formula below.

$$h_{midden} = R - \sqrt{R^2 - (a/2)^2} \quad (2.1)$$

In the product design the differences in curvature have to be taken into account. Machining of curved areas with low curvature values (red) is inefficient, because the deviation from flat panels is very low. The costs of a custom made curved panel compared to a flat panel however are much higher. Distinguishing panels for their curvature values and production technique will make the production process more efficient. This will be further explained in chapter.

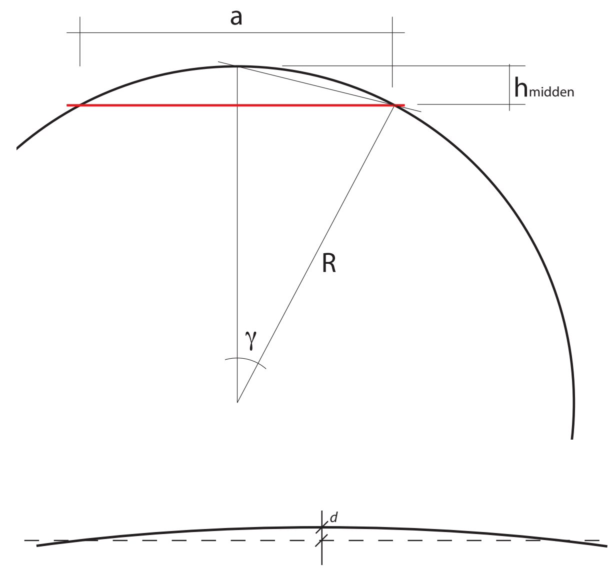


Figure 2.25 - curvature expressed in radius and deviation d

2.2.3. Appearance

The appearance discussion is very subjective and project specific. The applied materials and systematical order form the basis for the concept of a system that can be universally applied on freeform architectural surfaces. The shape of a freeform architectural surface is of course very unlikely to occur twice. However the systematical order and the used materials will have the same expression every time. With the fact in mind that architects want to express their own identity in their designs, it might actually be unlikely that a universal system will be often applied after a successful application.

Demand for architecture to be individual, makes it possible for the user to identify with a building (Kronenburg 2001, Spirit of the machine).

In case of the OV terminal the initial design has a set of rules it has to comply to, concerning surface approximation, surface material, seam patterns and finishing quality. But other in other projects the demands are probably not the same. It is not possible to pick one solution as the best.

Surface quality

Demands for surface quality can be stated at a certain minimum standard to make sure the system is applicable in practice. When the system performs in an esthetic way as well, by making sure its surface approximation is good, the surface is finished nicely and the seams are not visible or fit in the architects ideas. Higher demands need more effort to achieve and might be restricting the freedom of design.

A balance can be found in surface quality and functional performance. Functionalistic view on the appearance can be interesting were esthetical quality derives from its functional performance.

Additional flexible skin

Another considered option is making a structural and physical performing basis, with the possibility to add an additional esthetic layer. It follows form of reference surface and low functional performance is needed, because the functional aspects are solved in the basis of the system. Adding an additional layer is a less pure solution. It contradicts the goal of compressing all layers of a conventional façade into one, but the applicability in different design contexts increases a lot. Besides that, a system standard can be designed, which meets certain esthetic demands and leaves the possibility to add a skin when needed.

Options for additional layers are:

1. Deformable plastics
2. Wooden strips
3. Ceramic tiles
4. Spray coatings (with or without expansion joints)

Conclusions

The OV Terminal Arnhem is mainly used as a reference shape for setting up and testing a universal system for freeform architectural surfaces in general. The openings in the roof are not taken into account. The unsupported surface border is, the solution found might also be usable for roof openings.

2.3. Structural behavior Sandwich constructions

The structural behavior of sandwich elements is listed in two parts: The first part describes general theory on sandwich constructions (Allen 1969), the second part describes application of this theory within the context of the design. Stiffness and strength of a construction mainly depends on dimensional parameters and material properties. Using estimates for these parameters gives an idea of the magnitude of internal forces or needed dimensions or material properties.
The theory for structural behavior of sandwich elements will form the basis for the dimensional properties of the sandwich construction of the design.

Definition of units

E_f	young's modulus face	V	Shear force
E_c	young's modulus core	b	Width
G_c	shear modulus core	h	Height
v_c	poisson's ratio core	t	Face thickness
v_f	poisson's ratio core	c	Core thickness
B_1	buckling constant	L	Length
B_2	buckling constant	τ	Shear stress
C	constant wrinkling half wavelength	w	Deflection
k	Constant for irregularities	σ	Normal stress face

2.3.1. General Theory and definitions

A sandwich beam as described in this section refers to a layered construction as in fig. It consists of a relatively thick core with low density. Commonly foam like materials are used for the core. The core is placed between a top and bottom layer, which are referred to as faces. The faces have high density and compared to the foam core, but are applied in a thin layer. A broad range of materials can be used for the faces like wood, metal or composites. The faces generally have a high young's modulus, strength, density and price compared to the foam core.
The sandwich beam is considered to be simple supported i.e. all translations fixed at one end and vertical translation fixed at the other end. Expected is that this theory will be sufficient for argumentation on structural roof elements.

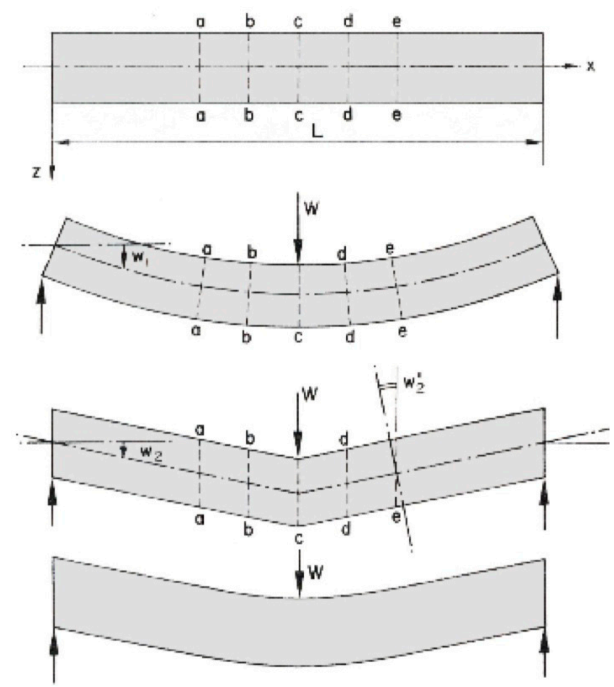


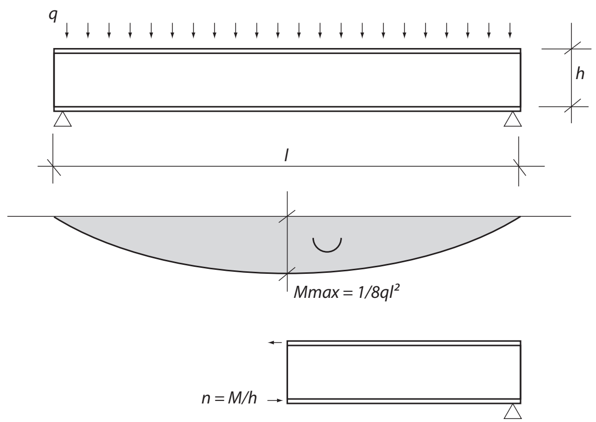
Figure 2.26 - shear and bending deformation

Bending stiffness and shear stiffness

Sandwich beams are submitted to two types of deformation: pure bending and shear deformation (Figure 2.26).
The flexural rigidity that is a measure for resistance to bending is given by the following formula. The first formula represents the second moment of area for a combined section (Steiner) which can be rewritten in the following form.

$$D = E_f(I_f + A_f\bar{z}^2) + E_c I_c \qquad (2.2)$$

$$D = E_f\frac{bt^3}{6} + E_f\frac{bth^2}{2} + E_c\frac{bc^3}{12} \qquad (2.3)$$



The terms represent resp. The flexural rigidity of the individual faces and the flexural rigidity of the core. The second term represents the combined flexural rigidity of the faces according to Steiner, which is dominant when faces are thin. Sandwich faces are considered thin when:

$$6\frac{E_f}{E_c}\frac{t}{c}\left(\frac{h}{c}\right)^2 > 100 \qquad (2.4)$$

Where ratio between thicknesses is related to the stiffness of the materials as well.

Provided that the sandwich beam has thin faces, the first and third term are considered negligible. Which gives the following formula for flexural rigidity:

$$D = \frac{E_f bth^2}{2} \qquad (2.5)$$

The deflection caused by bending under a distributed load q can then be defined by

$$w_1 = \frac{5qL^4}{384D} \qquad (2.6)$$

The bending moment is mainly carried by the sandwich faces which results in the following equation for maximum stress in the faces caused by bending:

$$M = \frac{ql^2}{8} \quad (2.7) \qquad n = \frac{M}{h} \quad (2.8) \qquad \sigma = \frac{n}{A}\frac{M}{hbt} \quad (2.9)$$

Shear deformation is caused by shear stress. The shear stress is distributed over the faces and core as in fig. When the faces are thin the flexural rigidity of the faces do not contribute much to the shear stiffness of the beam. In this case the shear stress distribution over the beam may be assumed to be constant over the depth of the core, given by the formula:

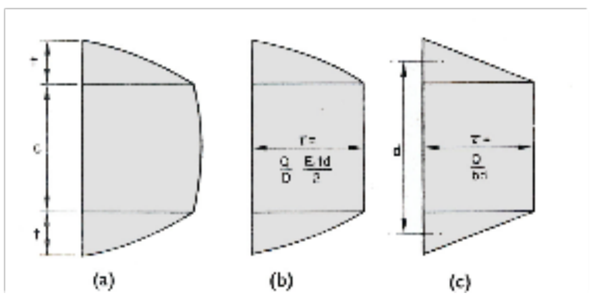


Figure 2.27 - shear force equal distributed over the height when faces are thin (c)

$$\tau_{\max} = \tau_{gem} = \frac{V}{h \cdot b} \qquad (2.10)$$

This is the case when the following condition is met, which is always true when condition ((2.4) for thin faces is true:

$$\frac{E_f}{E_c}\cdot\frac{t}{c}\cdot\left(\frac{d}{c}\right) > 25 \qquad (2.11)$$

For sandwich beams with thin faces the resistance to shear is given by the shear modulus of the core:

$$G_c = \frac{E_c}{2(1-v_c)} \qquad (2.12)$$

The shear deformation can then be given by the following equation:

$$w_2 = \frac{ql^2}{G} \qquad (2.13)$$

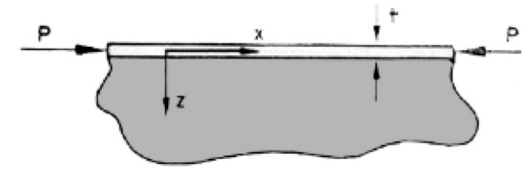


Figure 2.29 - face loaded with compressive force

Face wrinkling

Face wrinkling is a type of failure where the sandwich faces buckle under compressive normal stress. Two types of buckling are compressive failure of the core and adhesive bond failure. Failure due to wrinkling is an expression of E_f and E_c. Flexural rigidity of the face is internal resistance to buckling of the face, flexural rigidity of the core is external resistance to buckling.

Allen describes three types of face wrinkling face stresses are mainly caused by bending moment. Case I describes a situation where only one of the faces is compressed, which occurs when the element is submitted to a bending moment. Cases II and III are considered not applicable because they occur under only compressive normal forces of the element.

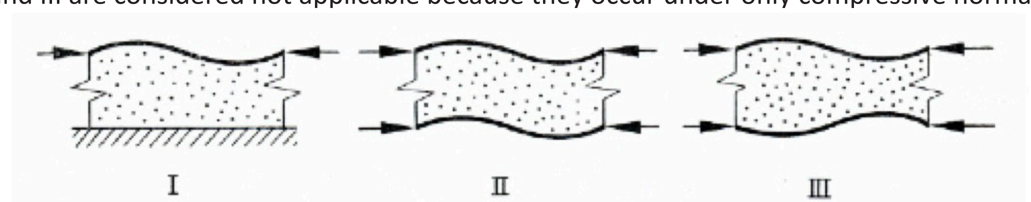


Figure 2.28 - wrinkling cases described by Allen

Case I is described by the following model where the face is considered a compressed strut subjected to buckling (fig). When a force P is applied to the strut, a sinusoidal deformation occurs which is counteracted by a reactional force from the foam core.

σ_{cr} is the maximum value of compressive stress in the face at which the core cannot provide enough support against buckling of the face.

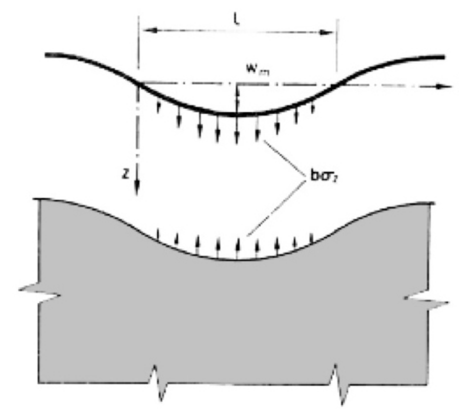


Figure 2.30 - sinusodial buckling of the face, couteracted by elastic medium

The function for critical stress is:

$$\sigma_{cr} = B_1 E_f^{\frac{1}{3}} E_c^{\frac{2}{3}} \qquad (2.14) \qquad\qquad B_1 = 3[12(3-v_c)^2(1+v_c)^2]^{-\frac{1}{3}} \qquad (2.15)$$

Where B1 is the buckling coefficient defined by the Poisson’s ratio of the core vc. The ratio between half wavelength l and face thickness t, which is most likely that wrinkling will occur at is given by:

$$\left(\frac{l}{t}\right)_{cr} = C\left(\frac{E_f}{E_c}\right)^{\frac{1}{3}} \qquad (2.16) \qquad\qquad C = \pi[(3-v_c)(1+v_c)/12]^{\frac{1}{3}} \qquad (2.17)$$

Where C is a constant determined by the poison’s ratio of the core v_c. The formula applies for sandwich elements with thin

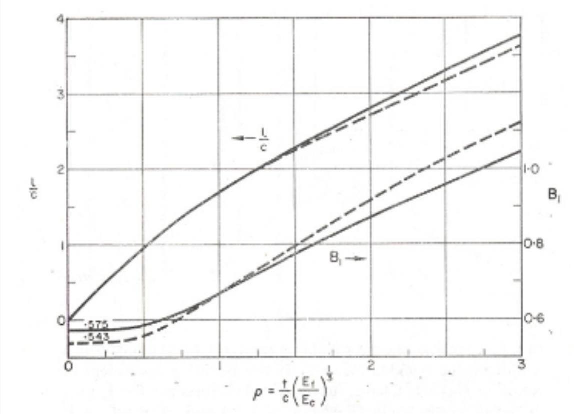


Figure 2.31 - Buckling constant B1 plotted against ρ, for most practical cases in building design ρ<0,25

faces only, which means the following condition is met:

$$\rho = \frac{t}{c}\left(\frac{E_f}{E_c}\right)^{\frac{1}{3}} < 25 \qquad (2.18)$$

The formula is a maximum ratio between absolute stiffness of the face and stiffness of the core. In many practical cases this condition is met, which implies as well that B_1 can be taken as 0,570 for v_c = 0,3 (Figure 2.31). The theory only applies when the face is perfectly bonded to the core material without initial irregularities in the face. The absence of any dimensional parameters in the formula for wrinkling implies that the critical stress value is the same for different layer thicknesses from same materials.

Initial surface irregularities

When the face has initial irregularities an extended formula is needed that implies the adhesive bond failure due to increment of irregularities of the face under compressive stress with a constant *k*.

$$w_{om} = \frac{kc\sigma_u}{E_c} \qquad (2.19)$$

where w_{om} is the amplitude of the initial irregularity c is the core thickness and σ_u the ultimate stress in the interface between face and core, for instance maximum tensile stress in glue.

The function for critical stress is similar but constant B1 get replaced by B2

$$\sigma_{cr} = B_2 E_f^{\frac{1}{3}} E_c \qquad (2.20) \qquad\qquad B_2 = \left\{\frac{\rho^2\theta^2}{12} + \frac{f(\theta)}{\rho}\right\}\left\{1 + k\theta^2 f(\theta)\right\}^{-1} \quad (2.21)$$

where functions f and θ are given by:

$$f(\theta) = \frac{2}{\theta}\frac{(3-v_c)\sinh\theta\cosh\theta + (1+v_c)\theta}{(1+v_c)(3-v_c)^2\sinh^2\theta - (1+v_c)^3\theta^2} \qquad\qquad \theta = \frac{\pi l}{c} \qquad (2.22)$$

When there are no initial irregularities then, k=0. The first term for B2 is equal to B1, for the least favorable half wavelength found in formula ((2.16). This implies that when k=0 the second term of the formula is 1 and the value for B2 is equal to B1. K acts as a correcting factor for the critical stress when initial irregularities occur in the face.

Wrinkling and overall instability ((Allen, 1969), p181)

2.3.2. Structural design Aspects

The design aspects described by Allen result in a minimum core thickness given a certain sandwich element loaded by a distributed load. The design aspects are based on three dominant failure types in building design. The minimum of three values is decisive for the element thickness. The emphasis on core thickness instead of face thickness is made because in building design structural optimum for face thickness often is impractically low. It is useful to look for an optimum core thickness with a given face thickness according to fire resistance or robustness.

Transverse shear failure, face wrinkling and exceeding maximum deflection are considered decisive failure types in building design. Shear crimping and buckling are not likely to occur because sandwich elements will not be structurally loaded in normal direction with other loads than own dead load. Facing failure and flexural crushing of the core are occurring at higher face stresses than wrinkling of the core will. A risk for Local crushing of the core applies at point were the construction is loaded with point loads, i.e. at the supports.

Exceeding critical value face stress

From formulas (2.7), (2.8) and (2.9) the function for minimum thickness according to maximum stress in the face can be derived and written as the following function:

$$h_{\min} = \frac{q \cdot l^2}{8 \cdot (\sigma_{\max} \cdot t \cdot b)} \quad (2.23)$$

The maximum face stress is determined by critical stress from wrinkling.

Exceeding maximum shear stress

In the same way the function for minimum thickness as a for a maximum value for shear stress in the core can be derived.

$$h_{\min} = \frac{ql}{2b\tau_{\max}} \quad (2.24)$$

Only the core material carries the shear stress, stated that sandwich faces are considered thin.

Exceeding maximum deflection

The formula for maximum deflection of a beam is given by formula (2.25). Where w can be substituted by a limit ratio for deflection to length (2.26).

$$w = w_1 + w_2 = \frac{5qL^4}{384D} + \frac{qL^2}{8AG} \quad (2.25) \qquad \frac{10qL^3}{384Ebth^2}\frac{qL}{8bhG} < \frac{w_{\max}}{L} \quad (2.26)$$

In building practice, the ratio is 1/250. Substituting the ratio in formula results in the function for required height at a maximum deflection of 1/250 of the length.

$$h_{\min} = \frac{ql^2}{16bGw_{\max}}\left(1 + \sqrt{1 + \frac{20}{3}\frac{b}{t}\frac{G^2 w_{\max}}{Eq}}\right) \quad (2.27)$$

Optimization of core and face thickness for minimum weight or cost

Total weight or cost of the sandwich element cost can be expressed by the following formula, with u_f and u_c as constants for density (weight or price) of the face and core material.

$$c = u_c h + 2u_f t \quad (2.28)$$

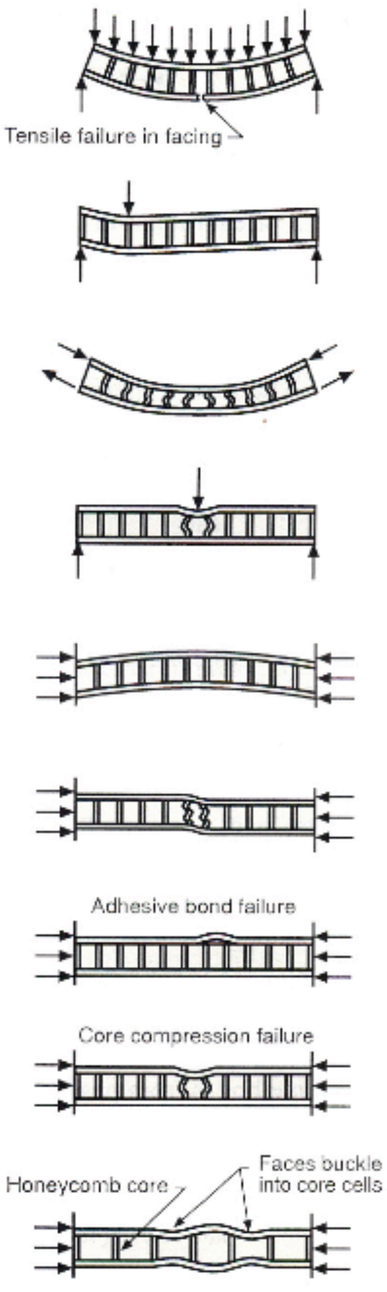


Figure 2.32 - failure types

When a minimum value for bending stiffness D is specified in order to stay within a certain deflection ratio, variable t can be substituted by the formula for D:

$$D = \frac{Ebth^2}{2} \quad (2.29) \qquad c = u_c h + \frac{4u_f D}{Ebh^2} \quad (2.30)$$

minimum value for c, which represents total cost or weight is found when

$$\frac{dc}{dh} = u_c - \frac{8u_f D}{Ebh^3} = 0 \quad (2.31)$$

or

$$h^3 = \frac{8u_f}{u_c}\frac{D}{bE} \quad (2.32)$$

This gives a value for optimum of height h. Ratio weight of the core to the combined weight of the faces is given by the following formula, where h^3 is substituted with previous formula:

$$\frac{u_c h}{2u_f t} = \frac{u_c h}{2u_f} \cdot \frac{Eh^2 b}{2D} = 2 \quad (2.33)$$

which means total weight of the core is twice as high as weight of the face in optimal situation for bending stiffness.

For a minimum value for bending strength according to critical stress value for wrinkling, c is again written as a function of h by substituting t. This time with a function for maximum bending moment given a critical stress value:

$$M = \sigma_{max} tbh \quad (2.34) \qquad c = u_c h + \frac{2u_f M}{\sigma_{max} bh} \quad (2.35)$$

functions for optimum core height and the ratio between core and face are:

$$h^2 = \frac{2u_f M}{\sigma_{max} b u_c} \quad (2.36) \qquad \frac{u_c h}{2u_f t} = 1 \quad (2.37)$$

which means combined weight of sandwich faces is equal to the weight of the core.

For a minimum value of shear strength in an element with thin faces only the shear strength of the core is important. The shear strength of face thickness is considered negligible. The optimum is found in the previous section with minimum core thickness.

2.3.3. Structural behavior Sandwich beam EPS/Epoxy

In order to get an idea of the theory on structural behavior in the context of a sandwich construction in Epoxy and EPS, a calculation is made where variables for young’s modulus, maximum stress and structural load are filled in. An analytical model of a sandwich beam is made with height as a function of length, evenly distributed load, face thickness. The model is based on the design aspects from the previous section and is enclosed in appendix.

Dimensions according to design aspects

The model concerns a simply supported beam with a width of 1000mm. Material properties are chosen from CES database.

Epoxy	EPS Closed cell 0,02
$E = 2{,}75e^4$ N/mm²	E = 7,7 MPa
$s_{t,max}$ = 375 N/mm²	$\tau_{max,eps}$ = *0,31MPa* (Allen, 1969)
$s_{c,max}$ = 280 N/mm²	n = 0,3

For the distributed load a value of 2,0kN/m is used for strength calculations. This value represents a live load of 1,0kN/m2, a combined dead load of the core and face resp. 0,12 and 0,14kN/m2 multiplied by the safety factors for live and dead load. The face thickness is chosen 2, 3 and 4mm, which is considered a reasonable production thickness. Both wind loads and live load of snow accumulation on the roof are taken into account assumed that they are similar in magnitude. Both pressure of wind and snow load can be decomposed in vectors perpendicular to the beam, resulting in vector that is factor *n* larger, but is distributed over an area that is *n* larger as well (Figure 2.33).

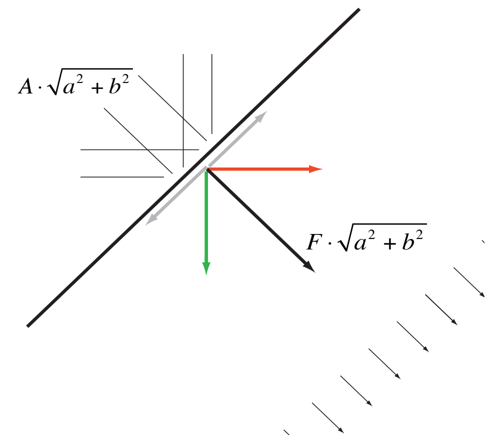


Figure 2.33 - combined magnitude of two orthogonal force vectors on an inclined plane

The minimum height of the core with sandwich faces of 2, 3 and 4mm thick within a range of length from 10000mm to 18000mm is plotted in the following graph:The minimum thickness from the structural design aspects was for all cases a result of maximum bending moment or maximum deflection. Shear stresses never exceed the maximum.

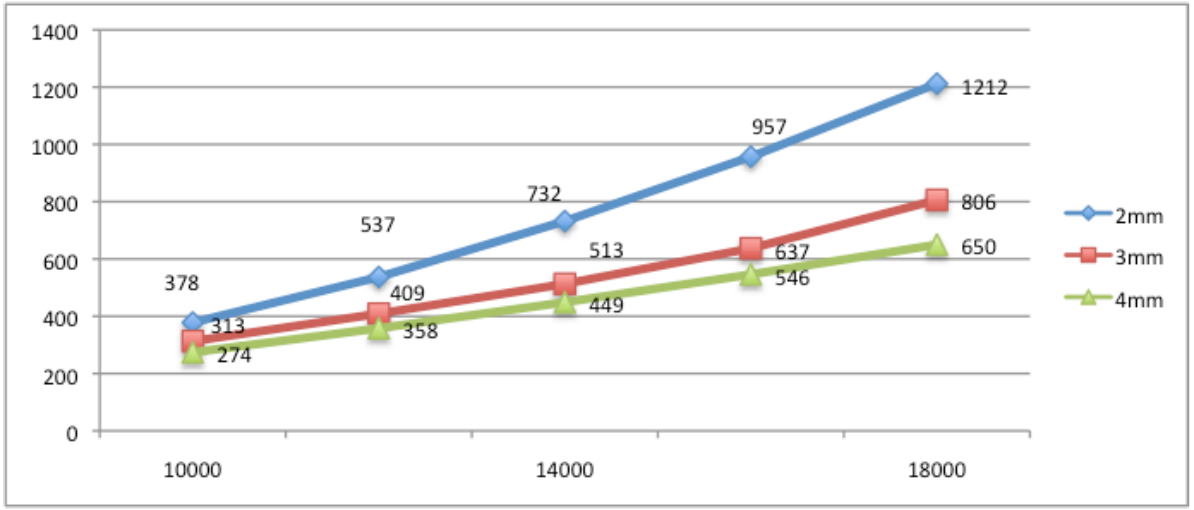


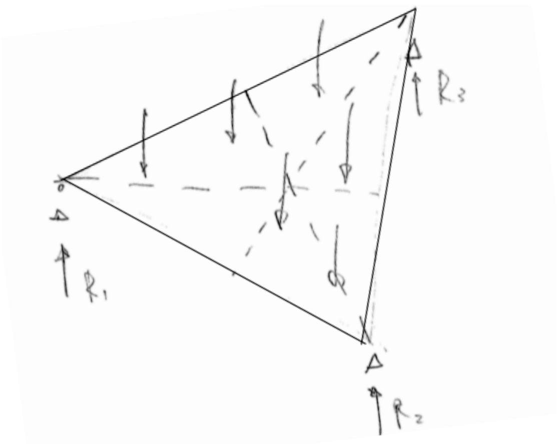
Figure 2.34 -

Cost optimization

The formula's for cost optimization have been implemented in the model as well. Prices for Epoxy and EPS were estimated at €20kg^{-1} resp. €2kg^{-1} multiplied by the density, this gives a price-density uf of €3,7e^4 m^{-3} resp. uc €60 m^{-3}. The optimum is found at a core thickness h of 1345mm and a face thickness t of 1,09mm.

Critical wrinkling stress

Critical wrinkling stress according to formula (2.20) is found at a half wavelength of 125mm and has a magnitude of 48N/mm2. An initial irregularity wm is chosen at 1mm to calculate this critical stress. It is plausible to say that the CNC cut surface were the face is applied on, can be cut within 1mm accuracy without any effort. Therefore the wrinkling stress may be assumed not larger than the found value at the given parameters for sandwich properties.
Notable aspect is that the critical value doesn't change for any change in shape parameters, except for the face thickness.



Shear stress in the core

Beam

In the simple supported beam described above the shear force and thus shear stress peaks are located near the support. The shear force peak is equal to the support reaction given by

$$V = R = \frac{ql}{2} \quad (2.38) \qquad \tau_{\max} = \tau_{gem} = \frac{V}{h \cdot b} \quad (2.39)$$

For a beam with length 14m with the thickness defined by design aspect for maximum deflection, the shear force and stress have magnitudes of resp. 14kN resp. 0,03N/mm2.

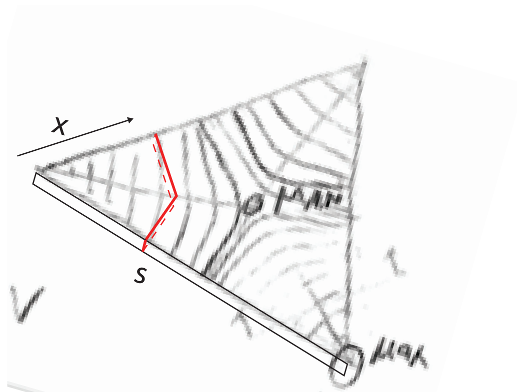


Figure 2.35 - Shear force peaks occur near the supports and is zero in the lines equidistant from the supports

Triangular roof segment

If we consider a triangular segment with equal sides the maximum shear force is given by:

$$R = V = \frac{P \cdot A_{tot}}{3} \quad (2.40)$$

the area expressed as a function of the side *l* is:

$$A = 0{,}25\sqrt{3} \cdot l^2 \quad (2.41)$$

Shear force is 0 at lines with equal distances to the corners. From the neutral lines, the shear force increases linearly to the corners. An indication of the maximum shear force in section S along the side is given by:

$$V_x = R(l) - R(x) \quad (2.42) \qquad V_x = \frac{0{,}25\sqrt{3} \cdot P}{3}(l^2 - x^2) \quad (2.43)$$

The sectional area over which the shear force is distributed given by (2.44) and the shear stress in that section by (2.45)

$$S = \frac{xh}{0{,}5\sqrt{3}} \quad (2.44) \qquad \tau_x = \frac{P}{8xh}(l^2 - x^2) \quad (2.45)$$

The shear stress is equally distributed over the section. When x -> 0, the shear stress becomes infinitely large. With the given thickness from the beam example, at distance x=300mm from the corner the shear stress in section S is 0,32N/mm2, which is larger than the shear stress limit for EPS.

2.3.4. Conclusions

Theory of simply supported sandwich beams loaded by a distributed load provides us with the following design aspects concerning dimensional properties.

$$\frac{10qL3}{384Ebtd^2} + \frac{qL^2}{8bdG} \le \frac{w_1}{l} \qquad [5.21]$$

Samengevat
De benodigde kerndikte d is de kleinste van de drie waarden die volgen uit de volgende betrekkingen:

T.g.v M $\quad d \ge \frac{ql^2}{8bt\sigma_1}$ [5.22a]

T.g.v V $\quad d \ge \frac{ql}{2b\tau_1}$ [5.22b]

T.g.v w $\quad d \ge \frac{qL^2}{16bGw_1}\left\{1+\sqrt{1+\frac{20}{3}\frac{b}{t}\frac{G^2w_1}{Eq}}\right\}$ [5.22c]

The results show the possibility to span 10 to 18m with a sandwich beam within a reasonable range of construction thickness.
The theory is applied to a sandwich beams with a length from 10m to 18m. With predefined face thickness from 2 to 4mm that is loaded with 2kN/m representing dead and life load element thickness varies from 300 to 1200 mm. An optimization of costs within the boundary conditions of strength and stiffness results in a sandwich beam with a height of 1,35 m with faces of 1mm. These values are considered impractical with regard to production process and possible stress concentrations. Critical value for compressive stress in the face with regard to wrinkling is 48N/mm2. The critical stress is not dependent on shape parameters other than the face thickness.

In a simple supported beam, shear stress concentrates near the supports. In a triangular sandwich element supported at three corner points the shear force increases to infinite magnitude with the decrease of sectional area towards the corner.

Concentrations of force at the corners should be avoided.

2.4. Physical properties sandwich construction

Weather resistance

Epoxy has an excellent water resistance (CES 2010). EPS foam however has an open cell structure and will absorb water by capillary action. Therefore it is necessary to prevent any EPS surface from being in direct contact with the outside air. UV resistance of epoxy sandwich face is fair. Coatings are available for improving UV resistance. This can be useful when surface quality is aesthetically poor. Applying a coating requires an extra operation in the production process.

Thermal conductivity

Thermal conductivity is described by Fourier as:

$$Rc = \frac{\lambda}{d} \qquad (2.46)$$

where λ represents thermal conductivity, d the thickness of the material and A the Area. Total resistance of multiple layers in construction is:

$$Rc_t = R_1 + ... + R_n \quad (2.47)$$

λ Value for foam like materials is low because of poor thermal conductivity of polymers and the inclusion of air (For instance polystyrene, λ = 0,04). Thermal resistance is dependent mainly on the core of the sandwich construction. For instance with a core thickness of 0,4m the total resistance is:

$$Rc_{polysterne} = \frac{0,4}{0,04} = 10 Km^2 W^{-1} \qquad (2.48)$$

The value for thermal resistance is high according to Dutch regulations, which prescribe a minimum Rc of 2,5 $K.m^2/W$. The minimum core thickness needed to achieve this value is 0,16m.

Acoustics (nijs, 2009)

Acoustical quality of the sandwich construction comes in two parts: sound insulation to exterior noise and prevent reverberation of interior sound.

Acoustical barrier for exterior acoustical sources

Acoustical resistance is dependent on the amount of acoustical mass and the occurring sound frequency. In general it can be said that the higher the mass, the more acoustical energy gets absorbed. The sandwich roof construction is a lightweight construction and will therefore perform not really good as an acoustical barrier.

m < 200 kg/m2 R500 = 13.3log(10 m)
m > 200 kg/m2 R500 = 15log(4 m) (jellema)

In the context of the OV-terminal Arnhem, large parts of the roof are enclosing the interior space of a railway station. Dutch regulations (bouwbesluit) do not prescribe any minimum values for sound insulation for railway stations.

Reverberation of interior noise

Internal acoustical loads have the disadvantage of long reverberation times or echoing. Especially large public spaces like airport or train terminals have floor paving with high hardness to ensure durability. Hard interior surfaces reflect sound waves, which increases reverberation. When reverberation gets longer than 0,6s (nijs, 2009) in a large public space, it is experienced annoying. Neither a normal sandwich construction nor a steel roof construction has sound absorbing qualities themselves. Additional solutions for sound absorption are added like suspended ceilings or acoustic baffles.

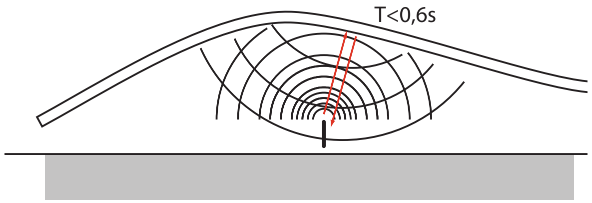


Figure 2.36 - reverberation

The sandwich face is a relatively hard and close material and is not very well performing in sound absorption. The foam sandwich core however, is relatively soft and has open cells when mechanically machined. A common solution to decrease sound reverberation is to add foam surfaces to the interior. Possibly making holes in the interior sandwich face can add to the absorbance value.

2.4.1. Thermal expansion

Temperature differences cause materials to expand or crimp. These deformations can cause internal stresses that lead to damage or unwanted esthetic effects like wrinkling or warping. In building design the unwanted effects of expansion are commonly avoided by implementing expansion joints at a regular interval that allow the material to deform.
Linear expansion is described by fomula (2.49)and the expansion coefficients of the used materials are given below. *L* is the initial length and *T* represents the absolute temperature.

$$\alpha_l = \frac{1}{L}\frac{dL}{dT} \qquad (2.49)$$

$$\alpha_{EPS} = 7{,}0 \cdot 10^{-6}\, m/mK \qquad \alpha_{epoxy} = 8{,}64 \cdot 10^{-6} - 3{,}3 \cdot 10^{-5}\, m/mK$$

Thermal expansion of the outer face of the elements causes differences in size between summer and winter situation. Given the stated temperatures of 50°C in summer and -10°C in winter, the temperature difference is 60°K which results in differences in length of 0,48mm/m to 1,98mm/m.

Thermal warp

Thermal loads less influence isotropic materials than layered (sandwich) elements. High thermal resistance of the core material and differences in indoor and outdoor temperature, cause unequal thermal expansion of the inner and outer face. Unequal expansion of two faces of a sandwich element results in curving of the panel. Interior and exterior face temperature in summer situation are stated at 20°C resp. 50°C or a temperature difference of 30°.

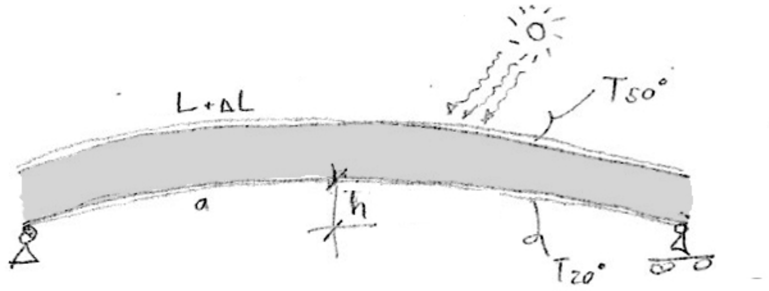


Figure 2.37 - Heat load by solar radiation

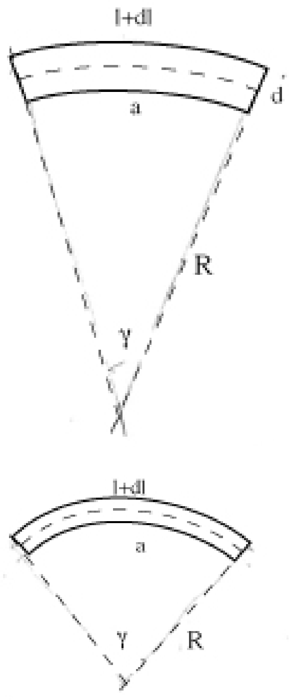


Figure 2.38 - curvature increases if top face expands

Besides that a situation with negative difference of 25° between inside and outside (resp. 20° inside and -5° outside) temperature in combination with snow load on the roof has to be considered. Additional deformation of roof occurs with snow load.

The following model describes the deformation of the panel: two faces form the segment of an arc. Expansion of the outer face (*l+dl)* relative to the initial length at 20°C results in an increase of radius R. In the initial state the two faces are equal in length, R is infinitely large and the panel in considered to be flat.

relation between arc length and radius for both the inner and outer face to angle γ:

$$\gamma = \frac{l}{R} \quad (2.50) \qquad \gamma = \frac{a}{R-d} \quad (2.51)$$

This can be rewritten as formula that gives a value for the radius at a certain temperature for the outer face**.** The radius can then be used to calculate h_{midden}, which represents the deviation in height from the initial state.

$$R = \frac{d}{1-a/l} \quad (2.52) \qquad R + \Delta R = \frac{d}{1-a/(l+\Delta l)} \quad (2.53)$$

$$h_{midden} = R - \sqrt{R^2 - (a/2)^2} \quad (2.54)$$

The angle of rotation at the end of the curved beam is equal to half the arcs central angle.

$$\gamma = \frac{l-a}{d} \quad (2.55) \qquad \gamma + \Delta\gamma = \frac{(l+\Delta l)-a}{d} \quad (2.56)$$

In order to understand the practical use of these values the variables can be substituted with values from the design context. A sandwich beam with thickness 450mm, derived from the structural aspects in section, is considered to get an idea of the magnitude of the deformation of a sandwich beam in relation to its length. As a measure for maximum displacement of a point in a beam, the limit of usability for roof structures, (gerrits, 2006) is used. With the given expansion coefficients and a temperature difference of 30°, the height deviation at the centre of a sandwich beam in relation to its length is given by the following graph.

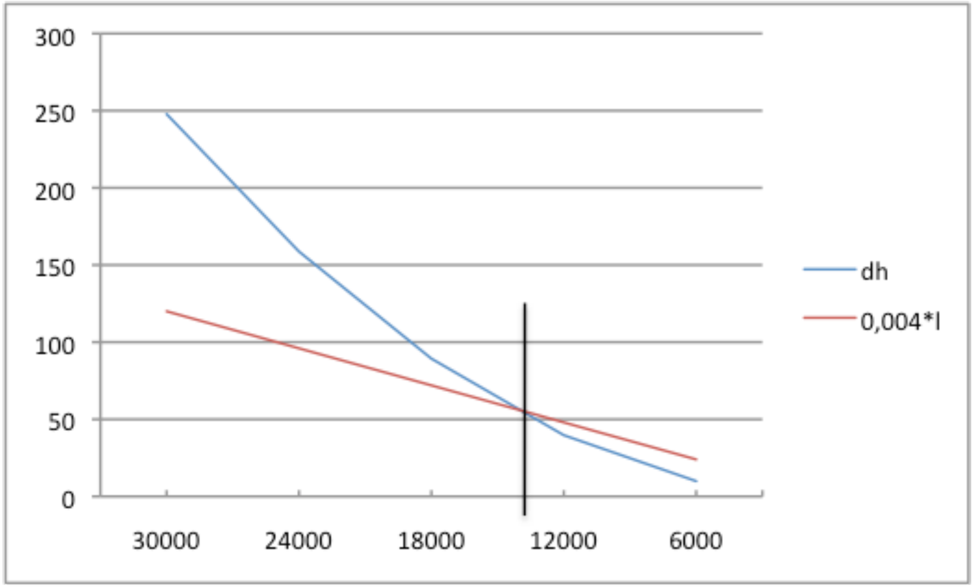


Figure 2.39 -

A decrease in length results in a smaller deformation. The maximum deviation of Elements up to 14m in length keep within the deformation limits. Apart from usability limits, the deformation of sandwich constructions the curvature affects the visual continuity of the surface as well. The angle of rotation at the end of the element causes a kink in the surface. Elements of 14m in length have an angle of rotation of 0,04rad or 2,7°. A smaller element results in a smaller angle of rotation.

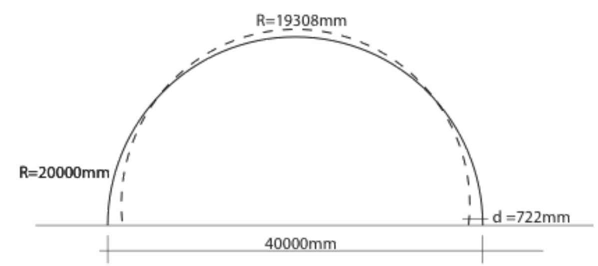


Figure 2.40 - theoretic curvature with circluar span of 40000mm

Single span

Because no discontinuity in the curvature of the roof occurs, a cylindrical roof structure spanning 40m at once, with thickness 450mm is considered. The structure represents the tunnel shaped roof of OV terminal Arnhem. Assumed that the length change of the outer face (*dl)* causes deformation in one direction the radius decreases to 95%. Without a change in arc length, this leads to the following deformation.

With a single span a translation of the base of 722mm has to be possible, which is not a realistic value. Retaining the deformations in the sandwich construction causes high stresses in the sandwich face and core. Retaining of the strain of the outer face causes stresses given by:

$$\sigma = E\varepsilon \quad (2.57)$$

$$\varepsilon = \left(\frac{\Delta l}{l_0}\right) \quad (2.58) \qquad \sigma = E\left(\frac{\Delta l}{l_0}\right) \quad (2.59)$$

With a temperature difference of 30°, retaining the deformation results in stresses in the face of 13 N/mm2. The stress is carried to the face by the foam core. The core will separate from the face by this stress. A single span cannot be applied this way.

2.4.2. Fire-safety

All construction elements that are exposed to outside air have to meet at least Euro Fire class D. Parts of a building higher than 13m have to be in Fire class B because these parts will be out of reach for the fire brigade. Also when a building has a residential area with a floor higher than 5m, the first 2,5m have to meet fire class B (Nen6065). Fire class B is a classification for materials that are almost not inflammable and add poor to internal heat load caused by fire. Dutch building regulations demand higher class A only for safety routes.

Flame retardant can be added to the EPS to make it almost inflammable and performing good enough for fireclass B (stybenex). Compared to EPS sandwich with steel faces composite faces add more to internal fire load. Despite that face material will define minor part of fire safety class, because of its small absolute mass compared to the EPS core. Besides that, Epoxy is classified as a slow burning material (Edupack, 2010) .

Dripping and smoke development are considered important property in fire safety as well. The smoke development of a material is particularly important when applied in safety routes. In the design context of the roof of the Arnhem OV Terminal, the construction is completely in contact with the outside air, which means smoke can be ventilated away.
Dripping regards the burning drops of material in particular that can form a risk in spreading of the fire. EPS foam with the right flame retardant will drip, but the drops will not inflame. The drops have no influence on the spreading rate of the fire. Epoxy is a thermoset and will not melt.

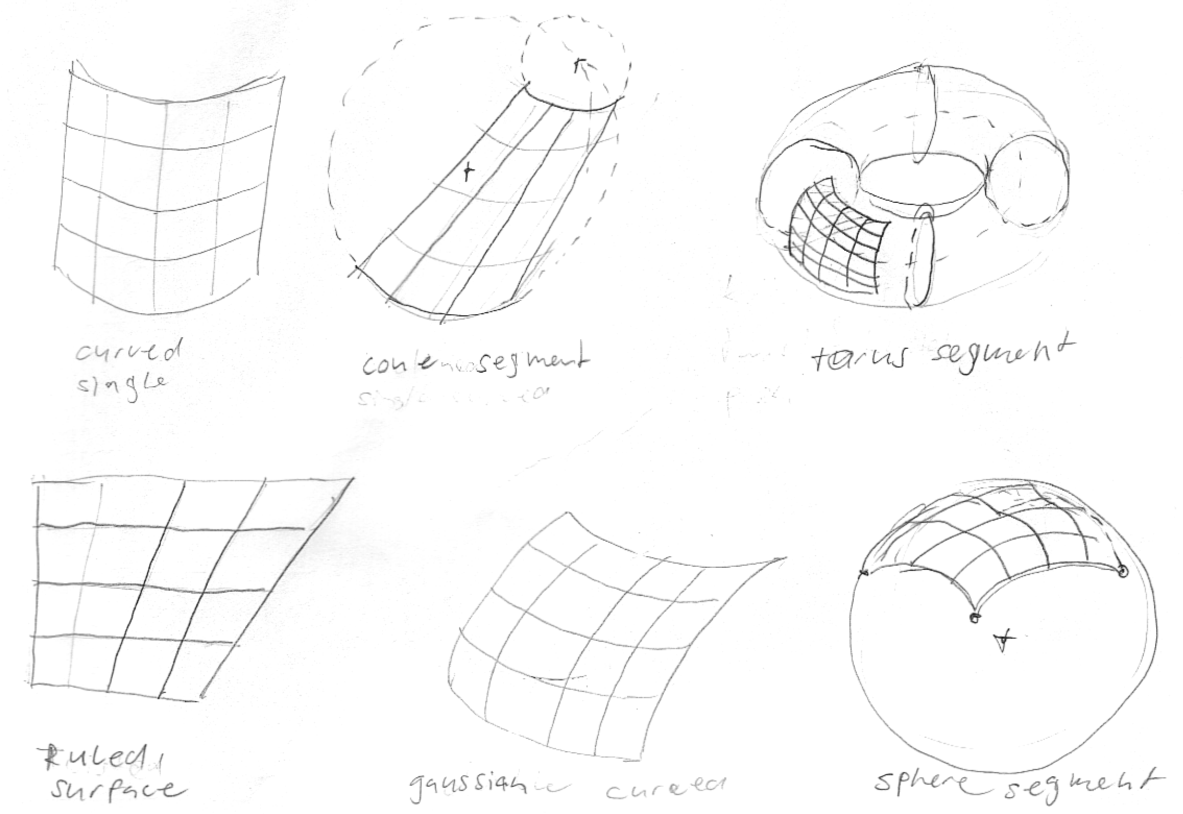
Conclusions
European fire safety class B1 can be achieved when flame-retardant polystyrene is used. Because this design concerns a building part that is not part of a safety route, the concerns of fire safety are limited. The roof concerns a large exterior surface; developing smoke is directly ventilated by outside air. Drops that leak through the face will be extinguished by the flame-retardant. Melting polystyrene causes sandwich element to disassemble, which has structural possibilities.

2.5. Production aspects

In this section the aspects related to the production process are discussed. Production aspects that are considered form a limiting framework to the design. The possibilities within the context of the production are explored. This concerns the production of both the freeform core as the application of the faces to the core.

2.5.1. Analysis of freeform Surfaces

Possible surface configurations in freeform architectural surfaces are generally described in the following image.



Surface types

1. flat
2. single curved/ cylindrical
3. double curved (regular)
    1. sphere segment
    2. ruled surface
    3. cone segment
    4. torus segment

5. saddle/ Gaussian curvature
4. irregular curvature

2.5.2. CNC wire cutter

The CNC wire cutter can be used to cut surfaces to certain extends in geometrical freedom. The CNC wire cutter is able to cut out any shape described by two paths, which can be imagined as a lofted surface between two curves. The machine works by a double XY-coordinate system or two working plane where the wire spindles can move on. The system is referred to as 2,5D for its limited possibility to work in the direction perpendicular to the working planes. A heated wire between the spindles melts the material to be cut. The spindles can move independently by two predefined paths.

The surface shapes that can be cut extend to flat surfaces, single curved surfaces and simple double curved surfaces. When two identical paths are defined for the spindles the machine will cut simple extrusions or tapered shapes when the paths have a different scale.

All shapes cut out by the CNC wire cutter can be reduced to ruled surfaces, because a straight line connects the subsequent coordinates of the spindles. Characteristic of a ruled surface is that every surface curve between two points on opposing edges at an equal period of the edge length is a straight line.

Figure 2.42 - CNC wirecutter (www.CNC-Multitool.de)

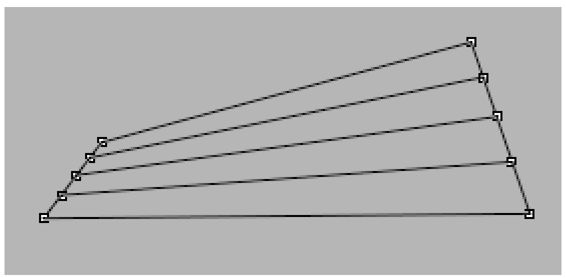


Figure 2.43 - ruled surface, points are at the same period at the opposite edge curves. Connecting them results in straight lines

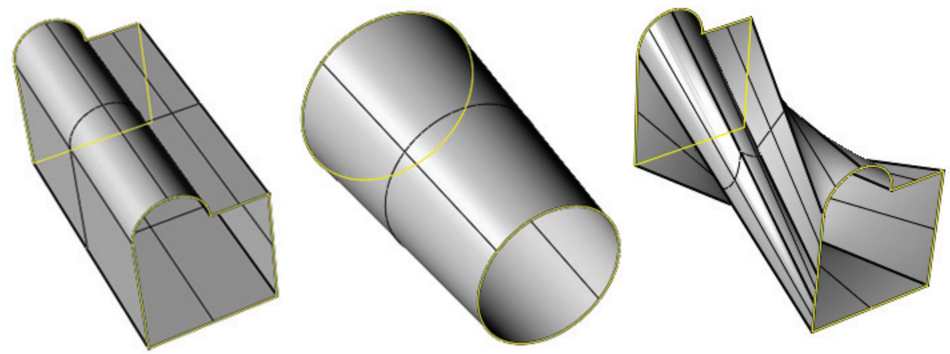


Figure 2.44 - extrusion, tapered loft and irregular surface (occurs when spindles have a different strating position)

An important aspect of the wire cutter is that the cutting speed of two unequal paths cannot be equal. With tapered objects the smaller path has to be followed in the same period as the larger path. Besides that, there could be points that the spindles need to arrive at simultaneously, such as corners, or start and endpoint. In some cases this asks for variable cutting speed along the length of a path.

The movement of the spindles is limited to the extends of the working planes. The low level of complexity however makes it possible to alter the machine for its needs. The distance between the spindles can be adjusted by moving the working plane and the guides and threaded rods longer ones can easily replace, which increases the reach of the spindles. The socket to place the model on can be replaced by a smaller one or other components to clamp the work piece.

Bulk sizes for EPS are limited to 5,0x1,2x0,5m. However sizes can easily be extended by combining blocks together.

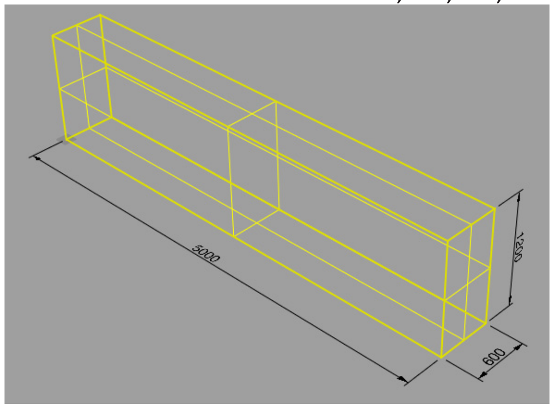
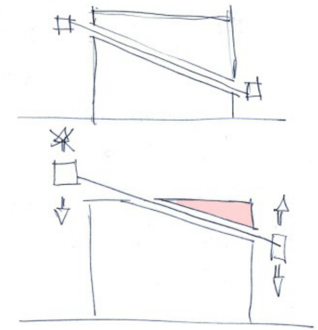
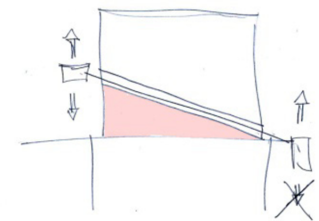


Figure 2.45 - bulk size material





A conversion between geometrical data and machine instructions is needed; often this step is done by machine specific software. In case of the wire cutter the machine instructions consist of two series of coordinates controlling both spindles in x and y translations which is also referred to as Gcode. The software for the used CNC wire cutter has limited possibilities, in the interface. Two paths need to be drawn or imported which define the movement of the spindles.
In order to have more control over the paths and independent speed of the spindles an algorithmic model is made which directly generates the Gcode for any element that can be described by two surface borders. This model is further explained in Appendix.

Model handling
Every manual step in the production process is submissive to possible inaccuracy and is expensive compared to automated processes. Options for refitting a work piece into the machine will extend the machine's functionality, but also needs an additional operation. Best is to machine a work piece without the need to manipulate the work piece manually. Rotation of the work piece extends the abilities of the machine to an additional working plane.

Hot wire temperature
The CNC hot-wire cuts trough the EPS foam without physical contact. A melting pool that is generated by the wires heat, precedes the wire. This means that foam is melted away rather than obstruct the wire in its path, if the wire is hot enough. The width of this melting pool or melting slot has to be implemented in the algorithm that generates the cutting data.
Cutting by two different paths for the spindles results in different processing speed. At path segments where the wire speed is higher, less heat is accumulated and less material is melted away. This results in different cut width.

EPS glass temperature is at 82°-92°C. Heating of the wire is dependent on resistance of the wire described by the following formula's, and the power generated by the electrical current.

$$P = I^2 \cdot R \quad (2.60)$$

$$R = \rho \frac{l}{A_{wire}} \quad (2.61)$$

P refers to the power that is lost due to heat production, and thus the heat that is generated by the wire. In the cutting process, there is a balanced state of heat transfer between the wire and its surrounding. Because the wire is moving trough the material by different cutting paths, the part of the wire inside the material is of variable length. This length change could also be implemented in the algorithmic model. The effect caused by this aspect is expected to be very small and besides that, external factors like convective airflows would influence the temperature as well.

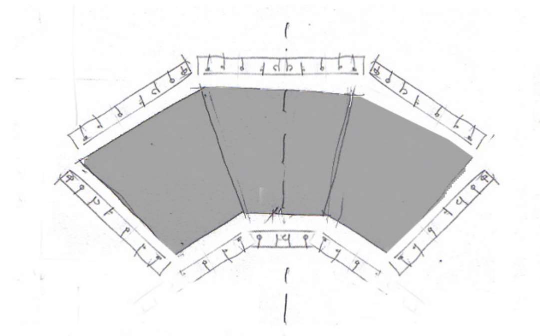
2.5.3. Referencing

The philosophy behind CNC machining is partially based on the principle of using geometrical data. An aspect CNC production in general is that a tool of any kind is moved according to a tool path based on a set of geometrical data points. The data set is extracted from a master model that describes the overall geometry. The CNC machine is using this data to move he tool to specific points in space, based on the master geometry model, which are automatically referenced to one another as a consequence. This implies that physical reference points are exactly conform the virtual model. If the production concerns a series of construction elements, the points or lines on one element that are shaped by the CNC machine, can serve as a reference for adjacent elements.
A consequence is that this takes away a major part of referencing or measuring in both the production process and the assemblage of the products on site.

2.5.4. Face application and accuracy

The face will be applied with vacuum injection moulding, using the foam core as an internal mould.
The accuracy of the applied face is of importance because the geometry of the construction determines its shape, reference points from the CNC core manufacturing should not be diminished by an inaccurate sandwich face.
In order to get the right amount of accuracy in the system the elements should be highly accurate at their reference points. The application of the composite face material can cause inaccuracy to occur due to some production aspects.
Deformation of the EPS core can occur because of vacuum pressure. The possible deformations are a combination of warp caused by surface tension of the vacuum Foil, which is referred to as 'Stretch effect' and overall shrinkage under the vacuum pressure.
The deformation is mainly dependent on an interaction between Young's modulus of the face, difference between atmospheric pressure and vacuum pressure and the tension in the vacuum foil caused by the pressure difference (fig).

Spring resistance glass fibre
Thickness of the face is dependent on the spring behavior of the glass fibres. The number of layers and thickness of glass laminate under the vacuum pressure is equal to the final thickness of the face. In theory higher pressure makes the face thinner.
The production aspects related to the vacuum injection technique are tested for their magnitudes in chapter 4.2.



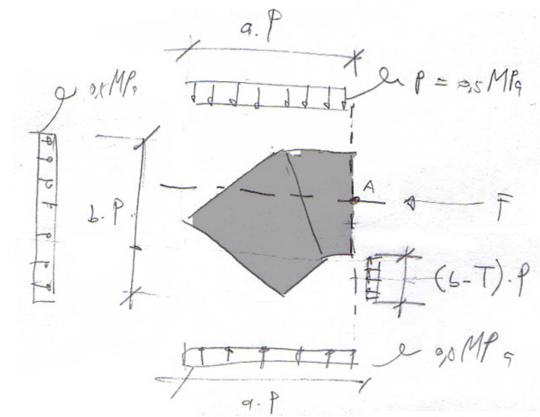


Figure 2.46 - vacuum pressure acting on the foam core of an injected sandwich element.

2.5.5. Transportation

Transportation sizes are limited to the size of a truck. Maximum vehicle size for road transport on trailers is restricted to width height and length of resp. 2,55m, 4,0m and 12,0m measured from the kingpin (pivot) of the trailer. Maximum load size of a standard trailer is chosen as a guide for maximum sizes, because the elements need to be transported from the production facility to the building site. The maximum size of a standard trailer is 13,6 x 2,55m x 3,0m (*l x w x h*).
When necessary the limits can be extended by using low-loader transport with extended length, width or height up to resp. 24,0m, 3,0m and 3,5m. There are however a license suspension and escorting vehicles needed.

Figure 2.47 - trailer (www.bostrailer)

2.6. Conclusions/summary

Besides the functional requirements for a façade, the design aspects from the previous section have to be taken into account.

Geometrical freedom with CNC wire cutter is limited to ruled surfaces. Limits have to be taken into account when designing the elements. Implementation of reference points in the elements is a key aspect in the efficiency of the system because it overrides a part of conventional measuring. Limits of the production size are not Size is limited to transportation size of 3,0x13,6x2,55m.

Design context

- Minimize interference with internal space
- Curvature radius > 20000mm for 80-90% of the roof

Structural aspects

- Maximum span 10-18m with variable thicknesses
- Maximum compressive stress at 450 mm core thickness is 48N/mm2

Physical aspects

- Expansion joint needed every 14m

Empirical research is needed for determining magnitude of several production aspects in order to be implemented in the algorithmic model generating the machine instructions

- width of melting slot
- influence of cutting speed on melting slot
- magnitude of the initial deformation
- deformation of the element due to face application techniques

level of control over thickness and accuracy in vacuum injection technique

3. Design

3.1. Subdivision and element geometry

Subdivision of the reference surface is needed because of size limits derived from structural, physical and production aspects. Several options for subdivision are discud=ssed in this chapter.

Requirements

- maximum span length within the range of 10-16m
- minimum interval for expansion joints, 12-14m
- transportation, max 3,0 x 2,5 x 13,6m

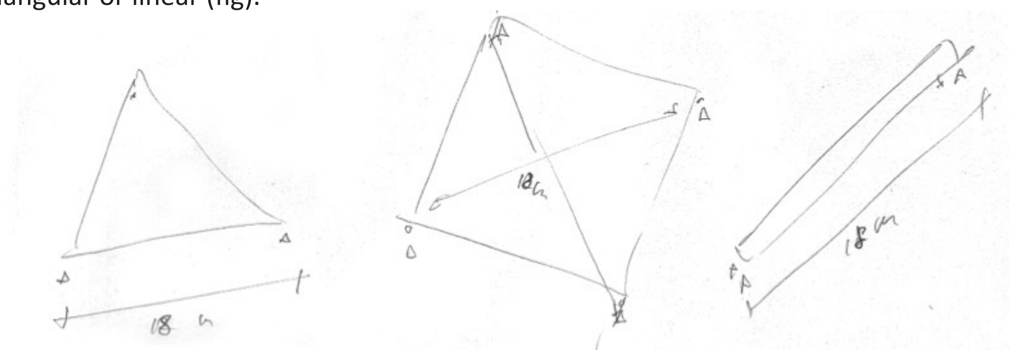
A range for maximum span and minimum interval is given, because values depend on dimensional properties, which still may vary at this stage of the design. The range can be regarded as a guide.

Production
A production aspect of major importance is the need for conversion of the reference surface in elements of uniform shape based on equal shape parameters. The uniformity is the most suitable for algorithmic generation of element geometry.

Design context
Minimize interference with internal space. In other words: minimize the addition of construction elements to the internal surface of the roof. This only concerns construction elements that are in sight. Construction elements inside the roof structure are considered not interfering.
This aspect is of course subjective to a designer's interpretation of esthetic demands and the visual effect he wants to elaborate. He might want to emphasize construction elements. However, it is possible to state that whenever the construction can be made without emphasized construction, it is not difficult to add one. This statement is not reversible.

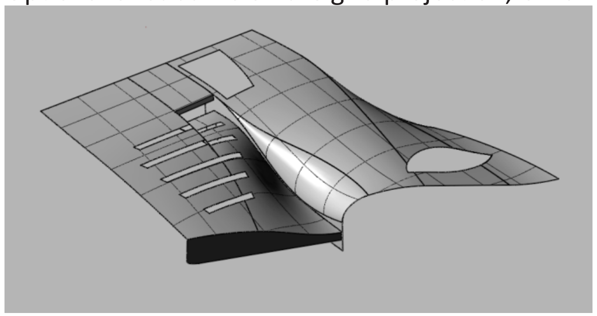
3.1.1. Design principle

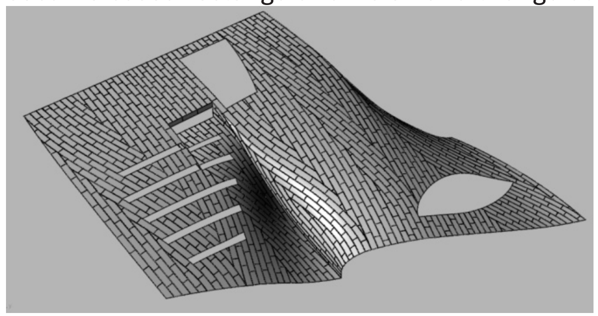
The minimization of construction elements together with the size limits for transportation make it plausible to construct roof segments from combined sandwich elements. The roof segments have the maximum spans and the sandwich elements stay within the transportation limits. 14m segments build up of four elements along the length. These elements can be square, triangular or linear (fig).

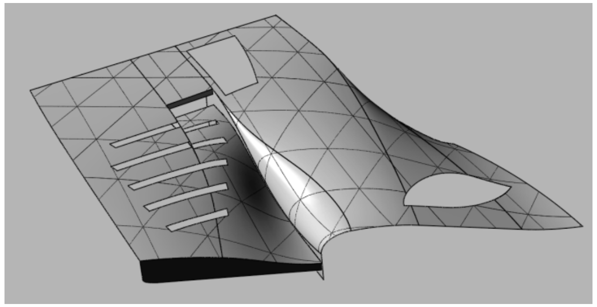


3.1.2. Segment division

Options for subdivision are grid projection, UV or isocurve based rectangular division and triangulation.







The segments are self-supporting over a span of 10 -16m, derived from the design aspects. The segments are subdivided in smaller elements.

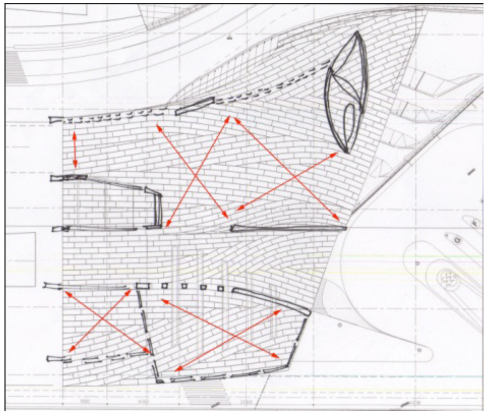


Figure 3.1 - single span or mutidirectional span

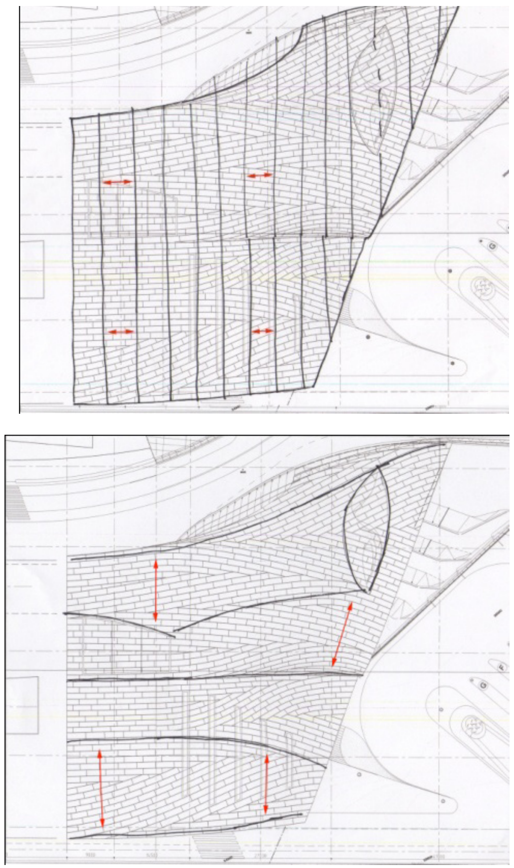


Figure 3.2 - linear span a. longitudinal (top), b. transversal (bottom)

Support Types

Three options for spanning the roof construction were considered. The spanning principles are based on present construction elements in Un studio's initial building design figure

Considered options were
1. linear span on linear supports
2. multidirectional span on point grid

Single Span

Single span is the purest form of spanning. The only support is from the construction elements in the initial design. Howerever physical aspects showed the effects of thermal warp make a single span impossible. Besides that Compressive forces of 200N/mm2 occur in the face with a thickness of 450mm (Appendix)

Linear span

Linear elements can be placed in two main directions. In the direction of the front opening of the building, which will be referred to as longitudinal spanning or in the direction of the roofs arc, which is referred to as transversal spanning.

The longitudinal elements (Figure 3.2a) are simply supported by beams perpendicular to the elements. Longer spans results in higher structural demands for the sandwich elements but reduces the number of beams needed and vice versa.
The beams have to follow the shape of the roof and thus have to be custom made as well. Also the beams will add to the construction height. Stated that the beams span from the initial supports, the spans will be 36m in length at max. Quick analysis using rules of thumb indicates a beam height of 1/30th the length (Gerrits 2006), which mean a construction height for the beam of 1,2m.

The transversal elements (Figure 3.2b), also simply supported two sided by beams, span from 15m to 20m in length. The elements have to span at least 15m, so there are little possibilities to vary construction height. Additional beams in longitudinal direction are needed to support the elements in the higher part of the roof.

Point support

Point support implies that the structure supports itself as in the single span. Two considered options for the point support grid were a rectangular or triangular grid. The rectangular grid however is considered not useful for freeform structures in general, because the strong regularity does not stroke with irregular freeform shapes. In the case of the OV terminal the internal planning as well as the appearance are better served with a triangulation.
Placed outside the context of the study case OV terminal, triangulated elements on point supports offer the flexibility that they can be used in radial support configurations and rectangular configurations as well.
A major advantage with point support is that the only the height of the columns have to be customized or variable. The surface geometry is formed with sandwich elements produced in a single CNC production process. Compared to the custom made curved beams needed with linear support this is more efficient.

Conclusion

In both linear spanning cases the interior space is free of columns, but beams with severe construction height have to support the roof. That is in case that the beams are not supported in any place. The linearity of the transverse beams in the first case do not stroke with the fluent shape of the roof. The beams have to be constructed in order to follow the buildings envelope.
Triangulation is preferred because of its flexibility in support. Either linear, radial or orthogonal support grid is possible. This is in accordance with the flexibility of the system, especially when regarding it outside the context of the OV terminal Arnhem. Within the design context a column grid based orthogonal projection is considered most interfering with the internal space. Besides that, the orthogonal expansion joints would not correspond with the characteristics of the freeform surface. However, in order to keep options open in for application outside the design context the orthogonal projection will be regarded concerning the other aspects.

3.1.3. Element geometry

The different division methods are compared with regard to the production aspects and the surface approximation. The elements have a thickness, in accordance with the thickness found in section, which means it concerns volumes instead of the surfaces regarded until this point.

Triangulation
Any freeform surface can be segmented in triangles by connecting the nodes of a hexagonal point grid on a surface. The triangles are always completely flat because they are part of a plane defined by three points. An offset of the reference surface can provide a second set of triangles representing a surface. The two sets of triangles form the base and top of a set of triangular prisms (fig).
Characteristics are that the top and base surface of the prism are flat and the sides are twisted (ruled surfaces). The sides are twisted because the vertical ribs that confine the sides are not in the same plane. The sides automatically fit to adjacent elements, defining a surface.

Orthogonal grid projection
The orthogonal grid projection is the most simple division type in regard to element geometry. The reference is offset to give it a thickness. World x, y and z planes are intersected with the reference surface and offset forming elements. The base and top surfaces are non-planar quads, forming the approximation of the inside and outside of the reference surface.

LOM
Rectangular elements as in the initial design of UN studio have five sides (top, bottom and four sides) that have to be custom shaped. According to the production aspects of chapter 2.5, this is not desirable within the wire cutting process.
An alternative technique is called Layered Object manufacturing. The reference surface and an offset of it are intersected by planes perpendicular to the centroid of the principal curvature (fig). Sectional strips with a predefined thickness are formed, which can be cut into smaller elements. In fact it is a mediate between orthogonal projection (of lines) and surface.

Production
The EPS elements are compared with regard to the CNC cutting process, which has its shape limits. Besides that, uniformity of the elements is preferred for making an algorithmically generated machine code.

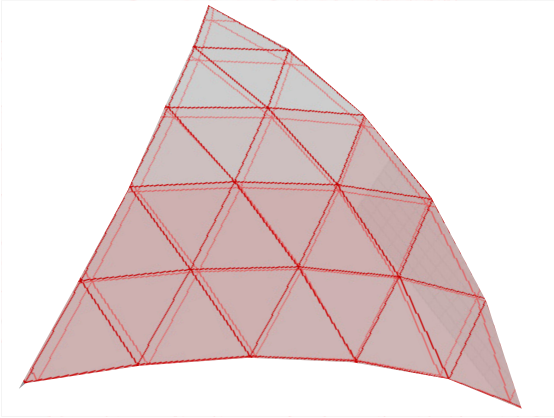


Figure 3.3 - Division by Triagulation

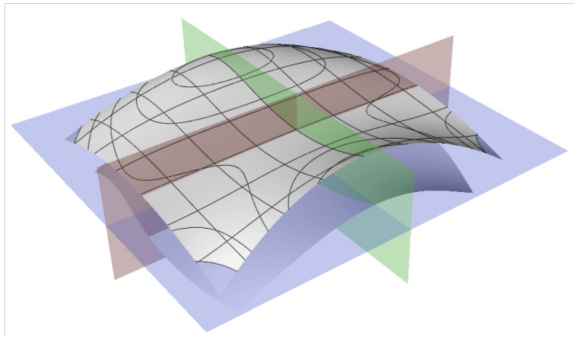


Figure 3.4 - division by othogonal projection

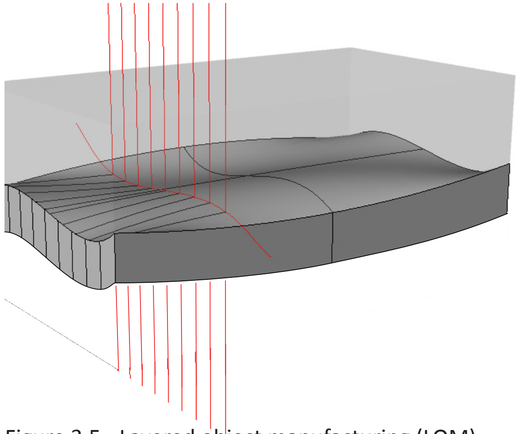


Figure 3.5 - Layered object manufacturing (LOM)

The orthogonal grid projection requires different element types. Most of which are, depending on their position on the reference surface, a vertical or horizontal projection of a square (or rectangle). This implies that they can be cut from square section EPS beams. Where both the interior and exterior face can be shaped within the limits of the CNC machine, the ruled surface.
Triangular elements with a flat base and top surface cut out of a plate with constant thickness. The thickness is equal to the core thickness needed for the roof construction. Only the three sides are machined In the triangulation, all the elements are uniform and all element sides are CNC cut. This makes the triangulation very suitable for algorithmic division. All sides are cut in similar way, which makes it possible to implement a systematic operation for referencing and connection elements.
When the base plane of the element (Figure 3.7, red) is referenced, three other sides can are referenced as well (green) . Both the surfaces, and the borders and vertices confining them are exactly accurate. LOM strips can be cut out of a plate with a predefined thickness just like the triangular prisms. The strips can be defined by two paths, which is in accordance to the production aspects. The exterior and interior surface and two of the four sides are cut out. The remaining sides are flat.

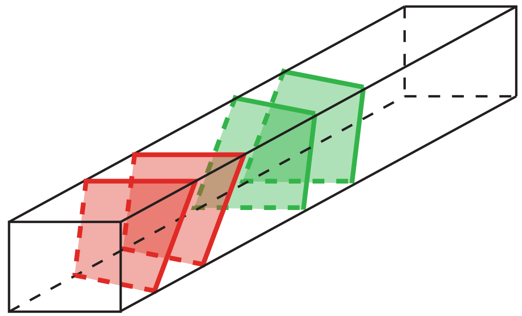


Figure 3.6 - othogonal elements cut from beam elements

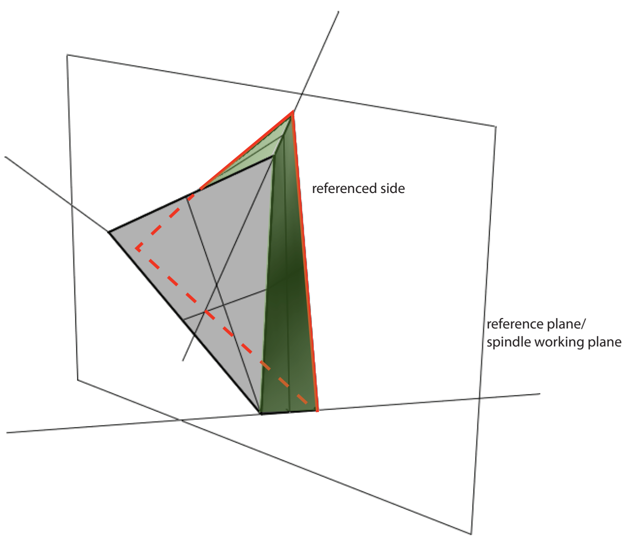


Figure 3.7 - referenced faces when raw material is placed against a reference plane in the cutting mahine

Uniformity

For production aspects concerning the CNC wire cutting, the main difference between division methods: orthogonal projection and triangulation, shows in the following image (fig).

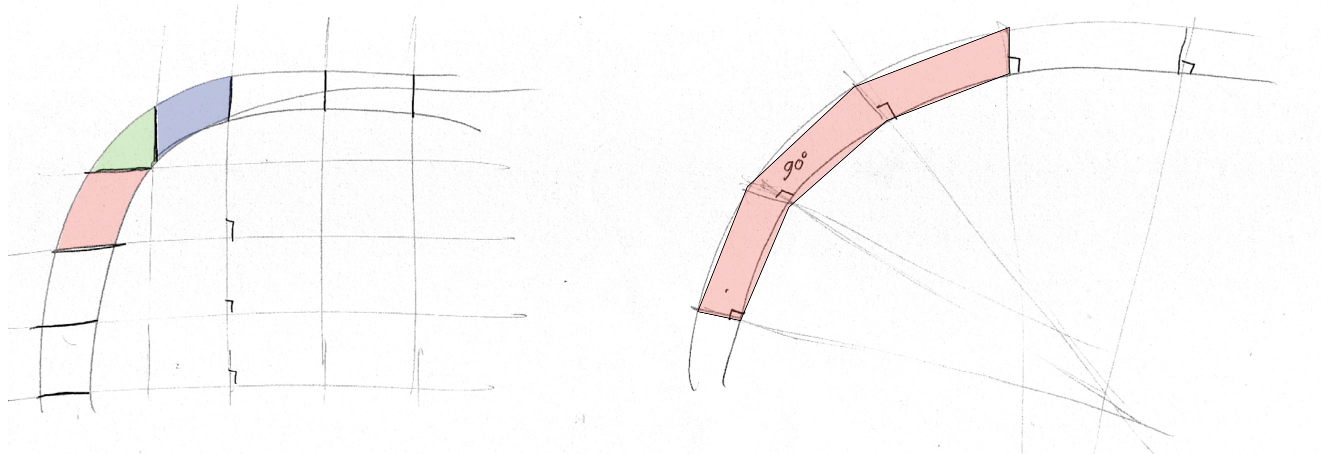


Figure 3.8 - uniformity of elements, right orthogonal, left triangulation

In the orthogonal projection method, there are elements in the transition zone (Figure 3.8, green) of more vertical regions (red) to more horizontal regions (blue), which are a combination of horizontal and vertical projection and the in- or exterior surface. The element could become quite small if the volume of the roofs surface is just outside a grid cell.
The machining instructions for the LOM Elements can be constructed using the same algorithm for each one. The strips are cut at the top and bottom side and on two of the four sides. The two remaining sides are flat. This implies that an inconsistent solution for connections and referencing has to be found, for the two different types of sides.

Approximation quality

The top and base surface remain flat, giving the surface an segmented appearance. Surface is approximation is poor com-

pared to the other solutions, because the reference surface is segmented in flat faces.
Surface approximation is really good in the direction of the sectional planes. The curvature can be exactly followed. It is segmented in the other direction and the quality depends on the ratio of the curvature to the strip width.
The surface approximation with orthogonal grid projection is slightly better then the triangulation, because the ruled surfaces forming the top and bottom surface are double curved and not flat. However, the edges describing the ruled surfaces are straight showing the segmentation.

The surface approximation is important to get a smooth surface, however the analysis in section 2.2 has shown that an estimated 90% of the reference surface has a curvature radius of > 20000mm and is considered relatively flat. With both the triangles and the lom strips, the segmentation size can be adjusted to the curvature magnitude, making it more dense at higher curvatures for better approximation.

Conclusions
From the comparison it gets clear that the three options have different advantages. The Surface approximation quality with flat triangular elements is less than the other methods, though the actual curvature of the roof is small 90% of the roof. Most important advantages of the triangular division is:

- Uniformity corresponds with methods for algorithmic modelling
- Relation between cutting length and actual curvature values most efficient
- Potential in production concerning construction and referencing of connections

With all division methods, a higher subdivision leads to a better surface approximation. In particular the segmented surface of the triangulation improves in quality. Accuracy of production will determine the quality of the shape of a segment.

Regions were the curvature radius is smaller than the thickness of the roof construction cause self-intersecting offsets to occur. A chance for the subdivision the subdivision algorithm is to implement a correction for structural deformation of the construction caused by dead weight.

3.1.4. Subdivision and refining method

The method for subdivision is making a mathematical subdivision of a surface. This subdivision constructed from lines and surfaces can have many forms and is called a mesh. Meshes are generally used in 3D surface models to make a representation of a mathematical surface with face segments(Pottmann, 2007). This makes a 3D surface better usable for calculation purposes. For instance it is easier for virtual image processing or Finite element analyses. A key aspect is its use of mesh refinement for optimal surface approximation, which uses the least amount of segments, needed to meet the specified requirements. Therefore it can also be used to create a production subdivision.

Rhino meshing engine was used with maximum distance edge-surface parameter h set to 20mm. When deviation exceeds limit value, mesh is made more dense. Edge length of triangles varies from 200 – 2000 mm.

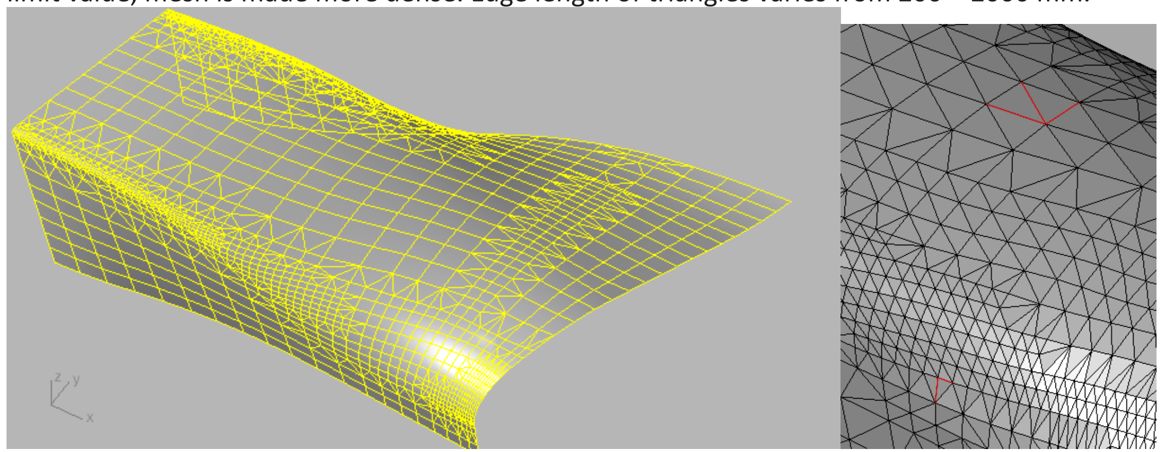


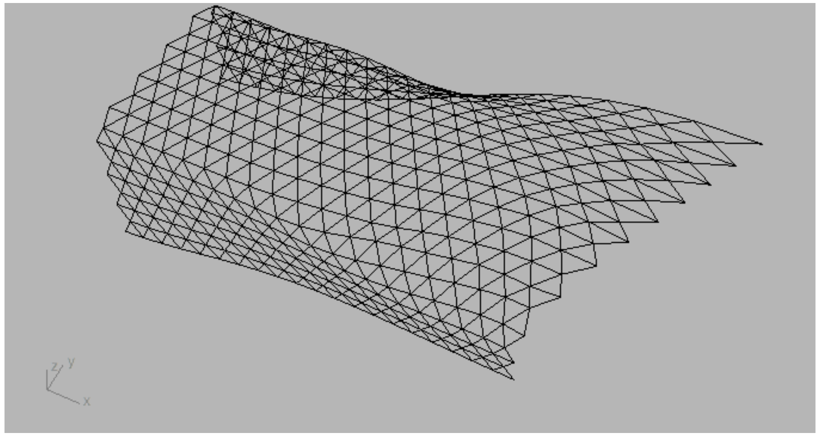
Figure 3.9 - Surface mesh generated by Rhino meshing engine

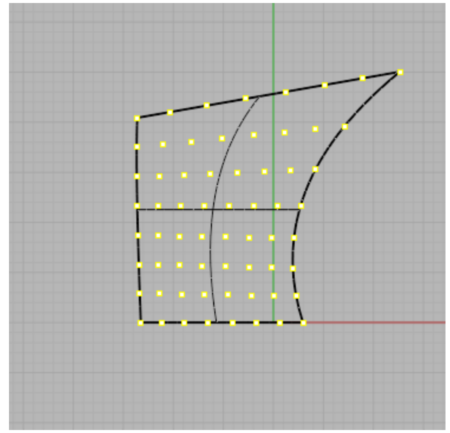
Rhinoceros meshing engine, higher mesh density with higher curvature. Meshing engine creates quads, based on a surface UV division, and divides quads in four smaller quads to refine the mesh. Quads are not planar, but can later be split into two planar triangles. Diagonals are added in transition zones between quads with different sizes.

A threshold for maximum distance between the reference surface and the approximation defines the mesh density. The shape of the segments is not controllable, but the methods can be used for subdividing the mesh.

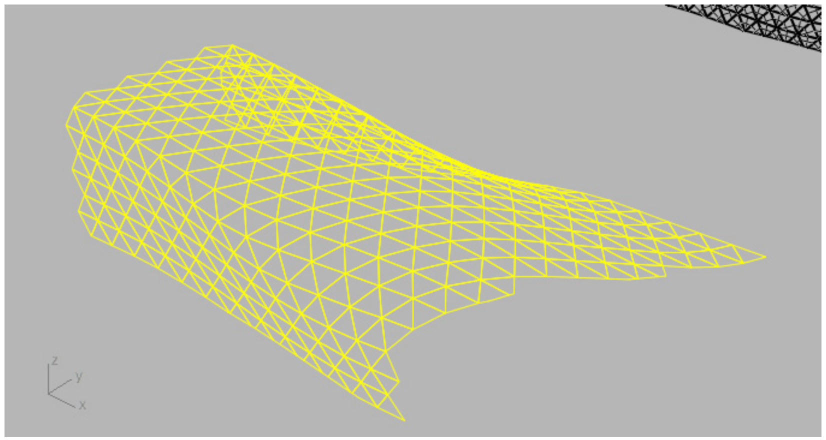
Controlled triangulation

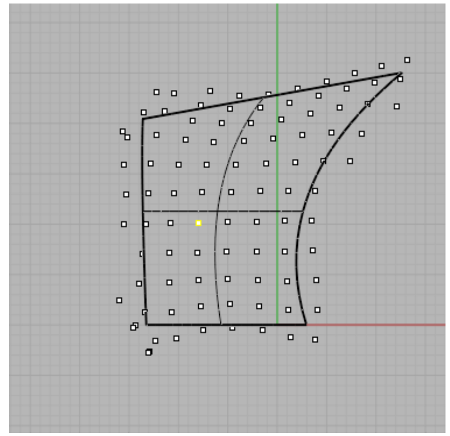
A meshing method is defined in order to control the size and shape of the mesh elements. There are two options for creating a controllable triangular mesh. With a grid based on a surface UV division and based on nodes with equal distances. For both methods the initial element size is a triangle with 3m side, based on the production aspects.





uv division
Points are distributed over surface according length of isocurves. Isocurves are generated by maintaining the same distance from a surface edge proportional to the opposite edge in each point. Subdivision gets stretched in upper right corner, which leads to deviant size. This influences structural behavior.





Triangulation based on maximum edge length. From one selected point a rectangular grid is draped over the surface, maintaining equal distances between points. This results in a more evenly spread division.

Mesh refinement
In the rhinoceros meshing engine, distance between reference surface and mesh is analyzed to refine the mesh. If it exceeds a given value, quads are divided in four, to form smaller quads with better approximation. This is an iterative process, after the first refinement, the refined mesh elements are analyzed again and subdivided if needed. Vertices are added at the centre of the triangles sides. New vertices are projected on the reference surface and connected by lines, creating four new triangles with a better surface approximation. (Figure 3.10).
A parametric 3d model is made to have full control over the surface division and refinement. It is described in Appendix A.

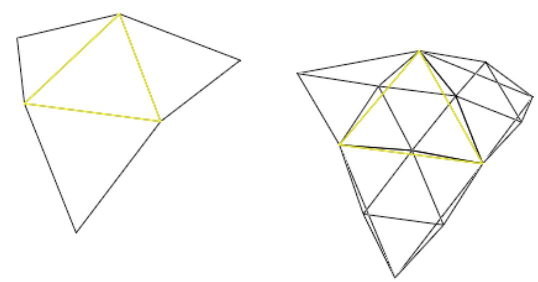


Figure 3.10 - refinement by splitting mesh and moving vertices to reference surface

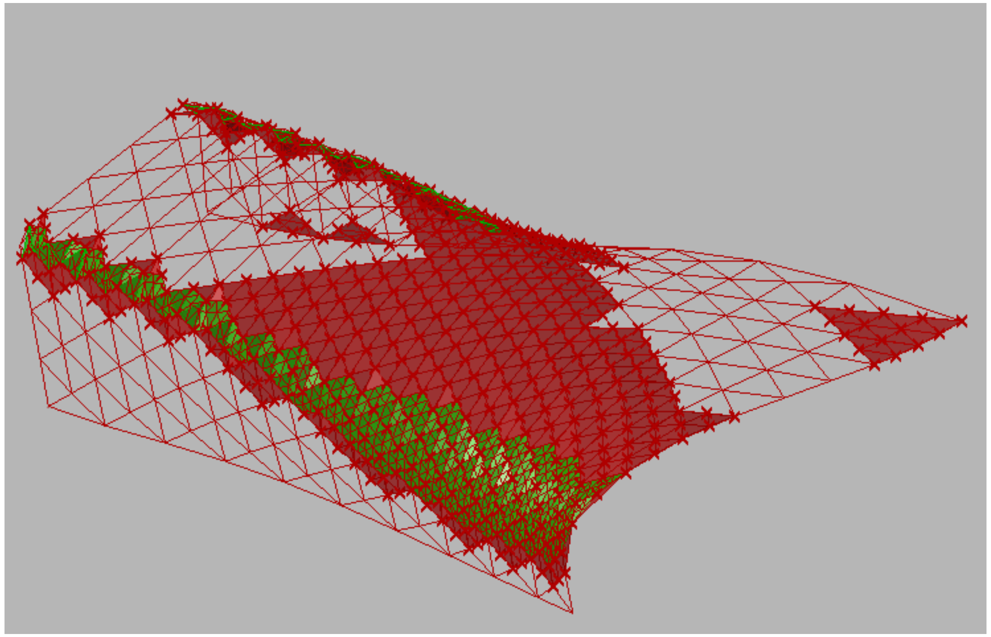
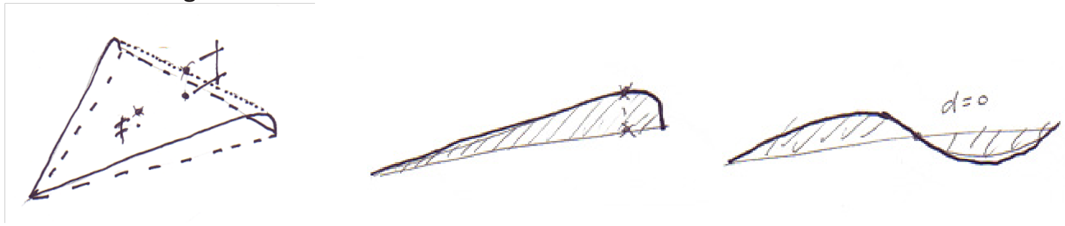


Figure 3.11 -   Parametric model for subdividing reference surface

A problem is that the maximum deviation is not necessarily near the centre of a mesh element. It might occur that mesh elements are not subdivided because at the centre, the distance to the reference surface is small enough to meet the requirements, but the maximum distance is not. Another problem is that multiple maxima and minima are present within mesh element, so essential details in the reference surface are overlooked by the method. This risk is only with sinusoidal patterns with a wavelength smaller than that of the mesh size.



In the Arnhem context, the transport size limitation of 3m elements result in a fine enough mesh to exclude this problem. There are no wave patterns within the reference surface.
The problem that the maximum distance between mesh and reference surface is not in the mesh elements' centre could cause problems in the region with the highest curvature value(chapter geometry).
To avoid this problem, a method is needed that analyses maximum distance instead of only the distance at the centre. There is a method available in Rhino plug-in Grasshopper to find the closest point to a surface. This can be reversely used to find the most distant point, which is the optimal point for mesh refinement. Another option is to use a tangency plane parallel to the initial mesh surface to find the maximum.

Milling of highly curved segments

Second step refinement results in triangular elements with edge 600-750mm. According to the formula for h_{midden}, element sides will start to intersect themselves when (Figure 3.12):

$$h_{core} > \sqrt{R^2 - (a/2)^2}$$

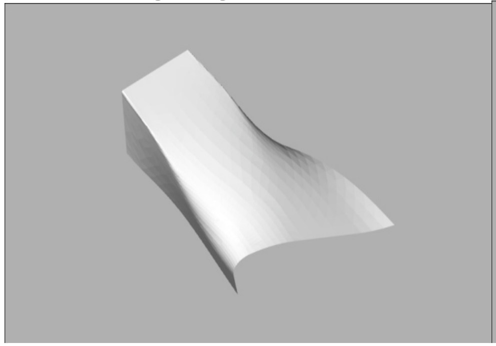
The thickness limit with an infinitely small value for a approaches R. However when the segment a is too big to fit within the curve this problem diminishes.

$$a^2 > \sqrt{2R^2}$$

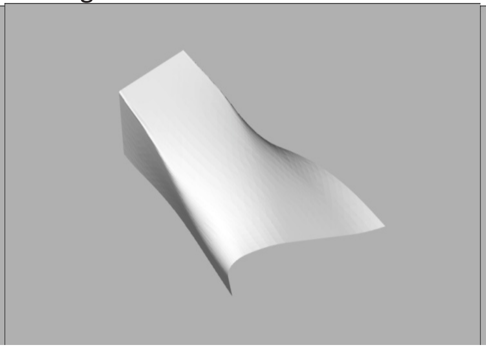
The milled elements will be much more expensive than the cut elements. However, this problem is only expected to occur at the highest curved areas, i.e. the blue regions in Figure 2.24 that cover less than 5% of the reference surface.

Effect of refinement

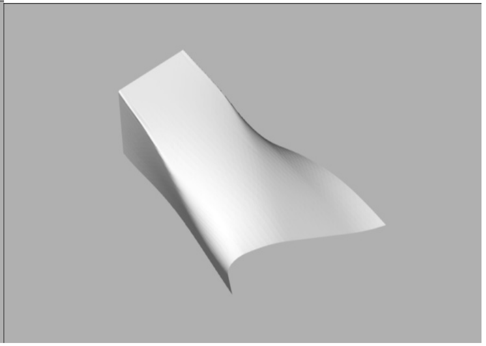
The following images show the effect of defining the threshold for maximum deviation from the reference surface.



mesh48
12617m edgelength



mesh24
16132m edge length(+27%)



mesh12
22003m edge length (+74%)

Increasing mesh density adds to an increasing number of operations such as cutting, handling and finishing of each individual EPS core element. Costs are exponentially increasing. Differences in rendered images of the surface are visible but slightly notable. The threshold for surface approximation quality can be adjusted to the architects needs, and will be different for every design. The threshold of 24mm is considered to be good enough for the OV terminal.

Conclusions

The density of the mesh is decisive for the approximation quality, but also increases the amount of operations needed. The extra costs for increasing operations are not only in cutting of core elements, but will have their effect on the entire production and finishing process. Probably accuracy decreases as well with increasing the number of triangles as well. The optimum balance between costs and surface approximation is very subjective and has to be decided on by the project architect. Within the context of Arnhem OV terminal a maximum deviation of 24mm from the reference surface chosen.

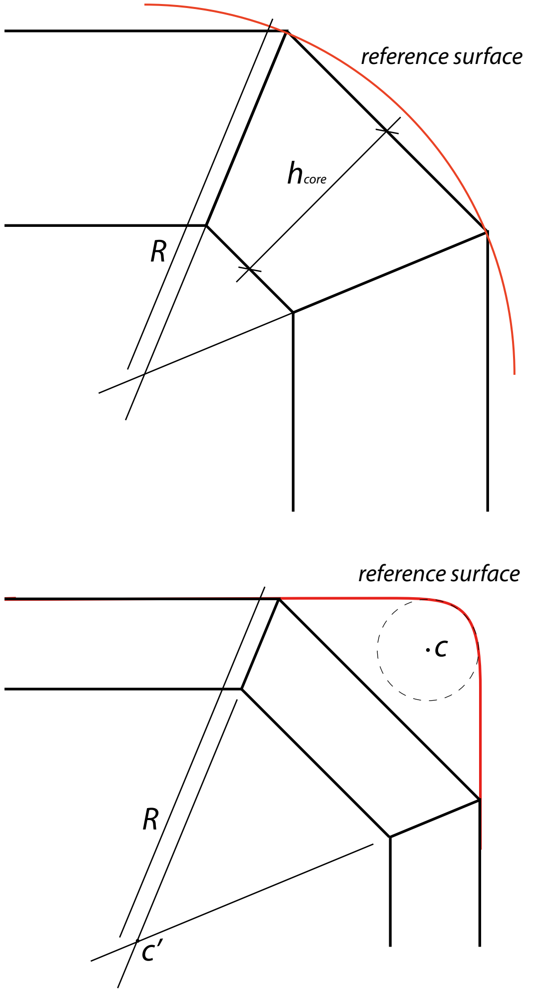
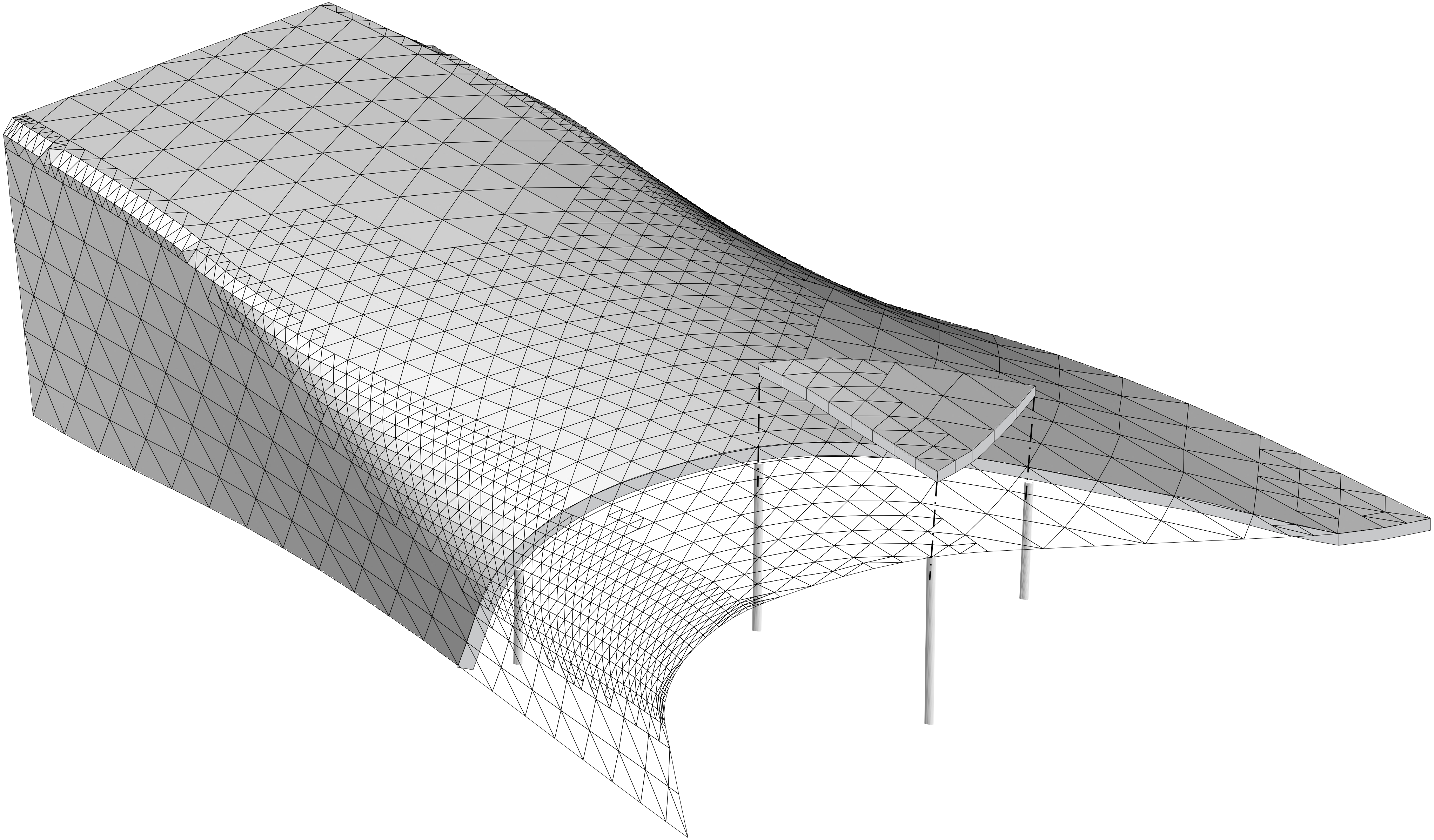


Figure 3.12 - relation between curvature radius element size and element thickness

Figure 3.13 - final solution surface division. Segments from combined sandwich elements



3.2. Connections

3.2.1. Introduction

From subdivision, thermal and structural research the principle of self-supporting sandwich construction was derived. This resulted in the principle of segmentation of the roof. Each segment is built up from combined sandwich elements.
This design principle results in two types of joints in the within the roof itself: rigid connections between the sandwich elements that form the segment and expansion joints around the segments, which will be referred to as type1 and type2.

Requirements
Physical requirements
Both connection types need to meet set of physical requirements

- Water tight
- Air tight
- Prevent water accumulation in connections
- Tolerances (size divergence/thermal expansion)

Structural requirements
Structural requirements are different for both connection types. The first type of connection or the rigid connection between the elements has to meet the following requirements:

- Transfer bending moments
- Transfer shear forces
- Transfer normal forces

A structural analysis has been performed on the triangular roof segment with a 12m side (chapter 4.1). The magnitudes of internal stresses with core and face thickness of 450mm and 4mm were derived. One of the curved roof segments was analyzed for occurring stress peaks at the location of the connections. Peak values for normal stresses in the face that occur are -30 to 33 N/mm2. Peak values for shear stress are 0,09 N/mm2.
The face stresses in the connections have to be transferred between adjacent faces. The shear stress has to be transferred between adjacent cores.

The second type, or the expansion joint must provide in free expansion and rotation of the segment edge. The only demand is that adjacent segments are structurally disconnected.

Production
The accuracy of the system depends on the accuracy of the element sides and the way they are connected. Necessary operations to construct the connections should be executed within the CNC process, in order to benefit from the accuracy of the CNC manufacturing process. The sides of the elements are defining the overall shape of the roof segments. Inaccuracy in the angle of the element side results in an inaccurate angle between two sandwich elements.
The angle of an inaccurate produced angle in the face is equal to the deviation of the element. Deviation in element side

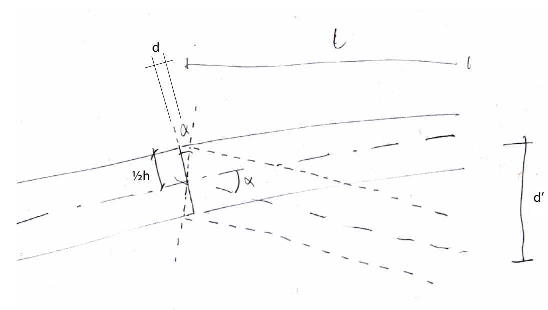


Figure 3.14 - inaccuracy in side can cause large deviations form the reference surface

results a deviation of the segment. The ratio is proportional to the ratio between the thickness and element length. For example, a 1mm deviation in the middle of a roof segment, can result in a 31mm deviation in height.

$$\frac{d}{d'} = \frac{\frac{1}{2}h}{l} \qquad d' = \frac{7000}{225} \cdot 1mm = 31mm$$

The number of manual operations that are needed to construct the connections should be minimized. A geometrically simple design is preferred, in accordance with the limited geometrical freedom of the wire cutter.

Options for connections

A brainstorm on different possibilities with connection types has given insight in the possible options for the connections between two adjacent elements.(Figure 3.15)

Prominent profiling
Compressed seal
Single face
Compound injections/sealant
Overlap

Profiling is too complex for freeform geometry. Profiling is a common way to join conventional flat sandwich elements (Koschade, 2000), yet in freeform shapes profiling will be complex to produce and to fit properly, forming a watertight joint. Besides that, the varying configuration of the joints requires a varying overlap principle.
Application of single face is not possible on lower side of the roof. The application needs to be done on the building site, which means a tent has to be placed over the roof segment. Quality control is much better when elements are prefabricated.
Compressed sealing is most suitable for CNC production because of its simplicity. More complex features, like fixture components can be added as well. More extensively described further in this section.

Conclusion
Connection serves both a structural as a physical purpose. A structural connection can be made by mechanically connecting the elements. The physical aspect, making the joint watertight, is more complex. The butt joint with a compressed seal has the most simple geometry. This is an advantage in the production process. Besides that, it has high potential to form a watertight joint.

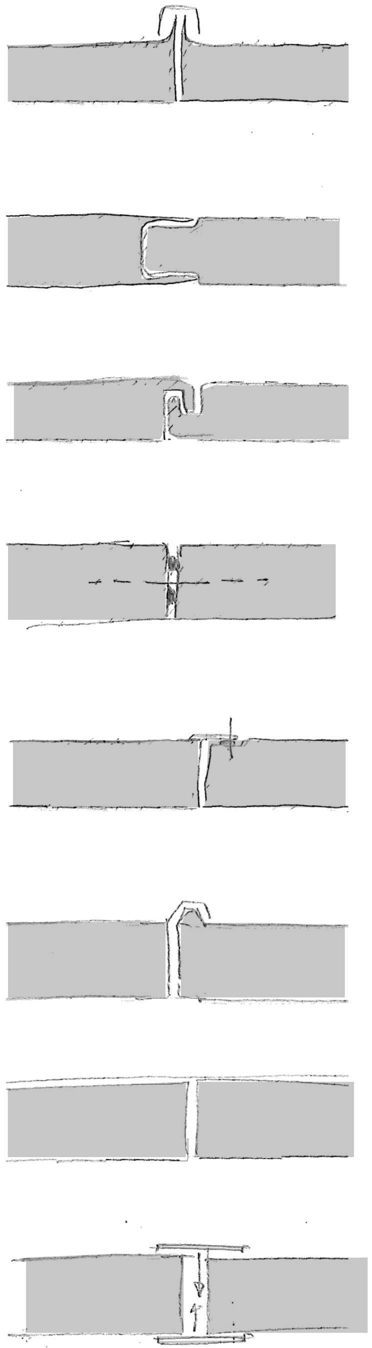
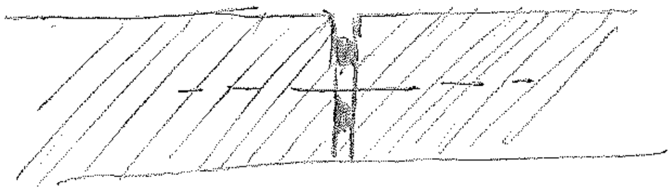


Figure 3.15 - brainstorm connection types

3.2.2. Type 1 - Rigid Joint

The rigid joint will be a butt joint with a compressed seal.



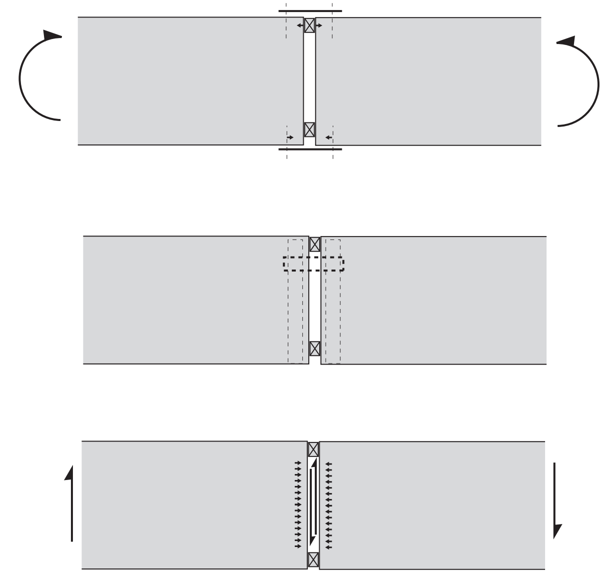


Figure 3.16 - internal forces in rigid connection

The butt joint with compressed seals is a simple solution. The sides of two adjacent elements are placed against each other. Seals are placed in between and the elements are pulled towards each other by a connecting element.

Structural quality

The butt joint that is applied with the compressed seals can carry compressive stress. Tensile stress has to be carried by a component pulling the two sandwich elements towards each other. Either this can be an external element, that influences the appearance, or an internal element. When two elements are pulled together, frictional forces can carry the shear force working on the section.

Seals

The compressed seals that are used to physically close the joints for air and water infiltration. The seals are a prefabricated solution for closing the joint.

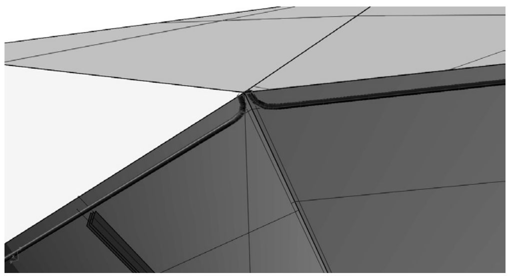


Figure 3.17 - seals curved upwards in the cornerpoints

Requirements for the seals:

- Variable in length
- Compressed between smooth surfaces
- Joined at corners were 6 elements meet

With every prefabricated solution the same problems reoccurred. Every joint has a different length so all the seals have to be custom made. The seals need to be compressed between two smooth surfaces in order to close the joint properly. In the corners were 6 joints meet the seals have to be either connected or curved upwards forces water out of the joint (fig). The problem occurred that water would accumulate in the joint, or could be diverted to the corner point and than flow into the joint.

Production tests in Section 4.2 showed that the surface quality that can be obtained is not sufficient to be sealed with a prefabricated compressed seal. Besides that, when loaded under compressive forces from the faces, the compressed seals will deform, causing the accuracy of the joint to change. This means at second thought the seals are not suitable for carrying compressive forces.

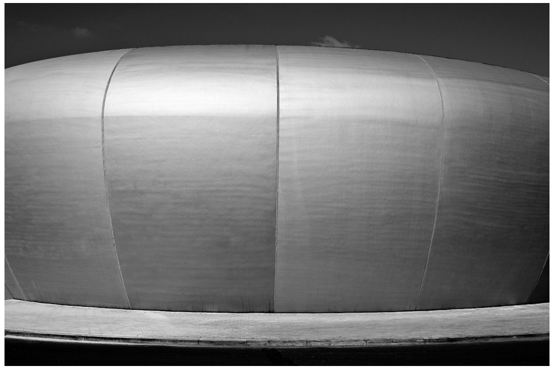


Figure 3.18 - Texaco Ruibeke - Boitink Architects

The final solution is sealing the joints with kit in stead of a compressed seal. Known issue is failure of seal due to thermal shrinkage (fig.). Because rigid connections within a roof segment do not allow thermal shrinkage this problem is unlikely to occur.

Consequences

- Accuracy of the element sides has to be perfect in order to construct an accurate model. Deviations must be within the range of 1mm.
- In order to apply the sealant, the joint must have an open seam.

Conclusions

Joints are sealed wit kit instead of compressed seals in order to avoid problems at the corner points.
The accuracy of the roof segment is dependent on the accuracy in production of the sides. Production tests were executed in order to verify obtainable accuracy. The main conclusion was that the accuracy of the faces was not good enough to use as reference planes. However, the thickness of the face appeared to be controllable and the CNC foam core can be produced within 0,5mm accuracy as well. CNC cut geometry in the foam core can be used for referencing adjacent elements.

Fixture components

Production tests showed that faces could not be produced with enough accuracy to ensure accuracy of the roof segment. However, with low vacuum pressure the core did not deform irregularly. This implies the problem can be avoided when the fixture components are used as a reference instead of the faces. Fixture components are added in order to join the elements structurally.

Requirements

Uniformity,

The fixture components need to be referenced with CNC machine in every element. The fixture components need to be uniform and variable in use for different configurations of the elements. Because shape parameters of the elements vary, the fixture components need to be able to cope with those variable parameters. This way a single component can be used in any configuration.

Structural

The fixture components need to transfer shear forces in core and normal forces in face. Normal forces concern both compression and tension, but the emphasis is on tensional stress in the lower face, and compression in the upper face, stated that the permanent dead load combined with snow pressure is decisive for horizontal elements, and wind pressure is decisive over wind suction.

The magnitude of shear stress in a connection, which is nearest to the supports is 0,09N/mm2. The maximum normal stress in the face is 33N/mm2. It must be taken into account that the stresses concentrate in the fixture components. Steel components are added, diverting the concentrated stress from one sandwich element to another.

Design

The element is accurate in at least 4 of 5 faces. The best option for implementing fixtures components at the CNC cut element sides. The CNC wire can be used to cut a reference line, were the fixture should be. A final reference point is needed to define the position on that line for which the base plane can be used. The sides of two adjacent elements are parallel for each point along the edge, which implies the similarity of a couple of shape parameters (fig).

Two options based on the referencing principle are considered:

External fixtures

Steel rods with parallel axes can be inserted in the cut out reference lines in two adjacent elements. The rods can be connected by a spacer maintaining the distance and at the same time pull the elements together for compressing the seal. The rods might perforate the vacuum foil, so they cannot be prominent. Replacing the rods by hollow elements were a spacer can fit in has the risk of letting water through the construction.

Internal fixtures

The internal fixture components are designed as parallel rails for a spacer. The spacer has the structural capacity for carrying the forces from one element to another and pulling two elements together for compressing the seal. A major advantage of the internal components is that the outer face can remain intact, which is better for preventing moisture penetrating the

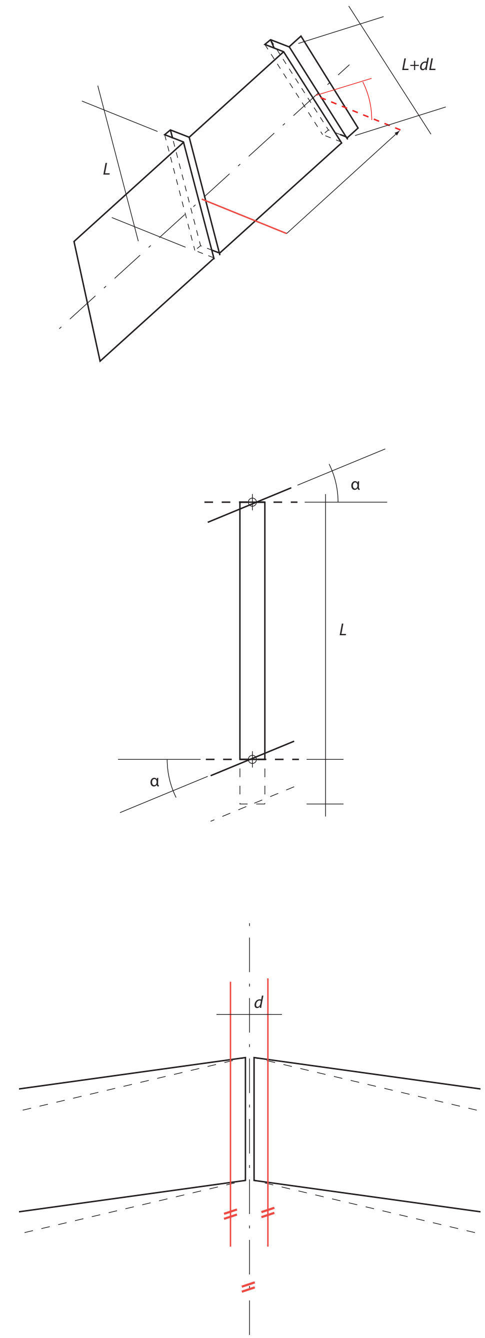


Figure 3.19 - Shape parameters used for referencing the fixture components. d is a fixed distance

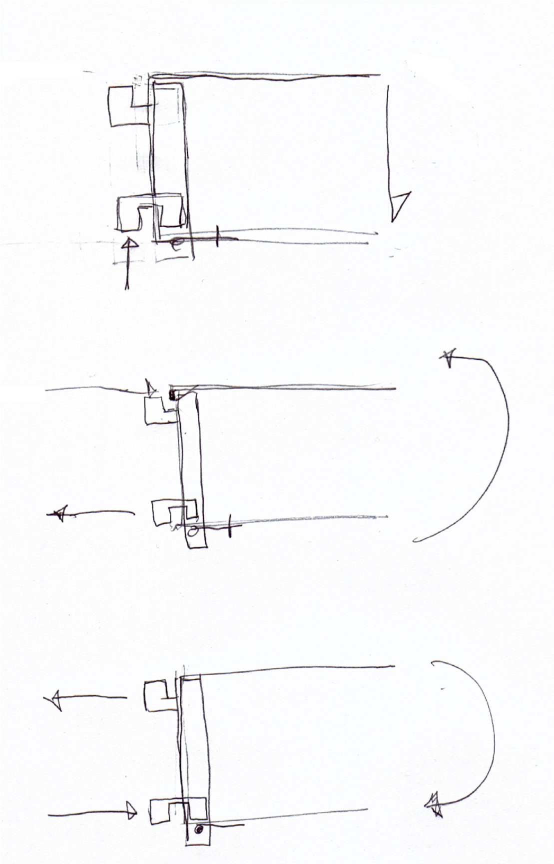


Figure 3.20 - carrying stresses by the fixture components

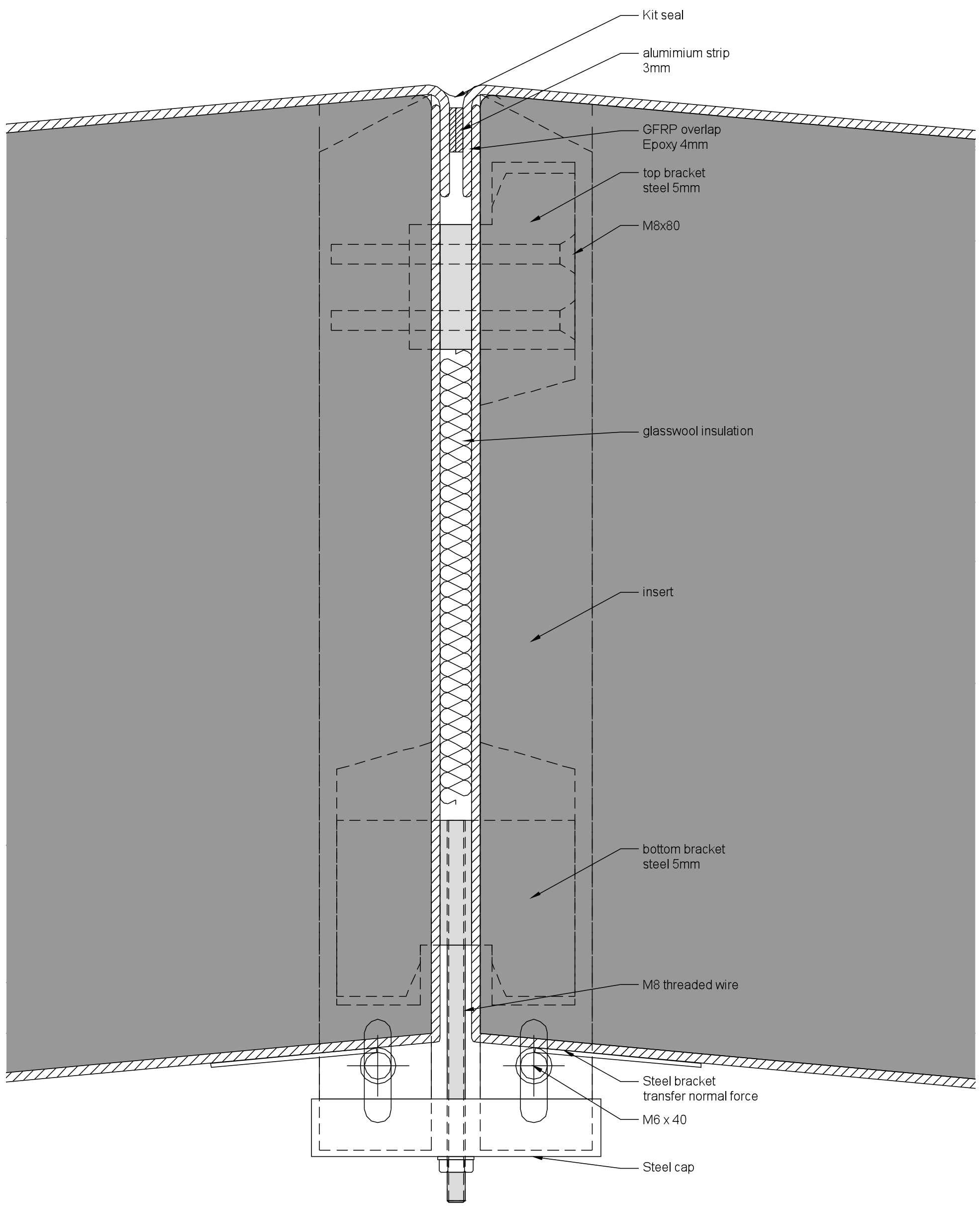
structure. Besides that, the appearance will remain simple and clean.

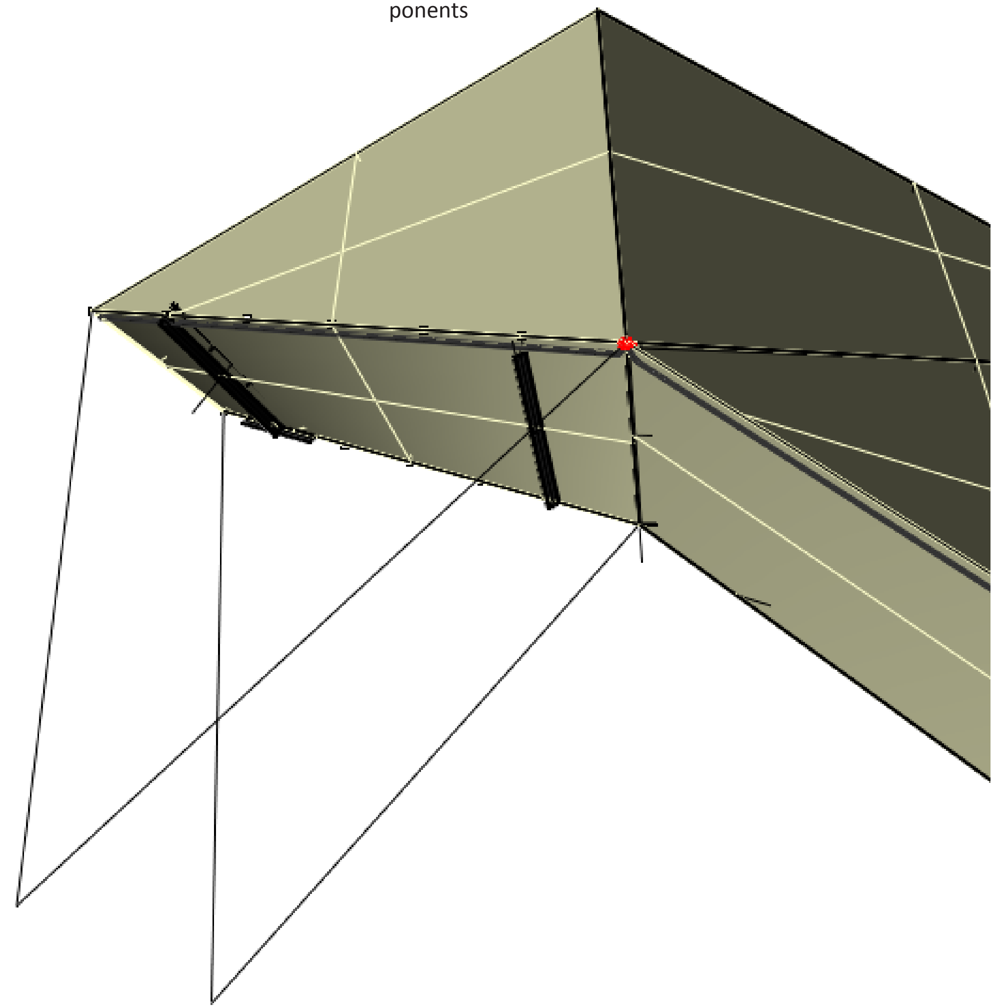
An optimum solution is where a minimum of fixture components is needed. A structural analysis in chapter shows that 6 fixture points at a 3m side result in tensile stress peaks of 48N/mm2. This is within the yield strength of the material. Compressive stresses of this magnitude could lead to wrinkling of the face. Compressive stresses in between the top faces are distributed over the entire edge length, to avoid the concentration of compressive stresses in the face. Tensional stress peaks around the fixture components in the bottom are avoided by diverting the forces trough a steel strip attached to the face. The strips are attached with screws or an adhesive to avoid puncturing the face.

Consequences
The direct contact between two top surfaces of adjacent elements implies that the edges of the connection need to be produced flawlessly. The control over thickness of the faces obtainable is within +/-0,5mm accuracy, according to the production tests. In order to ensure an accurate edge, an aluminium strip is placed along the edge inside the vacuum bag, constructing a clean edge at a fixed distance from the referenced side of the CNC cut element.
The concentration of the tensile stress in fixture components will probably result in higher total deflection of the roof segments. The level of abstraction used for modelling the connections in ANSYS implies that some parts of actual structural behavior are not examined. Physical testing is recommended to research the magnitude of all aspects including unforeseen ones.

Conclusions
The choice for the rigid element connection is a butt joint sealed with kit. Referenced fixture components are inserted that fix the angle and distance between two elements. In order to distribute the compressive forces at the face an aluminum strip is added to both elements, forming the referenced element edge.

Figure 3.21 - final design connections and fixture components





3.2.3. Type 2 - Expansion joints

The expansion joints dividing the roof in 14m rigid sections are referred to as type 2. The requirements for type two connections are derived from the physical aspects in chapter. The expansion joints need to take on the size changes and other movements caused by thermal expansion. The demanded freedom of rotation and translation implies that the only requirement is that to adjacent segments are structurally disconnected.
Physically the connections need to provide in waterproofing, thermal insulation and prevention of air infiltration.

Requirements:

- freedom of translation, 24mm in plane
- freedom of rotation
- Water-, airtight
- Thermal insulating

Feasible variants and argumentation

A common way to deal with expansion and size tolerances in building envelopes i.e. facades or roofs is to use overlapping elements or profiles to drain water out of the structure. Overlapping is not an option in this case because the configuration of each of the connections according to the world coordinate system is different. At some places the seams are horizontal which makes overlapping impossible. Making freeform profiles is also not considered an option for three reasons. The profile must be really prominent so water cannot get forced in by wind. It takes a lot of effort to produce freeform watertight profiles. It has a disturbing effect on the continuity of the freeform surface.

Design Type 2

Flexible seam in 1,5mm EPDM rubber is connected to two adjacent roof segments. Mounted to the segment side with an adhesive sealant. An edge profile is added in the vacuum bag, to create an overlap for the seam to slide in (fig).
The seam forms a gutter to drain water hitting the roof downwards, to the ground. Because the roof of the OV terminal Arnhem is arc shaped, there are no concave areas were water will accumulate.

Corners
At the corners the flexible seam is glued to a six-sided slab, which diverts water into another seam.

Esthetics
To protect the seams from damaging a covering plate is applied to the seam. An additional purpose of this plate is to hide the black EPDM rubber from sight. The plate is mounted to one of the segments to provide in free movement of the elements.

For thermal insulation, the space in between is filled with glass wool, able to take deformation of the roof construction.

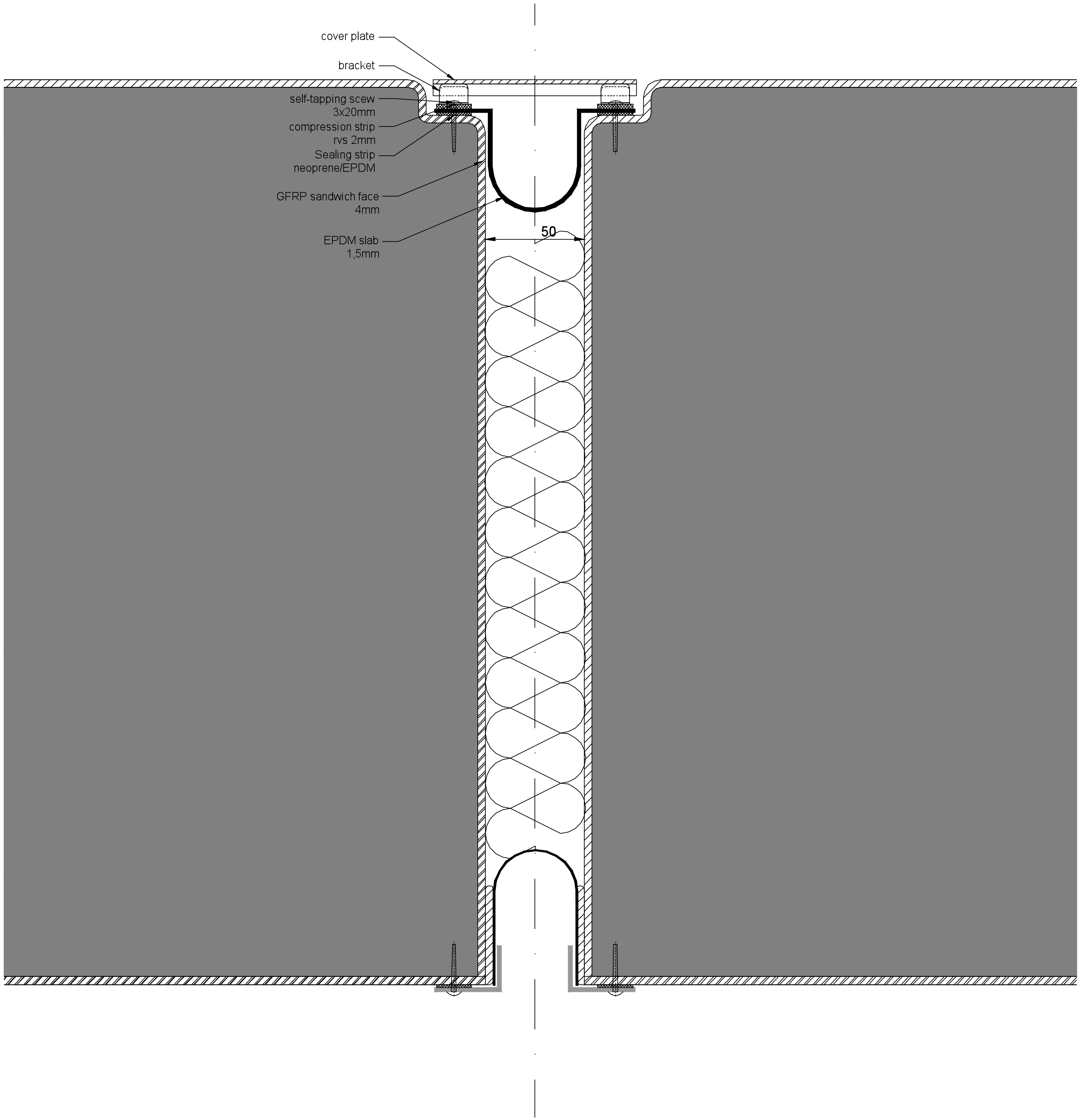


Figure 3.22 - final design expansion joint

3.2.4. Supports

Connections to structure
Each roof segment has three supports at the corner or connections to the main load bearing structure.

Requirements:

- take on support reaction segment corner.
- provide room for size tolerances and expansion of the segments
- adjustable in height.
- fix corners in Z translation

Structural aspects
Support reactions have a magnitude of 41kN maximum, resulting from the calculations in chapter. To avoid high stresses, the support reactions at corners need to be de-concentrated. Additional measures are needed to divert the high shear forces to the corner, because the foam core is to weak.

Physical aspects
It is assumed that adjacent segments have equal expansion at the edge where they are joined. The flexible seam in between can take some strain occurring when the segments expand, but the elongation must be in the same direction for both sides of the seam. Shear displacement can rupture the seam.

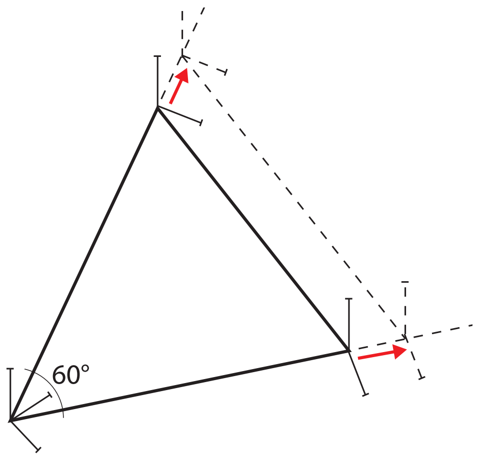


figure 3.23 - translations of corners under 60 degree angle

Design

An absolute size change of a triangular roof segment does not affect the shape. When one corner is fixed, the two other corners must be free in translation in one direction. The direction of translation is under a 60° angle.
When the fixed corner points of 6 segments are located at the same support, the supports with one degree of freedom are automatically located on the opposing side of the segment. The direction of translation of a corner is parallel to the adjacent corner. This is a repeatable pattern.

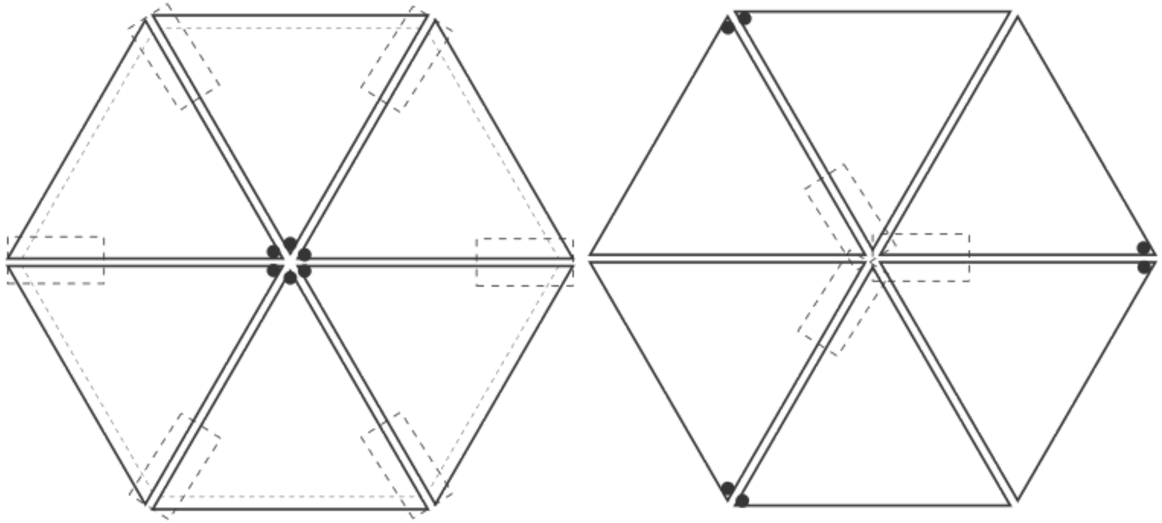


Figure 3.24 - support of roof segments, dots are fixed corners dotted lines represent supports with freedom of translation in one direction

The joints crossing the fixed corner do not shrink or expand, while the edges opposing the fixed corner have and absolute difference in width of 48 mm. From an average size at 15 Celsius, the joint will either decrease 28mm or increase 20 mm in width. A gap of 50mm at average temperature is sufficient to take on the expansion.

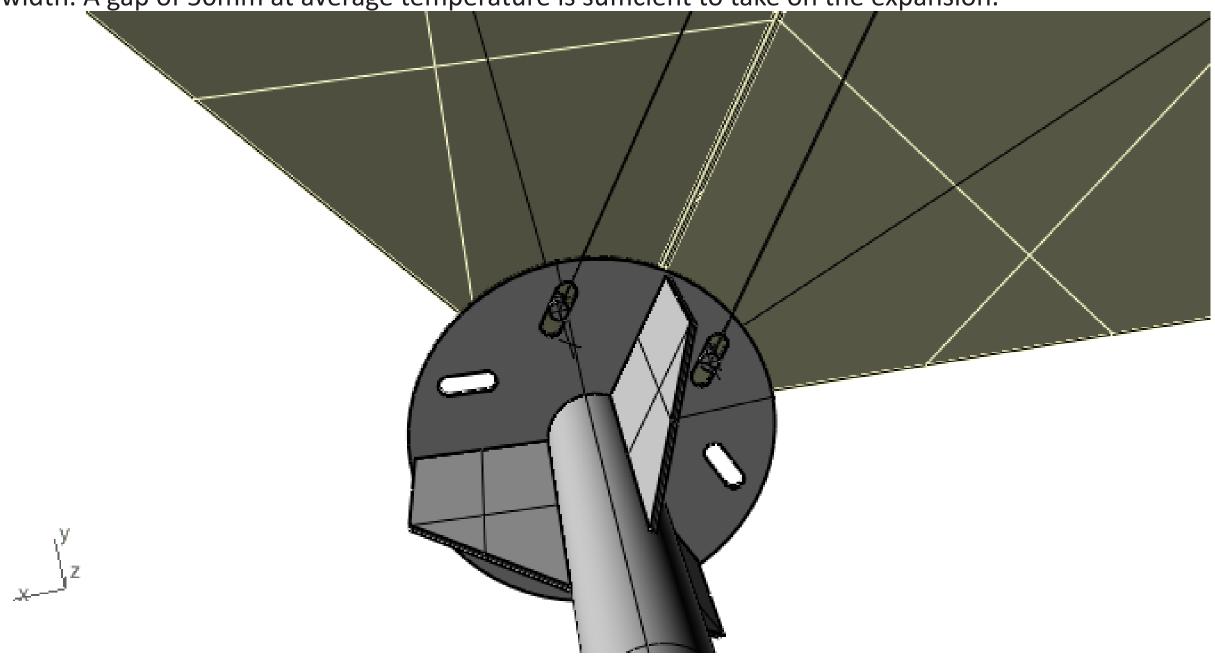


Figure 3.25 - supports

Structural aspects (feedback principal stress)

Because the supports are situated near the corners, the shear forces concentrate in this point. The principal stress trajectories resulted from the structural analysis in section 4.1 give insight in the way shear forces in horizontal roof segments and normal forces in vertical segments are carried to the construction.

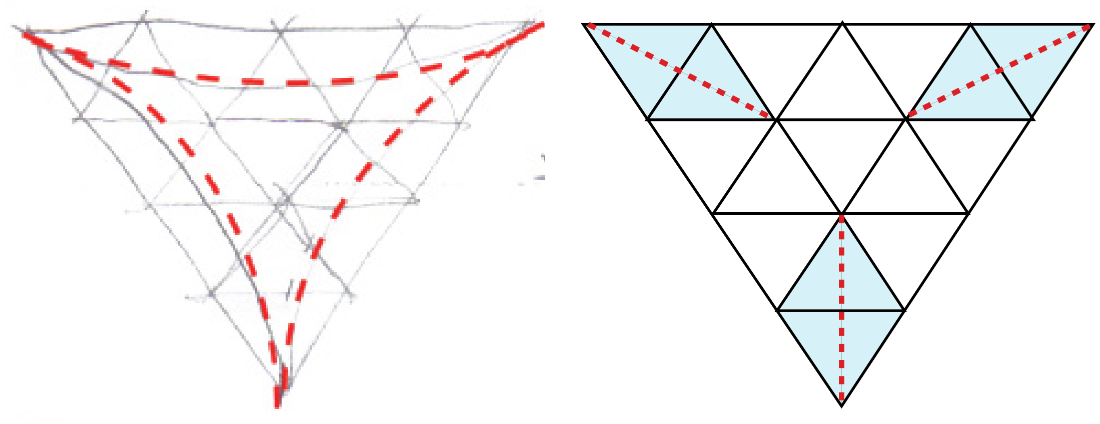


Figure 3.26 - locations for shear webs (red dotted lines)

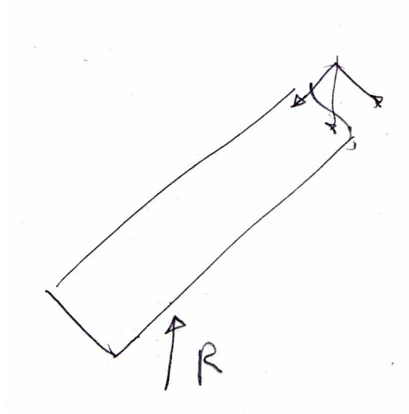


Figure 3.28 - shear forced decomposed when sandwch element is in an inclined configuration

Reinforcing the corner elements avoids high shear stresses in the relatively weak core. The vector trajectories correspond with optimal direction of reinforcement. Shear webs are implemented in the direction of the trajectories and reinforcement is added to the element sides. Besides that, elements for improving the load distribution have been inserted.

Requirements for the reinforcement are:

- Implementation in production process with regard to production aspects
- Adaptable to shape parameters

Shear webs

Shear webs are applied in the direction of the principal stress at the corner. The foam core elements are cut in half and glass fabric is laminated in the joint to form a vertical slab. Because the split core elements are triangular as well they can be cut in the same CNC production process. Implementing shear webs is possible when subdivision is refined as well. The least favorable configuration is when the corner is in horizontal position (Figure 3.28), because shear force is acting perpendicular to the shear webs.

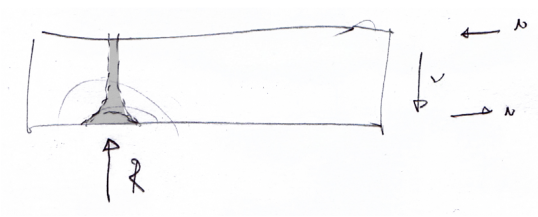


Figure 3.27 - shear webs reinforcement at the support. Bending moment at the connection (right side) occurs

Force distribution

In order to distribute the force from the support, metal inserts are applied (Figure 3.27). The elements are applied in the lamination process. Holes in the vertical slab improve bonding to the element sides. This is further described in section "3.3. production of Faces".

support exceptions

The triangular support points are as much as possible placed at locations were internal construction elements are in the initial plan. There are two excpetions on the system were the segments are supported by three columns at the corners.

- open edges
- supports near vertical regions.

Open edges

The open edges in the design need a special solution. Triangular roof segments are cut off at the roofs edge at the front side of the design. Open edges extend from roof openings to edges not supported by the triangular support grid. The red lines (fig.) represent internal construction. Supporting columns might be placed without any major interference with the interior space.

There is however a part of the edge that cannot be supported this way. Some options for supporting this region.

Options:

- edge beam, bended steel structure
- edge beam, composite beam
- cantilever

Cantilevered beams

Using cantilevered beams is not really an option, when beams are below the structure. Irregularly placed beams that submerge from the roof construction disturb the continuity of the surface. Internal beams need to be custom made for the structure and need space that has to be cut out from the sandwich elements.

Edge beam

The other option is to construct a curved beam supporting the edge of the roof. This can be a prefabricated steel beam, supported by the internal construction near the edge mentioned earlier. The edge is completely supported and confined visually by the beam.

Support near vertical regions

Placing a support near a vertical region in the design is impossible when it interferes with the roof construction. A solution is to place an internal column in the 500mm thick construction.

Consequences are, that the sandwich elements adjacent to the beam need some modification before getting into the vacuum injection process.

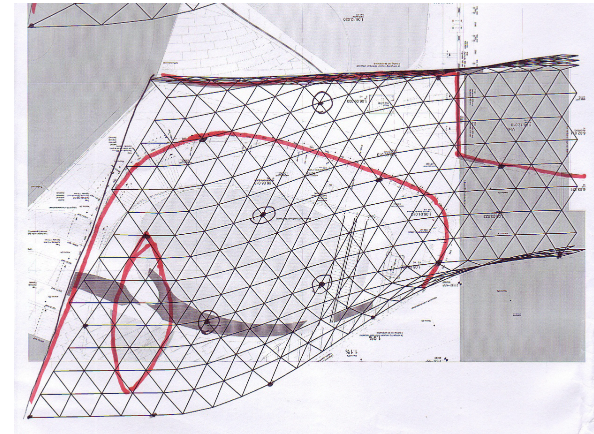


Figure 3.29 - floorplan of support positions

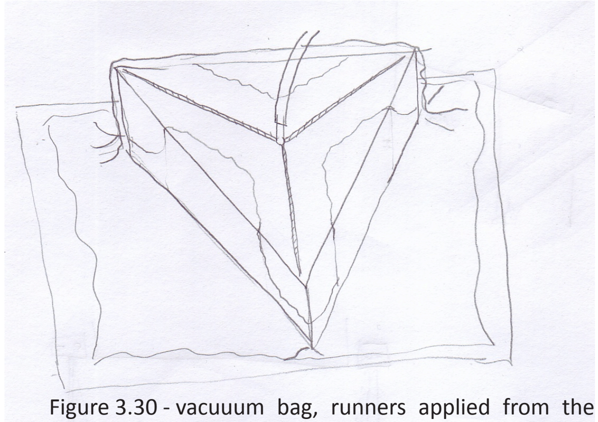


Figure 3.30 - vacuuum bag, runners applied from the centre to the corners for improving resin distribution

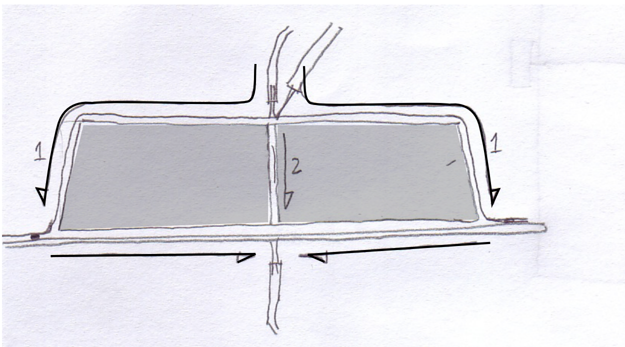


Figure 3.32 - base plate results in smooth exterior surface

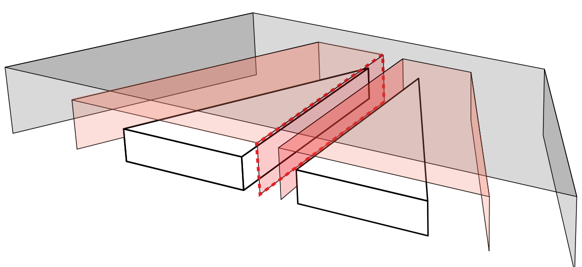


Figure 3.31 - seperate core elements are covered in glass fabric to construct shear web (red)

3.3. production of Faces

Production of the faces with vacuum injection technique

Requirements

- Position of vacuum and supply hose
- Mesh for flow improvement
- Splitting cloth
- Resin front

Lamination of elements

The production tests showed the importance of accurate placement of glass fibers. In accurate fitting of the glass fabric can result in creasing of glass fabric and face irregularities. Were two pieces of glass fabric meet an overlapping joint must be made, in order to carry stresses from one to another. The shape of the triangular prism is covered in two pieces of fabric: the bottom and sides from one piece and the top from one piece.

In an instant the glass fabric is under a negative air pressure. A resin supply hose is connected and resin will flow trough the glass fabric. In order to improve the resin distribution, a flow mesh with large pores is added. Also permeable tubes or runners can be added to improve the distribution.

Resin will distribute with the flow front equidistant from the supply hose or runner. Air bubbles can get enclosed in corners of the vacuum bag.

A Plexiglas plate is used to form the vacuum chamber at the elements top surface. The plate is treated with wax to prevent the resin from sticking. A tube is connected at the centre of the plate which will be used as the connection for the vacuum hose.

Shear webs

The introduction of shear webs within an element makes it more difficult to force all the air out, because an additional resin front will be needed. Multi-directional

4. Technical Research

A series of tests and analyses are carried out in order to verify the magnitude of some of the structural and physical aspects.

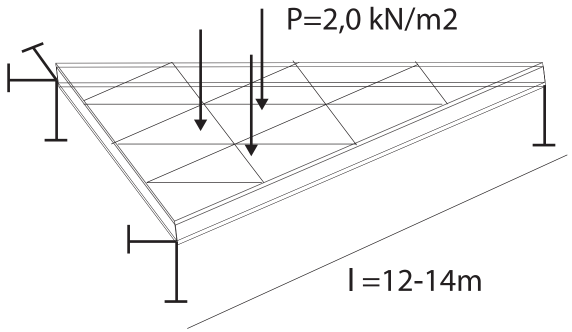


Figure 4.33 - loadcase for roof segments

4.1. Structural analysis

4.1.1. Triangular segment

Triangular curved roof segments with a side of 12m and a thickness of 450mm are analyzed in a finite element analysis. The data is used in the chapter for occurring normal stress in the face and shear stress in the core at the location of the connections between the elements.

A curved shell element, representing one of the roof segments with a 12000m side has been modelled in ANSYS (element type layered SHELL99). The segment is loaded with a distributed load of 2kN/m2 representing both dead and live load (chapter) and supported in z-direction at the three corners. The deformations were calculated with a distibuted load of 1,0kN/m2 representing only the live load without safety factors (Gerrits, 2006). The material properties used were:

T_c =450mm
T_f = 4mm
E_c = 7,7 N/mm2
E_f= 27500 N/mm2
$\upsilon_{c,f}$ = 0,3

An additional test was carried out on the final 14000m segment and a reference model of a beam was made to verify the results with the analytical model.

Results
In this section the 12m and 14m elements are described. More results are described in Appendix C

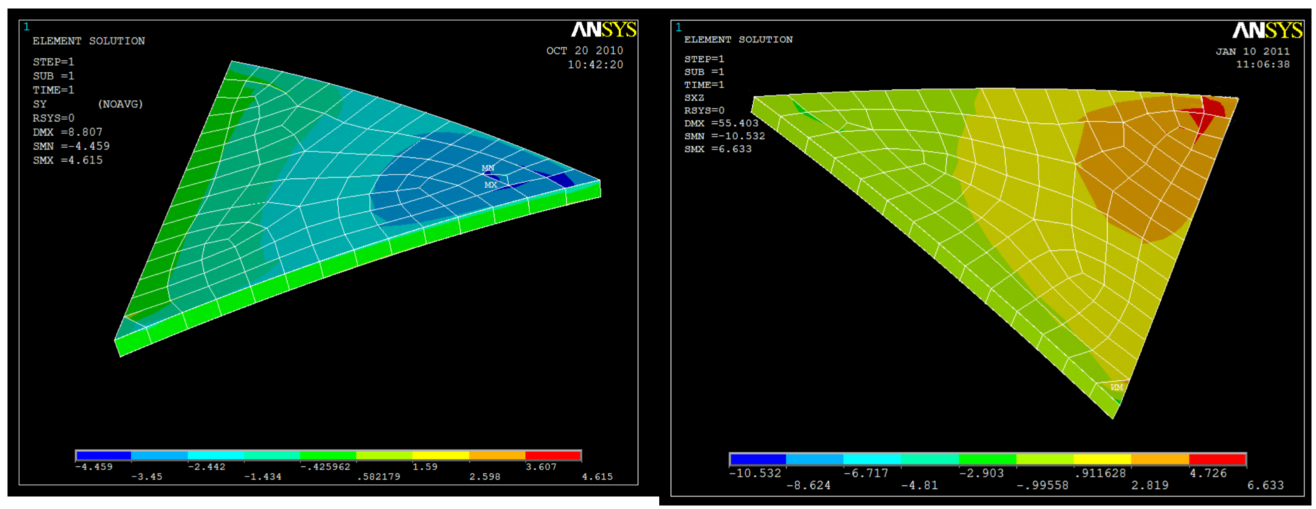


Figure 4.34 - normal stresses in the face and shear stress in x direction.

	umax [mm]	sxx [N/mm2]	syz [N/mm2]
beam analytic	48,21	20	0,027
beam fea	48,32	20,04	0,09
segment 12m	27,2	29,4	6,21
segment 14m	46,3	52,2	-

The deformation of the 14m roof segment is 46mm. Compressive stresses in sandwich face up to 52 N/mm2. The peak values for face stress are located near the corners. In both the triangular segment as the reference beam the shear forces concentrates near the supports in the region between the face and the core. The magnitude of the yz shear stress is 6N/mm2. Principal Stress trajectories are shown in Figure 4.35

Conclusions

Deformation or maximum deflection of 56mm is slightly higher than the maximum of 48mm. However maximum deflection is calculated with live load without safety factor of 1,5 only. This means the actual deflection is calculated with a distributed load of 1,0kN/m2. Face compressive stresses are not exceeding the critical stress value of 48N/mm2, found in chapter 2.3.

Remarkable is that shear force concentrates in the faces, while the expected result is that it would concentrate in the core. Two reasons for this are the method of calculation and dissimilarities between the theoretical and the FEA model.
At the supports a disturbance in force distribution occurs where the reaction force spreads trough the structure. This area is as large as the height of the beam. The theoretical model in section 2.3 only describes structural behavior in parts outside this area.

The results are usable though to localize problematic areas. Shear forces are carried as a shear stress distributed over the sectional area of the construction. Peaks in both shear stress and normal stress occur in the regions near the supports, where the sectional area of the core and the faces are is smallest. Therefore the value for shear stress is highest in the corner regions. An analytical model (chapter) will be used for calculating shear stress in the core from now on.

Structural reinforcements are needed near the corners (blue area, Figure 4.34) in order to create a 14m element.

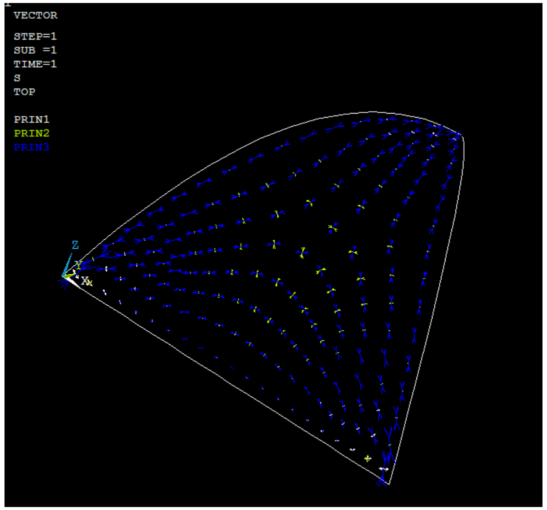


Figure 4.35 - Principal stress trajectories show stresses get diverted to the corners.

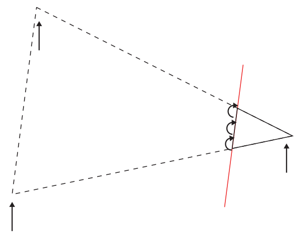


figure 4.36 - representation of corner of segment

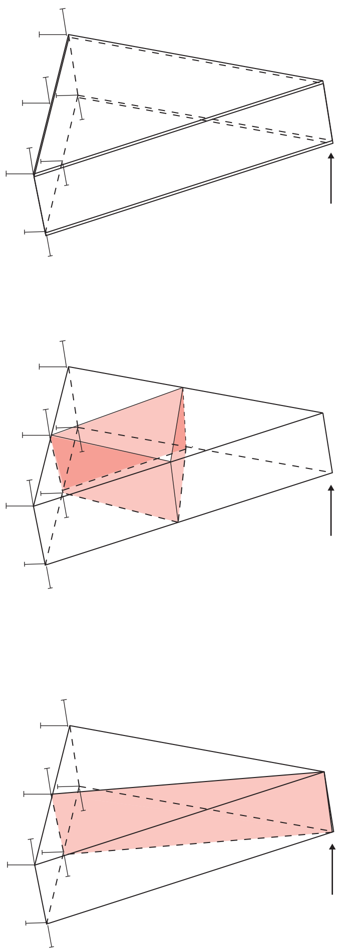


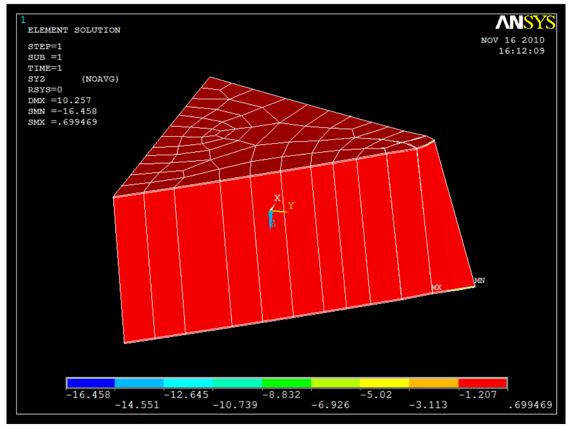
figure 4.37 - model 1, 2 and 3

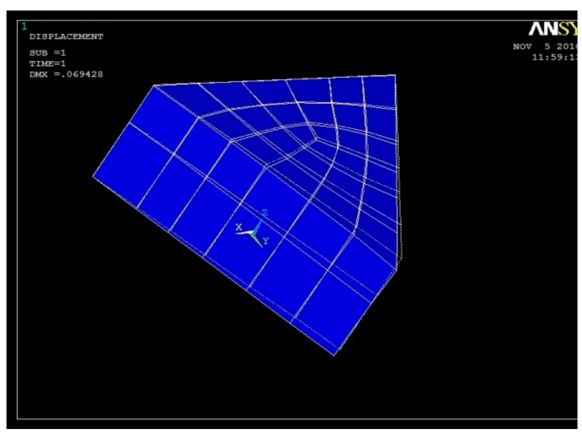
4.1.2. Shear webs at supports

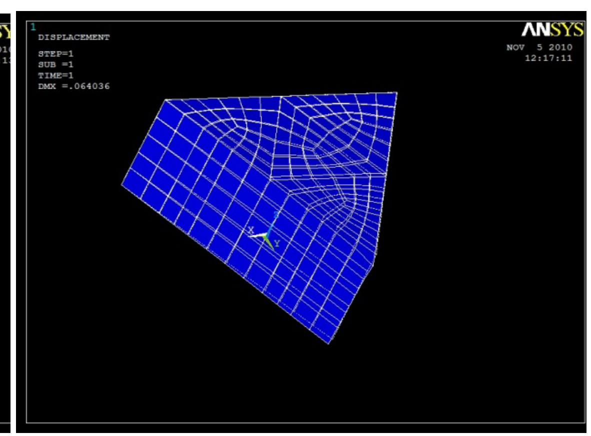
To carry shear force in sandwich elements a common solution is to apply shear webs or vertical slabs, able to carry forces in the direction of the shear force distribution lines. In case of the prismatic shape of the core elements the use of shear webs between the core sub elements is interesting to look at. The effect of adding composite surfaces to the 'open' edges of the sandwich panel have to be taken into account as well.

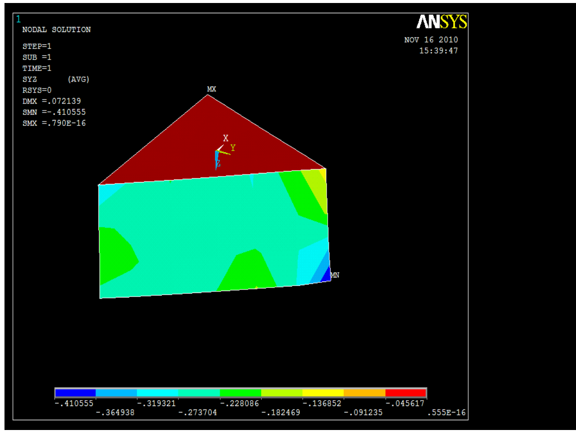
A fragment of the roof segment has been constructed in ANSYS. Three test models have been analyzed. In all three test models one edge has been fixed in all 6 degrees of freedom, representing the clamping from the adjacent sandwich elements. The opposite corner point is loaded with a point of 41kN load representing the support reaction.
Model 1 is build up from a layered curved shell as in the first analysis, model 2 is build up from 5 surfaces enclosing a single foam core. Model 3 is built up from 17 surfaces enclosing 4 separate core sub elements. The material properties that are used remained the same, though for the enclosed elements no core material was assigned.

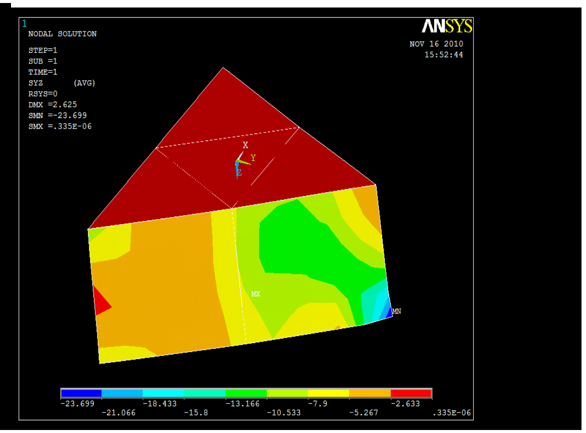
Results









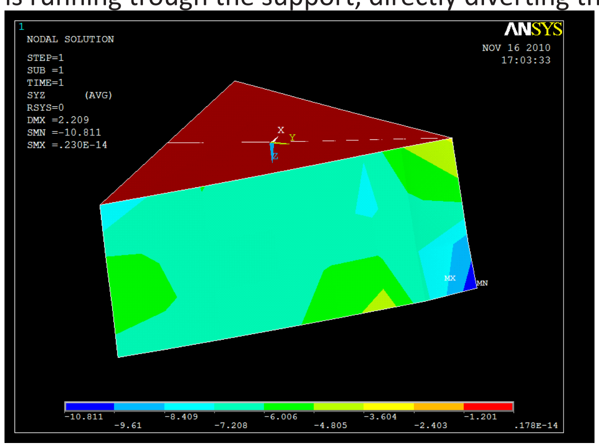


Results

Corner elements with and without shear webs resp. model 2 and 3, difference in deformation notable. Peak Shear stresses in global x,z,- plane are 16N/mm2 and 23N/mm2, only in face material. In model 3 the stress is distribution is different for two regions. Stress peak values have the same magnitude compared to model two. However stresses are distributed over more faces after the first shear web, showing a clear division.

Shear web in bisector

Another model has been analyzed with an additional shear web in the direction of the bisector of the corner. The shear web is running trough the support, directly diverting the reactional force.



Shear stress peaks have a magnitude of 10N/mm2.

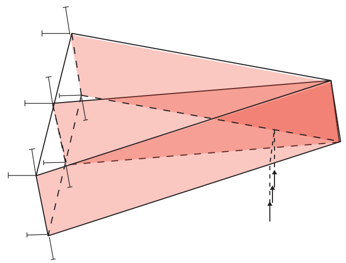
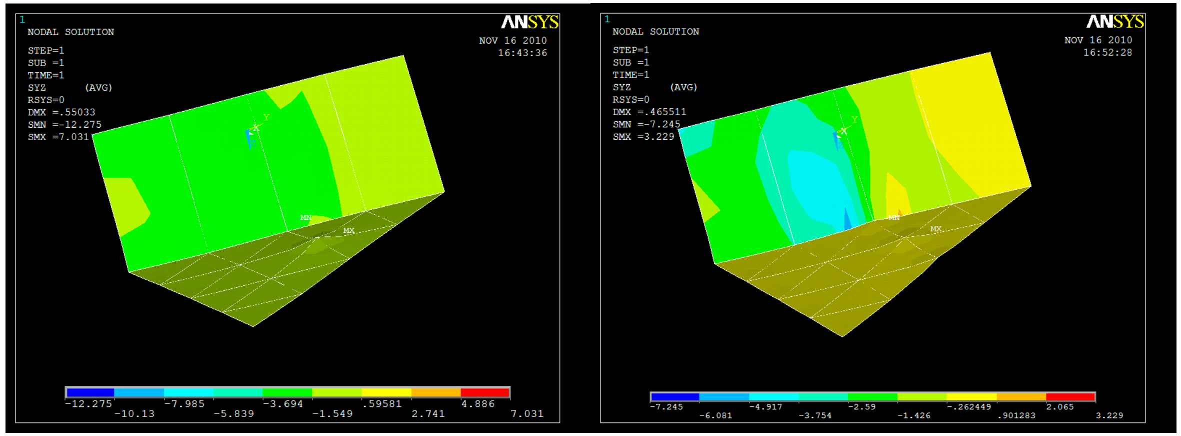


Figure 4.38 - distributed support at shear web and element sides

De-concentrating supports

An additional option to avoid shear stress to concentrate in the corners is to move the supports out of the corner and increase the area the support reaction is acting on. The support is placed 400mm outside of the corner.

Results



Shear stress is concentrated in three points instead of one, resulting in a better stress distribution. Peak stress did not decrease significantly by placing one support inwards form the corner. This is caused by the absence of a core material in the model, that would have better distributed the stress.

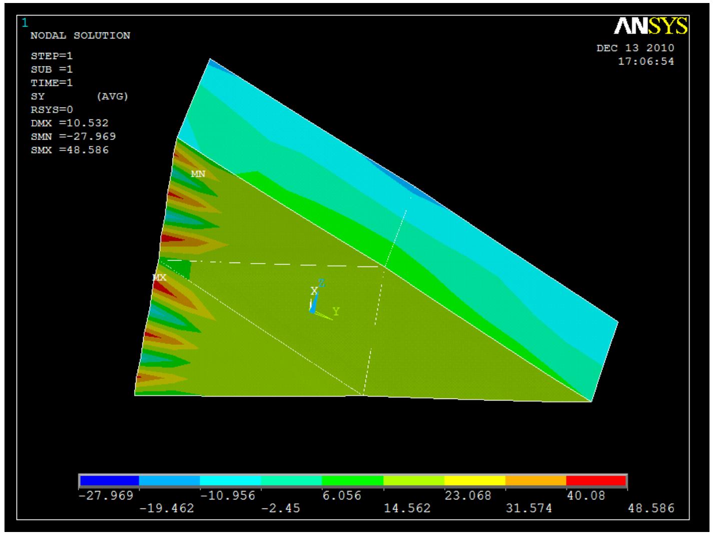
Conclusions

A sandwich element with rigid sides is better capable of carrying shear stress form the support than a sandwich element with open sides, even when the rigid element has an infinitely weak core. The element sides act as a shear web.
Shear webs in located in the bisector of the corner that run through the core carry a part of the shear stress in the corners. The shear stress is distributed over an extra construction element and shear stress peaks are lower. Additional shear webs that do not work in the direction of the bisector do not improve occurring stresses in the corner.
De-concentration of stress by adding multiple supports, decreases the peak stress values to 7N/mm2. The supports should be located outside the corner because it is distributed over a larger sectional area of the core. A linear support is preferred for better distribution of the reactional force.

4.1.3. CONNECTIONS

The concentrated forces in the fixture components are expected to cause higher stresses than in the continuous face. In order to get insight in the magnitude of these an extra test on a part of a roof segment is tested. The method is similar to the previous tests except an elemnt with a three meter side is tested. One of the sides is fixed in six points, representing the concentrated normal forces from the fixture components.

results



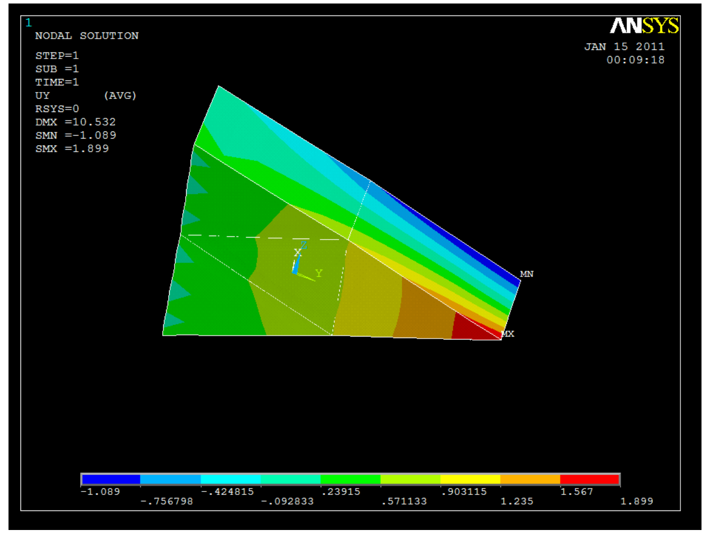


Figure 4.39 - normal stress in the face and deformation at the support

Stress peaks of 48N/mm2 occur in the lower face. No stress concentrations occur in the upper face. The stress in the upper face is -28N/mm2. Strain in the lower face causes a deformation of 10mm in the direction perpendicular to the fixed edge.

Conclusions

The stress peaks are within the stress limits. Maximum tensile stress for Fibre reinforced epoxy is 375N/mm2 (chapter2.3) however the deformation of the element will result in a large total deflection of the roof segment. This effect is larger with concentrated forces in the lower face than with a distributed stress. The inital deformation of the roof segment will be larger than calculated in the previous tests and it is recommended that it is compensated in the referencing of the fixture components.

4.2. Production tests

4.2.1. Geometry of foam core

The accuracy of the CNC cutting of the foam core is dependent on three aspects

- Accuracy of raw material and plate placement
- Accuracy of machine
- Heat accumulation due to differences in cutting speed

To get the accuracy of machining and placement right either a hardware solution can be found in improvements to the machine, and more careful handling of raw materials. Also software solutions can be thought of as digital compensation for backlash of the support rails for the moving spindles. Backlash is the inwards tilting of the spindles due to the wire tension. The effect increases when the spindles move up.
Heat accumulation is a bigger problem because it is found in the theoretical principle. The irregular shapes of foam core elements demand an unequal cutting path on both sides of the raw plate. This implies different path lengths being cut in the same time, which means the hot wire is relatively longer at one side of the cut object.

Production tests have been done, to measure the influence of the described aspect on the accuracy. The tests were done iteratively; the results from each test run are used as a basis for the next test run.

A series of EPS test elements is made of 200x200x150mm with one warped face. Four of those elements can be combined to represent two adjacent elements with an internal shear web (fig). The accuracy of the absolute dimensions and precision of the angles is compared to the digital mode. The elements are cut with DeskCNC software on a CUT1000-S machine by CNC-Multitool. The machine code is generated with the grasshopper model described in chapter. The EPS quality used was 30kg/m3
The dimensions were checked with a scale. Accuracy to 0,5mm possible.

Test 1
The first test run was done to gather data on the width of the cutting slot, at a certain cutting speed in relation to electric current and potential. The current and potential were set at 3,4 A and 42V. The wire temperature was not measured, because only the cutting slot width and surface quality are considered relevant. The feed rate was set at 600mm/min.
Test 2
In the second test the cutting process has been applied right after the script generation from grasshopper. The cutting speed was set to a lower feed rate of 300mm/min.
Test 3
The third test has improved accuracy of the machine. The top surface of the raw material has been used as a reference plane to align the plate perpendicularly with the initial position of the wire. The alignment of the element to the home position of the wire was done by hand using an engineer’s square. Thin EPS spacers were used to align the reference surface perpendicular to the wire.

Results

Spindles were rotated around central axis of guidance rods (backlash). Deflection of 20mm occurred at the top. (fig explaining table)

speci-men	d1	d2	d3	d4	gap [mm]
virtual	196	191	185	180	
virtual	191	186	180	174	
1	-	-	-	-	-
2	196,5	192,5	186	180,5	
	191,5	188	181	175	
2	196,5	193	186	181	
	192,5	187	181	175,5	
					3
					2,5
2	196	191,5	185,5	180,5	
	191,5	186,5	181	174	
2	196	191	185,5	181	
	191	187	181	174	
					0,5
					0,5

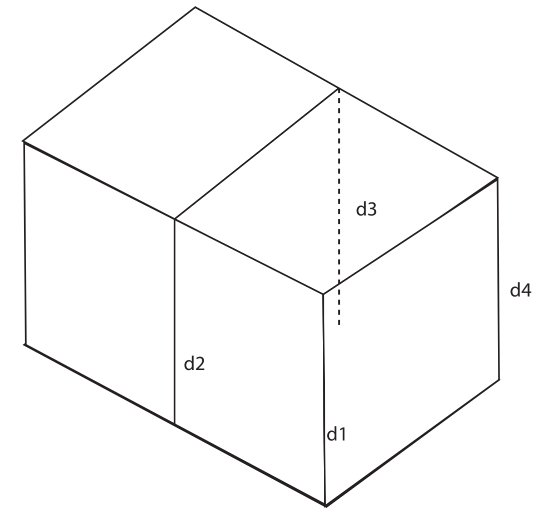


Figure 4.40 - distances measured for accuracy

Test 1

Corners not sharp, wire was dragged trough the material. Feed rate set back to 300mm/min resulted in a nice clear cut. Cutting slot thickness measured 4mm. Results were unusable

Test 2

Melting bath precedes the wire. A 2,5mm gap between cut specimens occurred at the edge representing the joint between two adjacent sandwich elements.

Test 3

No significant gap between specimens. Dimensions within 0,5mm accuracy

Conclusions

Test 1

The material needs to melt away before wire. In order to make the cutting slot precede the wire, either the wire temperature needs to set higher or the cutting speed lower. Threshold for cutting slot is set to 2mm in the parametric model. Recommended is to test cutting slot width, by stacking a number of cut slabs and calculate average cutting slot width.

Test 2

Spindles and referencing of raw material are inaccurate which causes the result to divert from the digital model. Aligning the raw material with one reference surface perpendicular to the cutting wire. Also rotated rails spindles cause slight inaccurate results. This rotating

Assumed is that the alignment to the wire is of bigger influence on the accuracy than the backlash of the spindles. The influence of the backlash is dependent on the angle of the wire compared to the horizontal start position. Figure
To illustrate the effect: The maximum difference in x-y-, coordinates of the spindles is 107mm. Over a distance *d* the maximum angle in the test specimen is 2,91°. With a backlash of 20mm each side, the angle new angle is 2,97°. The difference in angle of 0,06° causes a size deviation of 0,2mm.A 20mm backlash is really big, it is not difficult to prevent this from happening with minor hardware changes.

test3

The result shows that there is no significant effect of differences in heat accumulation and melting behavior at the curved surface, cut with different spindle paths.
Although the spindle paths have significant difference in length, the cutting paths in the raw material are actually quite similar in length. The projection of the cutting path onto working plane of the left spindle, magnifies the path and the difference. In some cases this results in a negative displacement of the spindle, while the path is cut in positive direction.
Placement of the spindles closer to the work

Summary

Inaccuracy due to unequal heat accumulation is negligible, but placing the spindles closer to the work piece would make the difference smaller. The projection is then
Inaccuracy due to backlash not of significant influence, though effects can easily be prevented by adding a guidance rail at the top. More advanced wire cutter machines are already provided with it.
Accurate placement of the raw material is of importance. Physical reference plane should be introduced by a set of clamps or rollers, to ensure one face of the raw material is perpendicular to the wire in the initial state.

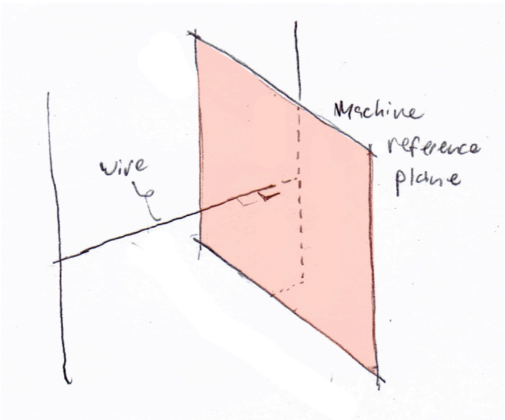


Figure 4.41 - reference plane perpendicular to initial wire position

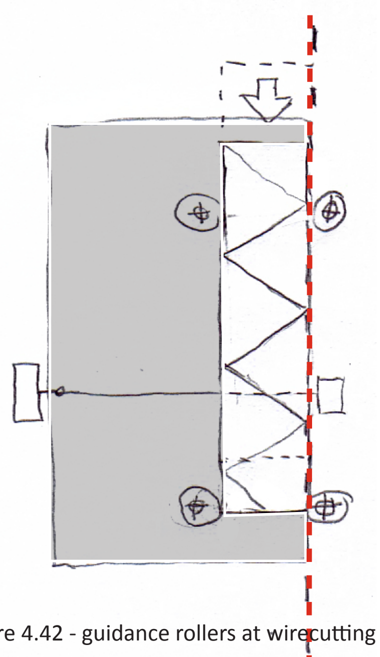


Figure 4.42 - guidance rollers at wirecutting macine

4.2.2. Production of faces and inserts

Test topics are :
accuracy of faces
stretch effect
spring resistance of fibers

4.2.3. Accuracy of faces (stretch effect/ vacuum deformation)

The vacuum injection moulding was tested for the magnitude of the deformations under vacuum pressure. Besides that, the implementation of shear webs within an element was tested. The difficulty is that the shear web has to be impregnated by the resin in the same time the complete outside face is impregnated.
Injection resin used is Sicomin S8100 with hardener SD7831 (slow hardening for injection applications). Mixture of 100ml: 30ml resp. resin and hardener. Used vacuum pressure of -0.8 bar compared to atmospheric pressure of 1,0bar. A flow mat was applied to improve resin distribution over the work piece. Two resin supply tubes were used; one for impregnating the shear web and one for impregnating the face.

Result 1
Application of resin in two stages worked fine, resin flows out of glass fibres forming shear webs. After first valve was closed, flow stopped completely. Other resin front flowed by without being obstructed or enclosing air bubbles.

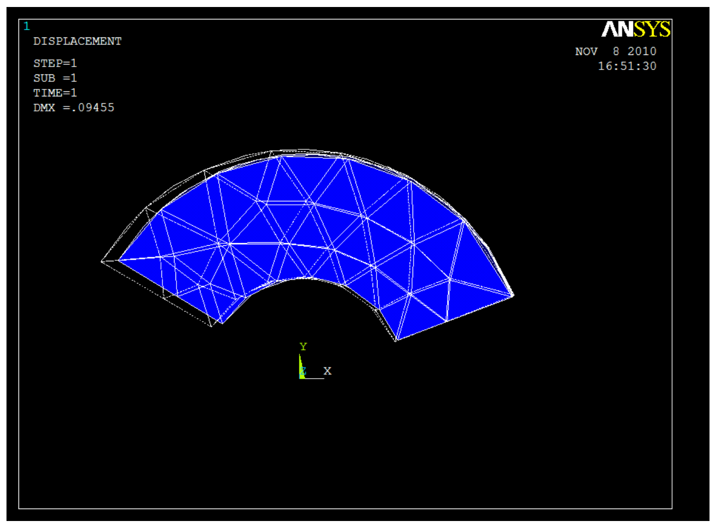


Figure 4.43 - Finite element analysis on deformation under vacuum pressure

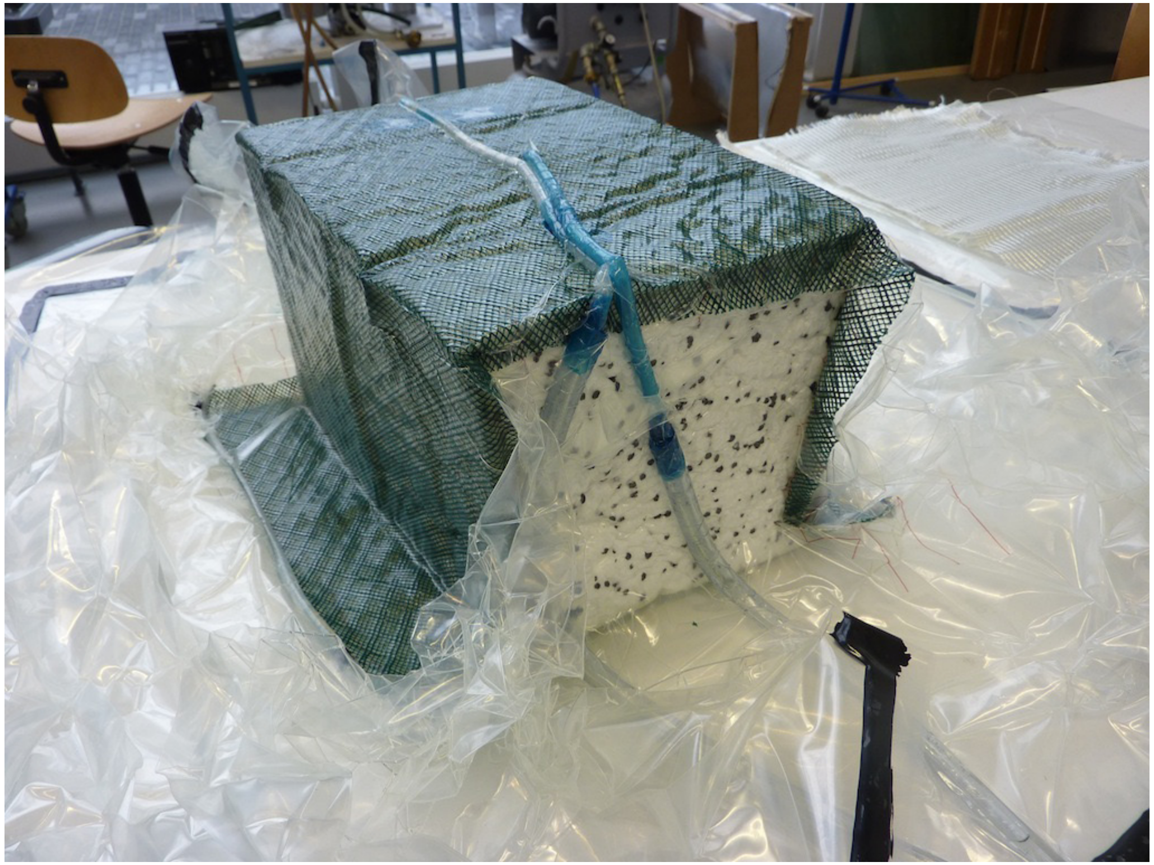


Figure 4.44 - first production test model

Foam core deformed, with irregular pattern. Dents on the surface of the core occurred and the composite face was not smooth. First hours result looked all right. Air bubbles kept flowing out of the element.

Conclusions
Bubbles keeping flowing out of the element are probably formed from air initially enclosed by the foam. This effect was slow by the high resistance, which caused the result not to be visible in the first 2 hours. But caused the foam core to partially collapse during the hardening process of 24 hours. Another test with significant lower pressure is necessary.

Test 2
A second test of vacuum injection has been performed with a vacuum pressure of -0,35bar compared to atmospheric pressure.

Result 2


Figure 4.45 - second test element

No significant deformation with occurred with lower vacuum, resin distribution was good. Dimensions of the core were checked and corresponded with initial dimensions of cut EPS elements. Surfaces showed some irregularities.

conclusions

Control over elements shape is good, but surface accuracy is not good enough for producing accurate segments. Inaccuracy of surface implies that the side surfaces of the elements cannot be used for accurate referencing of two adjacent elements at the connection. Because the core maintains its dimensions, the core can be used as a reference for the connections.

4.2.4. Spring resistance of glass fibers

Fiber mats were tested for their deformation and thickness control under vacuum pressure. Specimens are cut from two test models, which were injected with resin under vacuum pressure of -0,35 and -0,8 bar relative to atmospheric pressure. 1 bar = 0,1N/mm2

$$\sigma = E\varepsilon$$

$$\varepsilon = \left(\frac{\Delta l}{l_0}\right)$$

Results

Average face thickness was 2,7mm with 6layers of -0.8 bar vacuum. At -0.35 bar average thickness was 2,8mm. Values are close to expected thickness of 2,9mm. Irregularities in specimen thickness occur were glass fabric was creased.

Figure 4.46 - specimens measured for thickness

1	3	2,9
2	2,9	3,1
3	2,7	2,8
4	2,8	2,9
5	3,1	3,2
6	2,9	2,7
	2,9	2,93

Figure 4.47 - table thickness of specimens in mm

Conclusions

Vacuum pressure is not of significant influence on face thickness. Strain is negligible. Calculation of the mechanical strain of glass is in accordance to a negligible strain (formula).

$$\varepsilon = \frac{0{,}080}{70000} = 1{,}1 \cdot 10^{-6}$$

$$\varepsilon = \frac{0{,}035}{70000} = 5{,}0 \cdot 10^{-7}$$

Irregularities in glass fabric caused values to fluctuate. Glass fabric needs accurate fitting and cutting. This can cause significant problems when double curved surfaces are considered. All surfaces of the sandwich element that are covered with glass fabric should be developable[?]. Warped surfaces are possible to cover as well.

5. Evaluation

The design can be evaluated to the requirements stated at the start of this report.

Stated requirements:
- Universal system
- Physical barrier wind and rain
- Structural performance

The design aspects in chapter 2 formed a frame of additional aspects that had to be taken into account with the design of the system. These aspects were inherent to the choice for designing a sandwich element from Epoxy and EPS and the chosen production techniques.

Universal
A main goal of this research was to design a universal construction system for freeform architectural surfaces. However the application is tested in the context of the Arnhem OV-terminal only. Despite that, the freedom of form within the reference surface represents a broader variety of forms. The 3D- algorithmic models for subdivision and machine code generation, allow any surface to serve as an input reference surface.
The design of the system resulted in a segmentation of triangular flat faces. Approximation of the freeform surface is not perfect, but the exterior faces are smooth and the surface quality is good. Any design were a triangulated freeform surface is appropriate the system can be applied. If a certain freeform design requires other materialization or texture, the system can act as a structural and physical performing basis. An esthetical finishing layer of any kind can be added broadening the possibilities for application.
The point support can be replaced by linear or radial beams and in vertical configuration, floor edges can act as supports.

Structural performance and physical performance
The structural analyses in chapter 4 showed convincing results to believe that the system performs structurally. Self-supporting triangular segments with a 14m side can be applied in any configuration. High shear forces and stress concentrations occur near the supports. Additional construction elements are implied in the elements to carry the loads without exceeding stress limits of the used materials.
The physical performance is terms of protection for weather influence is good. Water cannot penetrate the construction. The rigid joints are sealed with kit and the expansion joint connected by a flexible seam acting as a drain as well. The EPS core is acting as thermal insulation and the minimum construction thickness exceeds the minimum thickness for insulation. Thermal expansion of the faces is taken by the expansion joints. Thermal warp remains within the deflection limits when the segments have a maximum size of 14m.

Efficiency
The uniformity of the elements results in CNC production of elements without the need of manual operations, saving valuable production time and the accuracy of the CNC referenced production process.
The only additional structural elements are columns with a specified length. Compared to the complex constructions of

the reference projects, a simple column support is very efficient. Only a small amount of linear construction elements have to be custom produced. Besides referencing the support position, there is no need for measuring at the building site. The elements can be bolted together quickly resulting in decrease of building time. The lamination process of the elements is a bottleneck in production efficiency.

6. Recommendations

- Analyze all elements before starting to built

Structural tests are performed on one element in particular with the assumption it represents a the least favorable conditions in a freeform building envelope. Despite that, the possibility exists that there are exceptions. It is recommended to perform structural analyses on the other segments as well before building.

- Possibility of integrated building surfaces.

The sandwich elements have a thickness of 450-550 millimeters, derived from the construction aspects. The core however is weak and its main structural use is to maintain the distance between the sandwich faces. Besides that, the thickness is not necessary for insulation. An option is to implement internal ducts for electrical wiring or ventilation or sprinklers. Because the direction of the ducts will be perpendicular to the CNC cutting wire, an additional manual operation is needed to implement the ducts. However, because the ducts are inside the sandwich element accuracy demands are low and removing material from the EPS core is easy.

- Deflection compensation

The initial deformation of the roof segments caused by its dead weight can be compensated in advance by performing a finite element analysis on the roof segments, loaded with negative gravitational force. The segment will deform in the opposite way of the initial deformation. Using the deformed segment as an input reference surface in the division model will counteract the initial deformation.

- Environmental impact

Epoxy is toxic and there are health hazards for people processing the material. Alternative composite materials could be considered, for instance acrylic based resins or fibre reinforced concrete. Different material properties should be researched for their effects.

7. Terminology

CNC
Computer Numerical Controlled, automated machining from digital data.

Core
Internal part or middle layer of a sandwich element, commonly foam.

Envelope (building-)
Barrier between interior and exterior i.e. façades, roof

EPS
Expanded polystyrene

Face
Structural outer layer in a sandwich element

FRP, gfrp
(Glass) fibre reinforced plastic

Reference surface
Surface describing global geometry of roof/façade structure

Thermal warp
Deformation caused by local differences in thermal expansion

XPS

Extruded polystyrene

8. Literature

Books

Allen, H.G., 1969, *Analysis and design of structural sandwich panels*, 1st ed.
Pergamon, Oxford

Schodek, D., 2004, *Digital design and manufacturing* 1st ed.
Wiley, John & Sons, Incorporated, New York

Kolarevic, B., 2003, *Architecture in the digital age, design and manufacturing*, 1st ed.,
Spon Press, New york

Koschade R., 2000 *Die sandwichbauweise*, 1st ed.,
Ernst, berlin

Pottmann h., Asperl A., Hofer M., Kilian A., 2007 *Architectural geometry*
Bentley institute press, Exton

Knaack U., 2007 *Facades: Principle of construction*
Birkhauser Basel

Gerrits J.M., 2006 *Draagconstructies basis*
Delft university press, Delft

articles/theses

Diks M.E., 2005 *Translucent sandwichsysteem voor dubbel gekromde toepassingen*,
Master thesis, Laboratory Materials & Constructions Faculteit Bouwkunde TU Delft

Huyge K., Schoofs A., 2009 *Precast Double curved concrete panels*,
Master thesis, Laboratory Materials & Constructions Faculteit Bouwkunde TU Delft

Eigensatz M., et al. 2008 *Panelling freeform architectural surfaces,*
Advances in Architectural geometry conference, Vienna Austria 18/09/2010

Eekhout M., Visser R., *GRP sandwich structures for liquid design architecture*
International symposium on Shell and Spatial Structures September 6-9, 2005, Bucharest, Romania

electronic sources

Granta design limited, 2010, CES material database
Cambridge

Bokel R.H.M., at TUDelft (2008) *Lecture sound insulation*
powerpoint slides retrieved from http://blackboard.tudelft.nl

unknown author/date of publication, Brandveilig bouwen met EPS-SE
Stybenex, vereniging van fabrikanten va EPS bouwproducten
retrieved from www.stybenex.com

Appendix A. Parametric Modeling and machine code generation

Subdivision model

Requirements

Triangles with edge length in range of 2,2-2,6m

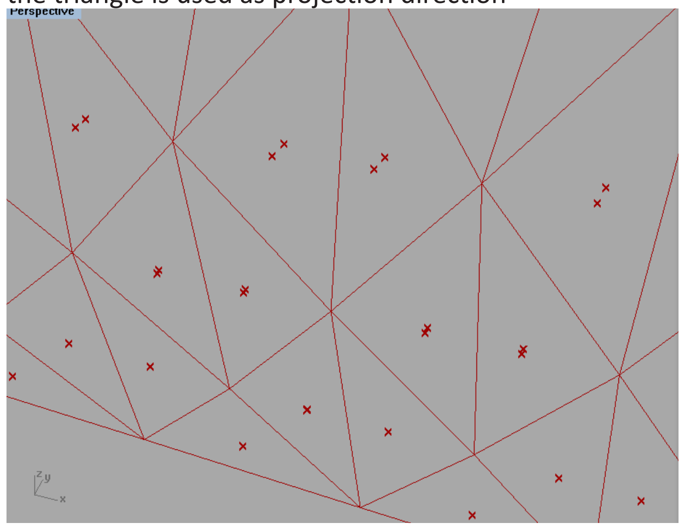
Subdivision initial triangular surface grid

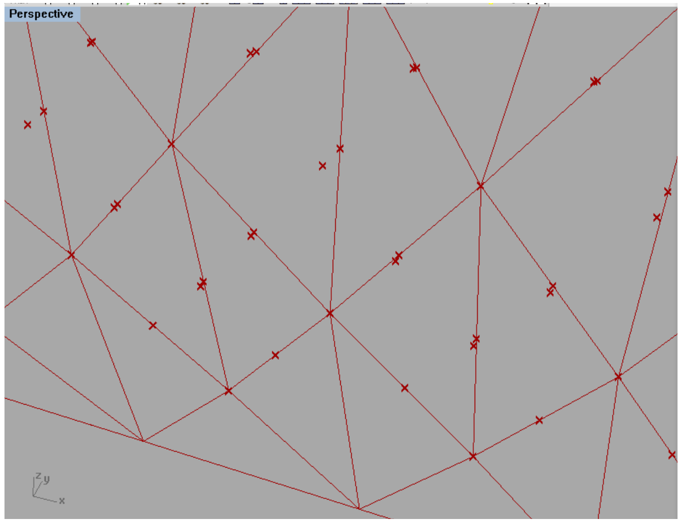
Starting point and x, y –directions are specified. Rectangular grid with equal surface distances created triangular mesh based on surface grid.

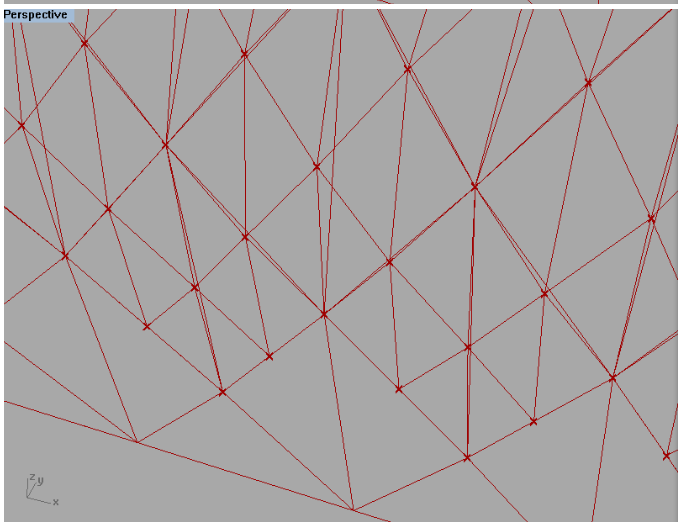
Mesh refinement

Parameters

Triangular surface mesh and Offset mesh. Maximum distance between mesh triangle and reference surface analyzed. When distance exceeds threshold, midpoints of edges are extracted and projected on the reference surface. The surface normal of the triangle is used as projection direction







4 new triangles are formed from the 3 initial corner points and the new points projected on the reference surface.

Mesh and offset of entire mesh at 450mm form bases and tops of prismatic elements

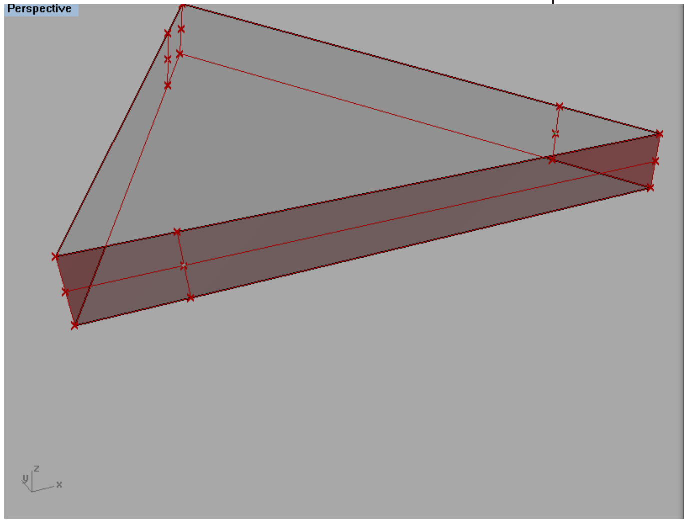
Consequences
mesh size < curvature radius results in self intersecting elements.

Conclusions
Regions with curvature radius smaller than element thickness need to be revised, milled out, manually finished.

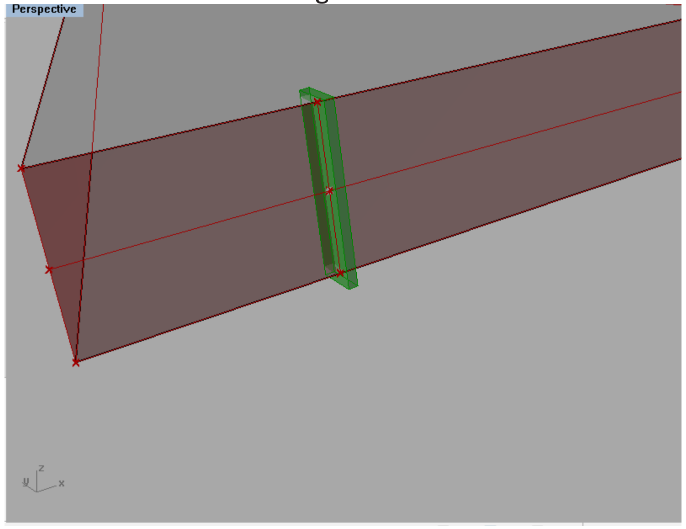
Elements

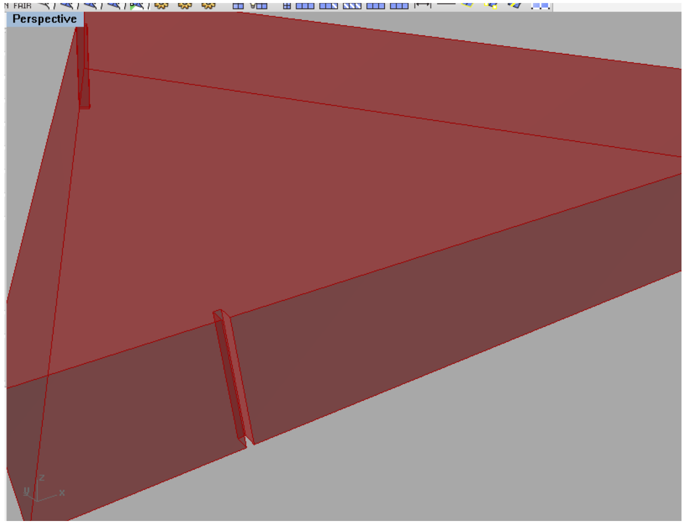
Elements are exported and used as input for the machine code model. Elements geometry is described by two triangular face borders.

References lines are introduced between two points at same period along bottom and top edge curve.

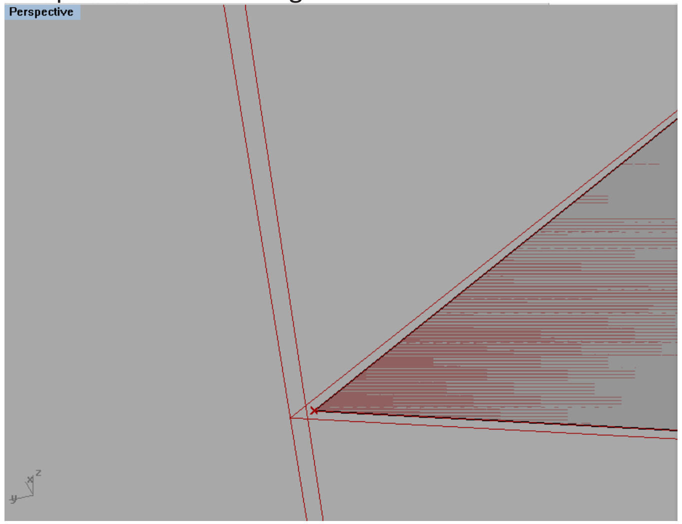


Extrusion is oriented to align reference line of fixture components forming the space for fixture components.

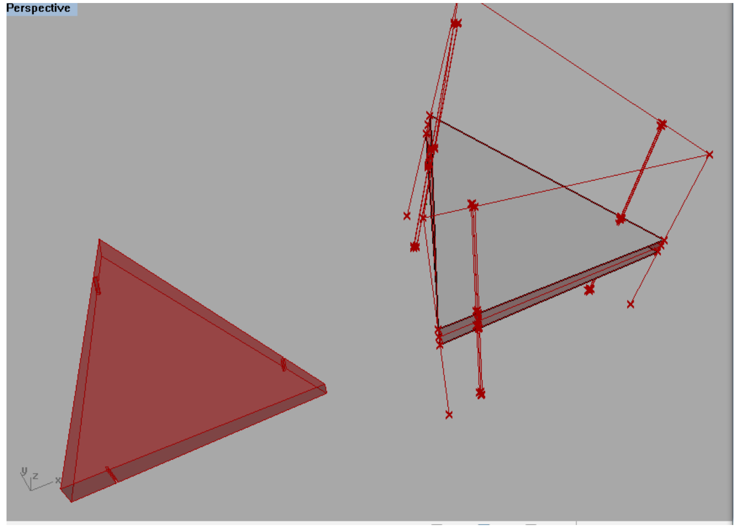


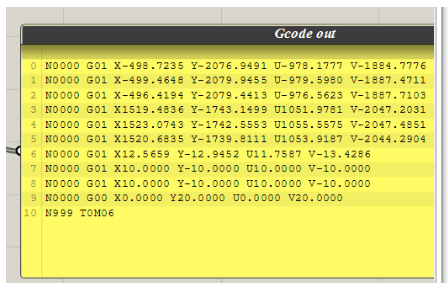


Face borders are extended with extrusions and joined into one curve. Curve is offset in plane with variable threshold as a compensation for cutting slot. The element faces are offset



Corner points are connected and projected to two planes perpendicular to the base of the element, forming the coordinate points for the CNC spindles to move to.





Points coordinates are converted into Gcode, readable by deskCNC.

Appendix B. Analitical calculations model Chapter 2.3

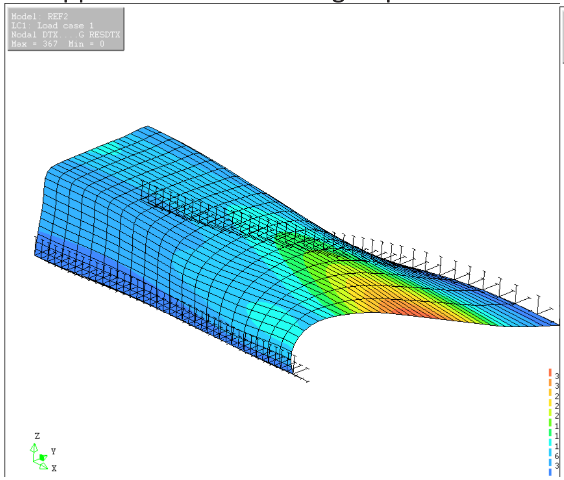
	ρ	γ	t		
live load	1,50	1,000	1,5		
deadload	0,32	0,530	1,2		500,000
deadload	0,14	20,000	1,2		6
	+				
loadcase 1	1,96			N/mm2	
Variables					
load	q		2,00	N/mm	
length	l		14000,00	mm	
face thickness	t		3,00	mm	
width	b		1000,00	mm	
Emodulus face	Ef		2,64E+04	Mpa	
Emodulus core	Ec		7,70	Mpa	
poissons ratio core	vc		0,30		
yield strength	sgmax		280,00	N/mm2	
core thickness	c	dmin-t	513,37	mm	
sectional area	A		516369,82	mm2	
shear modulus core	G		5,50	N/mm2	
buckling constant	B1		0,57		
	B2		0,39		
critical stress wrinkling	sgcr_wr		45,81	N/mm2	
critical values normalstress, shearstress and deflection					
	sg_maatg		45,81		
max shear stress core	*Tau*		0,31	N/mm2	
max deflection	w1	0,004*l	56,00		
min thickn. bending mo	dmin M		356,56	mm	
min thickn. Shear force	dmin V		45,16	mm	
min thickn. Deflection	dmin W		516,37	mm	
min thickness	dmin		516,37	mm	
flexural rigidity	D		1,06E+13	mm4	
maximum bending mom	m		4,90E+07	Nmm	
normal force face	N_huid		9,49E+04	N	
normal stress	sg_n		31,63	N/mm2	
shear force	V		14,00	N/mm	
shear stress	tau		0,03	N/mm2	
deflection	w		56,00	mm	
	rho		0,09		
			1,04E+13		
deflection1			47,93	mm	
deflection2			8,63	mm	

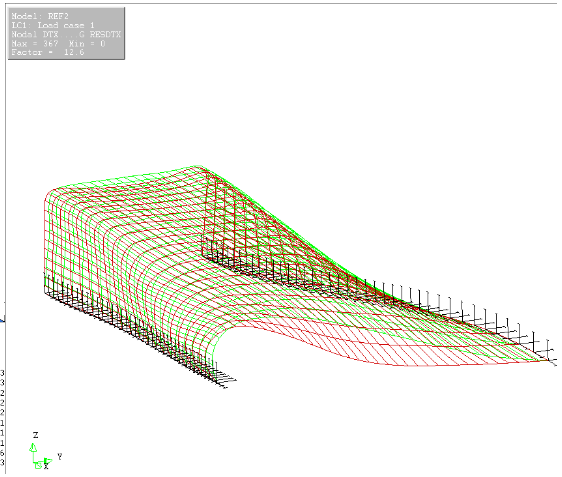
analitical calculations (continuation)

cost optimization thickness ratio					
cost face	uf		37000	eur/m3	
cost core	uc		60	eur/m3	
	h^3		1950259448,70		
optimum height	h		1249,39	mm	
optimum face	t		1,01	mm	
	t		0,51		
height core	c		1248,38		
optimum height	d2		1148,60		
combined face thicknes	t		1,86		
	t		0,93		
calculation of critical face stress initial irregularties					
	t		4,00		
	c		450,00		
	Ef		27500,00		
	Ec		7,70		
	C		2,09		
half wavelength/thickne	l/t		31,45		
wrinkle half wavelength	l		125,78		
initial deflection	w0		1,00		
ultimate stress	su		0,25		
konstant	k		0,068		
measure for sandwich p	rho		0,14		7,360
	teta		11,24		
		(	7810358861,61	)	
		(	154059188632,29	)	
	f(teta)		0,05		
buckling constant 1	B1		0,57	first term B2	
			0,70	second term B2	
buckling constant 2	B2		0,39		
critical stress	s cr		46,44		

Appendix C. Structural Analysis

unsupported roof shell - single span

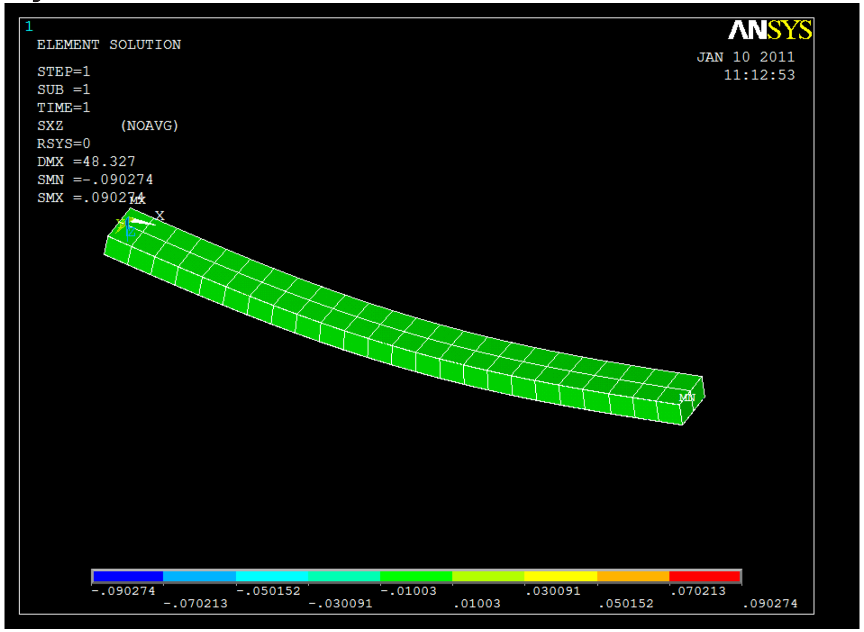




Conclusions

Deformations too big face stresses of 204 N/mm2. Analytical model shows minimum thickness of 1700-2500mm, unrealistic

reference beam 12m

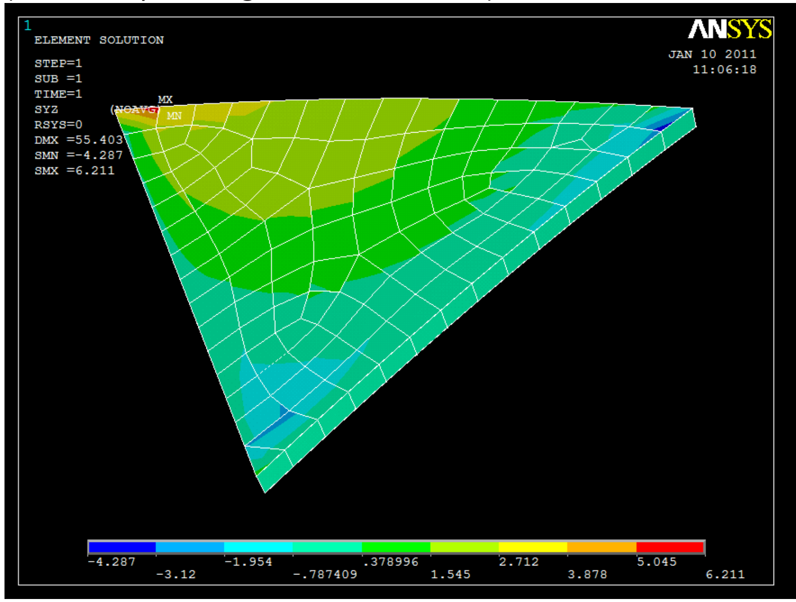


shear stress 0,09N/mm2, total deflection 48mm

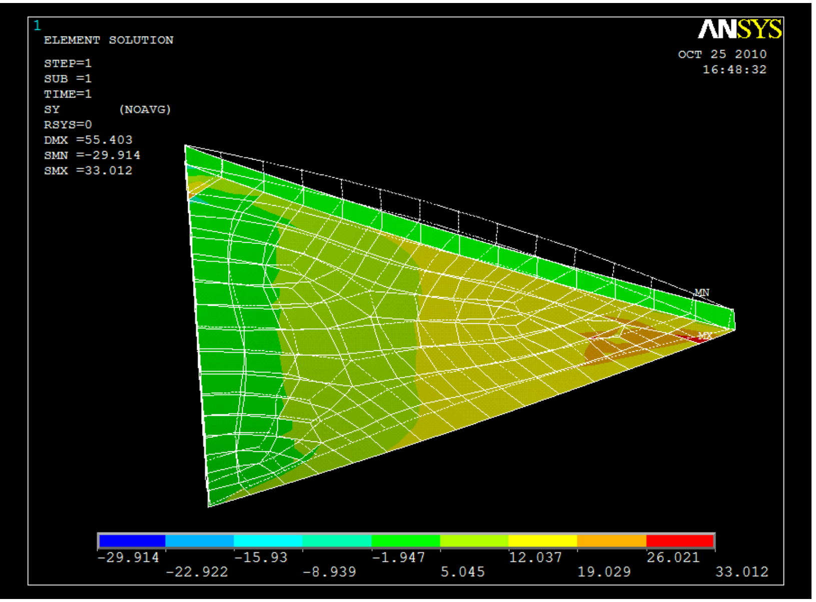
Appendix

Roof segment 12m

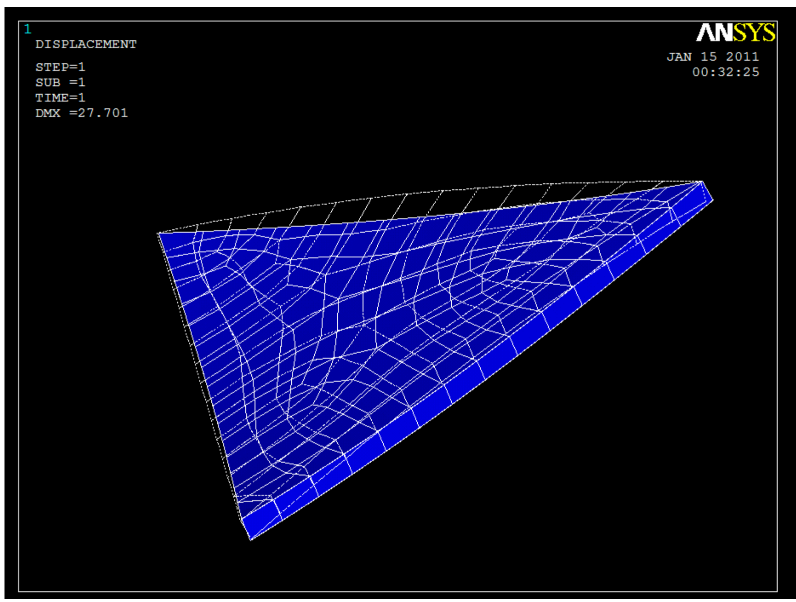
(all same layer configuration 4-450-4mm)



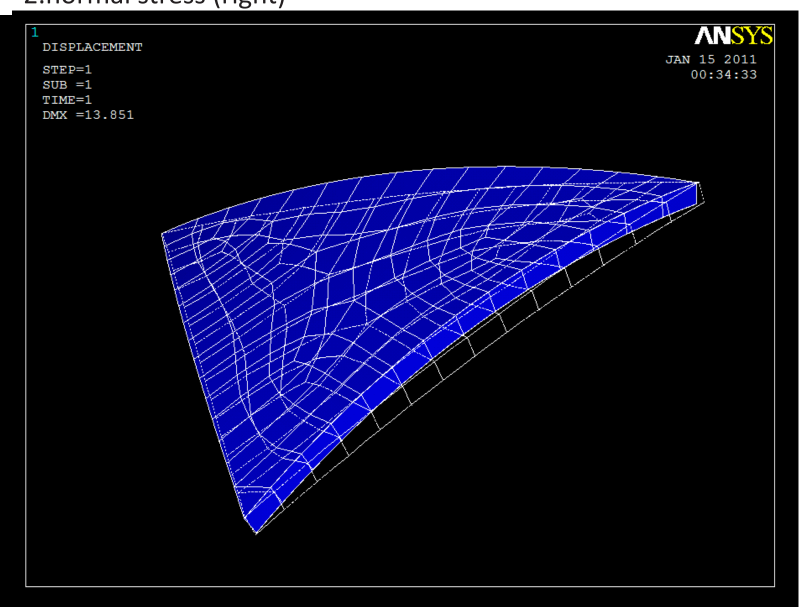
1. shear stress



2.normal stress (right)

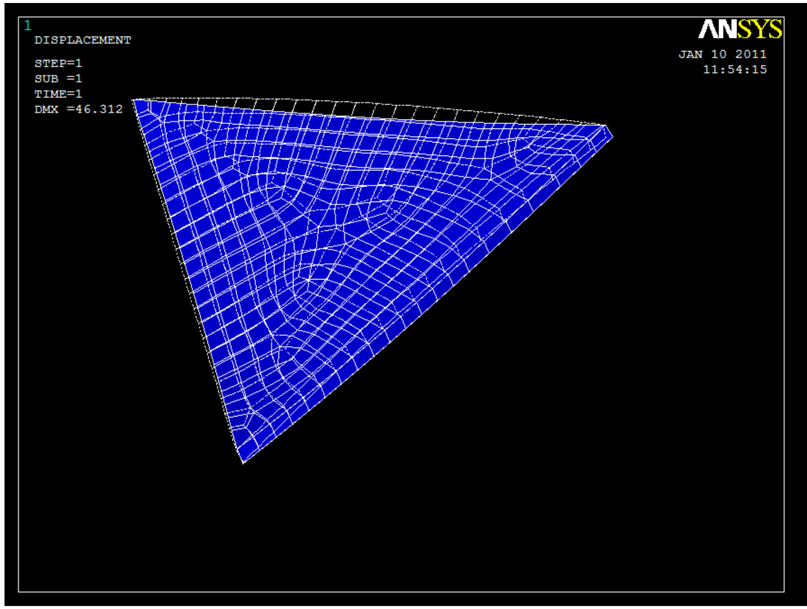


3. deflection caused by live load without safety factors (1,0kN/m2)

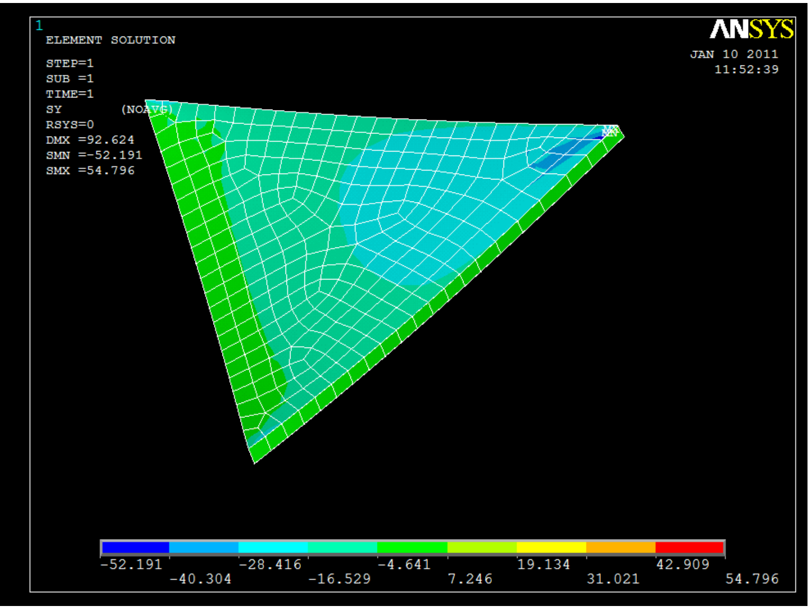


4. deflection caused by negative gravity to compensate initial deflection

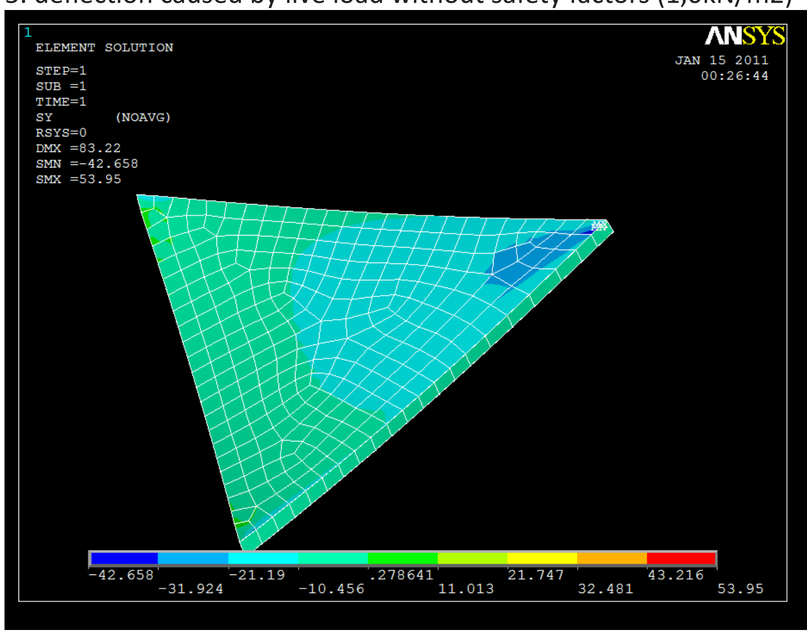
Roof segment 14m



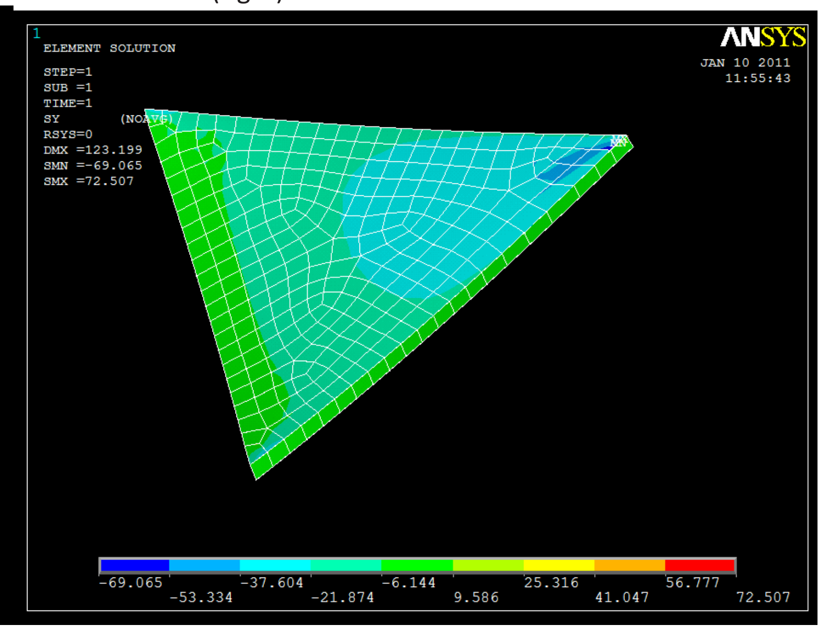
5. deflection caused by live load without safety factors (1,0kN/m2)



6.normal stress (right)



7. normal stress with layer thickness 5-500-4mm



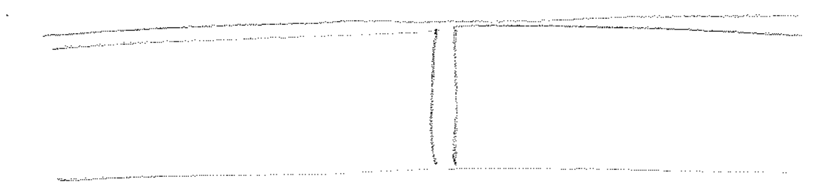
8. normal stress with layer thickness 5-500-4mm

Appendix D. Connections

Continuous sandwich face

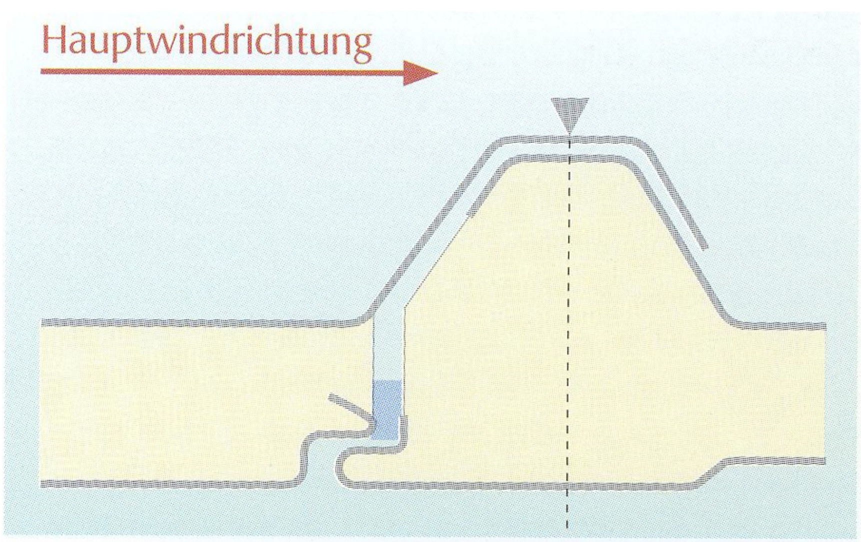
The continuous face is providing structural, physical and an esthetical quality in one solution. Despite that, it is difficult to apply the entire inner and outer sandwich face on site, either with vacuum injection or spraying of resin. The roof geometry has to be built up from EPS core elements supported by scaffolding. Liquid resin has to be applied on the interior were it has to be held in place and must not intervene with scaffolding parts. On the exterior the resin needs protection from weather influences, which can be achieved by placing a large tent.

Single surface solutions only up to lengths of 18m (chapter thermal).

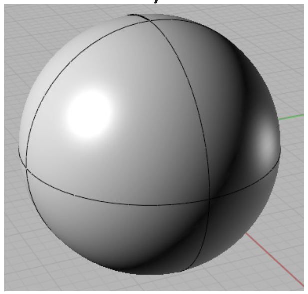


Prominent profiling

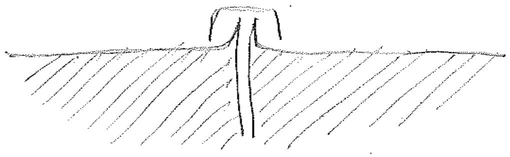
Analysis of sandwich elements for flat roofs (sandwichbauweise) showed a common solution for preventing water flowing into the construction. Prominent profiles at the edges of sandwich faces have been applied to ensure that water coming from the top flows to the lower part of the sandwich element, away from the seams. This principle is very useful for sandwich elements in a flat horizontal configuration. It is very complex in production because when the elements are curved or double curved.



The lines on the sphere can represent all the possible edge configurations. It can be possible to use the sphere and its world coordinate system to make the overlap in downward (or –z) direction.

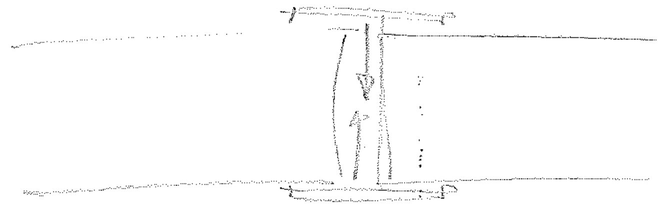


A less complex variant is to detach the overlap into separate upstanding edges at the sandwich face edge and make a profile fit over it. Water will flow to the lowest point and not into the construction. This, however, does not work when al the edges on the top face are directed upwards, the face will act as a basin and water will accumulate. At the lowest point water will flow over the edge into the construction. This means the profile is of no use.



Seal strips

Seal strips can be placed on top of the connection and consist of a pressurized strip with rubber seals underneath.
The solution allows some dimensional tolerance, without giving up the rigidness in the connection. This is an advantage when production is not accurate. The seal strips might also be useful for type 2 connections.

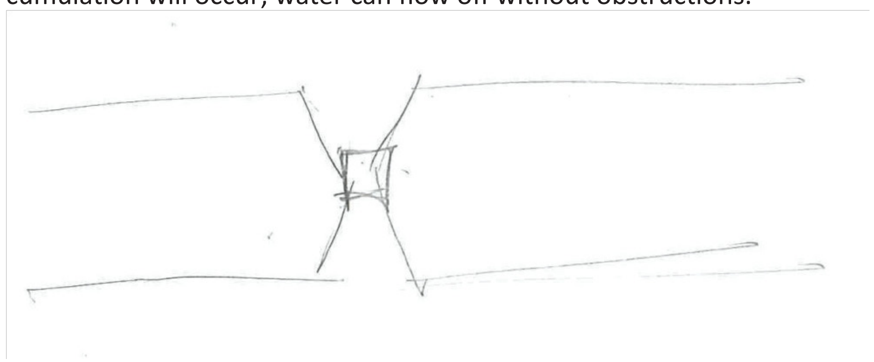


Structural quality
The seal strips can also add in structural quality when build up from two components. The lower part of the strip is a structural connection between two separate sandwich faces. This will mainly carry face stresses and not take care of shear stress. Additional measures for shear stress can be thought of like adding dowels or constrain the strips in rotation.

Adding dowels has the disadvantage that shear stress working in a section plane is concentrated in points. Because the dowels are placed in the foam core, this concentration of stress is undesirable.

Consequences
The faces of the element have to be tough enough to resist the pressure from the strips. Besides that the face edges have to be flat to ensure a good seal is possible. Profiles stand out of the surface, which emphasizes the subdivision.

Compound injections
Considered options for compound injections were flexible sealant or liquid resin. The major advantage is that no water accumulation will occur; water can flow off without obstructions.



Structural properties
Structural properties depend on how the connection is made. This connection type carries shear forces and compressive stress, but tensile forces cannot be carried without reinforcement like for instance fibres.
Cracks in the surface might appear in rigid resin injections, sealant is has no structural quality. A combination of a structural resin and a flexible coating can offer a solution.
Another risk is that the injected material does not fully seal all the seams. This causes leaks in the roof construction.

Consequences
Additional friction patches are needed at the elements face edges to ensure good adhesion of the compounds. This addition will be difficult to fit in the cnc production process and will probably need extra an extra manual step in production.

Cables
- Potential of quickly assembly
- Principal stresses trajectories
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Consequences
- Wind pressure and suction
- Positioning in structure
- Increasing compression