Faculty or Engineering Science and Technology

# Analysis and Optimization of Sandwich Panels

*Final Report*                                      *06.06.17*

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# Preface

In the last semester of the Engineering Design on UiT-Campus Narvik, it is written a Master thesis on 30 credits. We had the option of finding a project ourselves, or we could choose from a presented list in class. I chose the problem, "Numerical calc. and optimization of sandwich components (TAM AS)" from the list in the class. I chose this problem, because I think sandwich construction are an exciting topic, and I like mathematical equation and numerical analysis. That the project was for a company, was also positive, because than I got to get in touch with the company.

# Acknowledgements

06.06.17.     Narvik

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# Abstract

The first part of this project, are general about sandwich structures. A sandwich construction, consist of two plate outsides (facings) glued to a core in the middle. Sandwiches are used in construction that must have a low weight, but a high stiffness. This indicated racing cars, aeroplane, ship shelters. To understand a sandwich construction, the basis, is to understand the sandwich beam. The are given a short description to find the deflection of the beam.

The rest of this project, regards the calculation of a homogeneous, isotropic sandwich shelters. The objective is to reduce the mass of 20ft sandwich shelters from TAM AS. The background for this project, was the article: "Optimal Stiffness Design Plates with Variable Core Densities". When we use, the methods described in this article, we find the inverse stiffness of the shelters, and from this optimal facings thickness, shear modulus for the core material and d, to reduce the weight of the shelters. The optimization are do it graphically. In the optimized of the shelters, only the walls are optimized, because the roof and floor is not symmetrical.

When we optimize the parameters, the weight of the shelters can be reduce with 43.2kg. This are approximately 7.3%.

To verify the calculation of the inverse stiffness of the shelters, the deflection of the shelters was calculated both analytical and numerical with four random pressures. The largest difference between the analytical and numerical value was only8.8%, which is good.

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# 1  Introduction

The Master thesis "Analysis and Optimization of Sandwich Panels" have the objective to reduce the weight of a mobile lightweight shelters from TAM AS. The project has the background in the article "Optimal Stiffness Design Plates with Variable Core Densities" by Dag Lukkassen, Anette Meidell and Herman Myrvoll [1]. By using the algorithms in this article, the objective is to find the stiffness of the homogeneous, isotropic sandwich shelters, and from this, find out how much the weight of the shelters can be reducing. In this project, the calculating will be only of the walls of the shelters, because the roof and floor are not symmetric.

In the first part of this project, the will be given a generally info about a sandwich, so the calculation of the stiffness of a shelters is easier to understand.

## 1.1  TAM AS

In 1981 Tor O. Engvoll and Tor Arne Mentzoni established the company TAM AS at Bardufoss in Troms. Tor Arne Mentzoni give the name to the company, taking the first letters in his name, therefore TAM AS [2]. TAM AS designed and produced all types of tailor-made mobile lightweight multipurpose military shelters [3]. A sandwich shelters produced of TAM AS, is shoven in Figure 1. The mobile lightweight hard-skin shelters and expandable shelters for communication, radar systems, command posts, laboratories, command and control, offices, etc.



*Figure 1. Sandwich shelters from TAM AS [4]. .*

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## 1.2  The scope of the project

The aim of this project is to use the methods describe in the article "Optimal Stiffness Design of Sandwich Plates with Variable Core Densities" [1], from this find the inverse stiffness of the shelters  and from the calculation of the inverse stiffness, change the free variables, so the shelters have a low weight. Because the shelters are to be transported by small helicopters low weight is important, when allow for more payload in the shelters.

The plan is to first do a literature study to find the general algorithms, material properties of the sandwich, standards etc. After the literature study, the objectives to find the material properties and the dimension of material used in the sandwich shelters today, and from this properties calculate the inverse stiffness of the shelters. The stiffness of the new design of the shelters must be the same that the stiffness in the shelters today.

## 1.3  Constraints

In this project the calculation of the inverse stiffness of a sandwich shelter to reduce the weight of the shelters, involves the analysis of several variables. These variables are:

1. The materials used by TAM AS
- For the skins: aluminium
- For the core: polymer foam from DIAB

2. The weight of the shelters
The weight of the shelters must be low, because the shelters are to be transported of small helicopters. The lighter the sandwich shelters, the more payload can you have in the shelters.

3. Panel size.
The shelters are produced after the ISO 20 feet container standard[5]. The outer dimensions of the shelters are presented in Table 1. The thickness off the roof, walls, and floor are 42.5mm, 42mm, and 52.5mm Appendix A. Since the roof and floor are not equal on both sides, the calculation will be only of the walls.

| Length | 6058mm |
|--------|--------|
| Width  | 2438mm |
| Height | 2591mm |

*Table 1. Outer dimension of the shelters.*

## 1.4  The methods

An important part of this project, consists of calculating the inverse stiffness of the sandwich shelters, from TAM AS, which have dimension after ISO 20 feet container standard [5]. A drawing of the shelters, can be see in Appendix B. The facings shall be of aluminium and the core material are the H-grade core material from DIAB. The density and thickness of the core material can be changed. The calculation and graphing will be used in the program Scientific Workplace, as this program allows you to calculat with units, and makes it very easy to draw graphs. The numeric calculation will be simulated in ANSYS.

# 2  Interdiction to Sandwich Construction

For the reader of this project to be able to understand what a sandwich structure is, I will in this chapter describe what a sandwich is, how the sandwich is used, and the basic calculation of a sandwich.

A sandwich construction, is a construction of two skins/facings glued to a core, see Figure 2. Sandwich construction have a low weight and high stiffness. Therefore, are a sandwich good to use in a product who have claim to these properties. This can for example be a racing car, where these two characteristics are very important. A racing car must have a low weight, because the car must have a quick acceleration, but at the same time, have a high strength, when a collision occurs [6].  A sandwich are also used in aircraft, ships, shelters, ski, kayaks, etc [7].
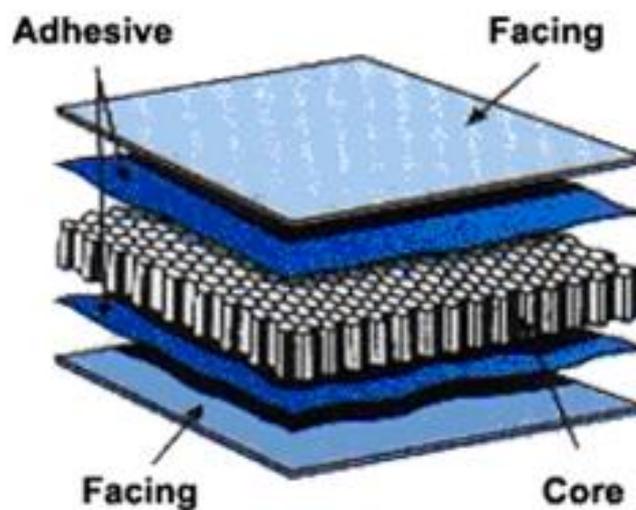


*Figure 2. A principle sketch of a sandwich plate [8].*

## 2.1  The history of a sandwich construction.

Historical we can look back to the 1820, then Frenchman Duleau, and later Fairbair, discussed the concept of using two co-operating faces, separated by a distance, but it was not until several year later, the concept was first applied commercially. Sandwich panel of asbestos faces with a fibreboard core was used in World War One. During the World War Two, the sandwich principle was used in the Mosquito aircraft in England. This was the first mass production of the sandwich. The faces to this aircraft was made of veneer and the core material was balsa wood [9]. The successful landing of a space ship on the moon, 20 July 1969, was a combination of many factors including the sandwich construction [10].

The first theoretical analysis of the sandwich construction, was used in World War Two. Between 1945 and 1955, was the several publications of the sandwich construction, about the strength and stability of sandwich beams, columns and plates. From the first theoretical analysis, and to about 1980, the publications was on primarily due to the practical difficulties such as in bonding the face sheets to the core, providing course of sufficient stiffness and establishing reliable repair and inspection procedures [9].

From 1980, the theoretical analysis of a sandwich, was concentrated to the optimization of the laminates with FE[1]-analysis. When uising FE-analysis, we get a more exact solution of the deriving and the solving of the difficult differential equation for the deflection of the sandwich panels, than the analytical calculating [9].

## 2.2  The main principles of a sandwich structure.

A sandwich construction is a construction consisting of two thin plates on the outside, also called the facings/skins, glued to a thick core material in the middle, see Figure 3. The facings are thin, stiff, and strong, and the core material is thicker and lighter [6].
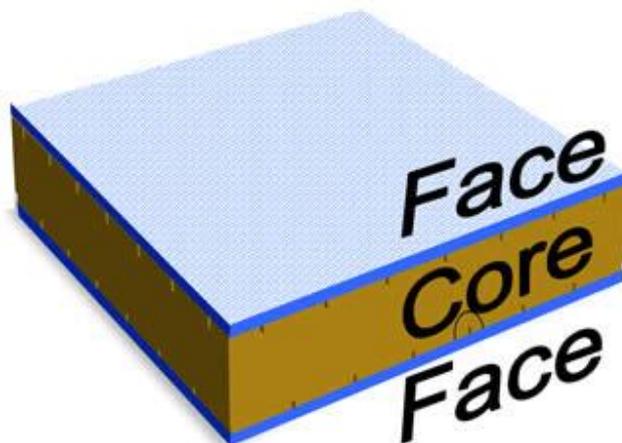


*Figure 3. A sandwich plate* [11]*.*

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[1] Finite element

The faces are glued to the core to obtain the load transfer between the components. The sandwich construction is like an "I"-beam, where the facings on the sandwich can be comparable to the flanges on the "I"-beam, and the core similar to the web see Figure 4. The facings carry the bending moment, there one facings are in tension, and the other facings is in tension see Figure 5. The core is resist to the out of plane shear loads, and separated the facings apart. This gives the sandwich panel a high moment of inertia, and thus high stiffness. The sandwich panel has the benefit, that the whole areais of the facings, are connecting to the core, but in the I-beam, are the flanges connecting to the web, only one the middle [12].
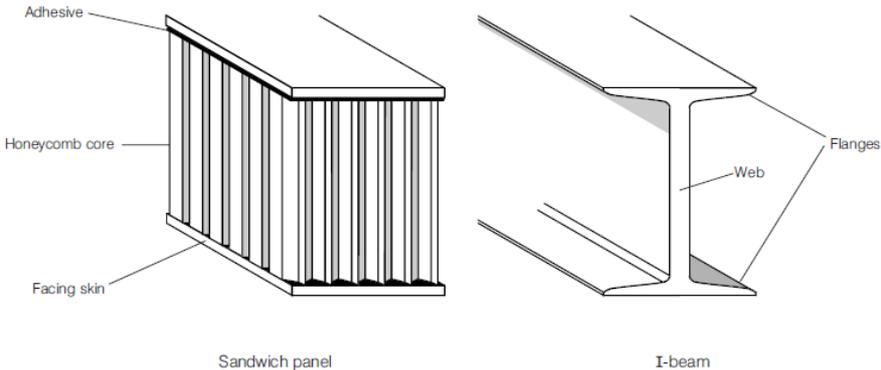


*Figure 4. Sandwich panel, and a I-beam [12].*
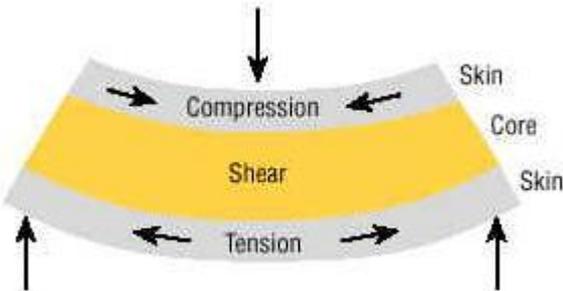


*Figure 5. The compresion and tension in a sandwich beam [13].*

In Figure 6, you can see the difference between a simple supported beam made of steel, and a sandwich beam. As you can see, the beam made of sandwich have nine time less weight, than the beam made of steel, but have the same deformation, with the same load [6].
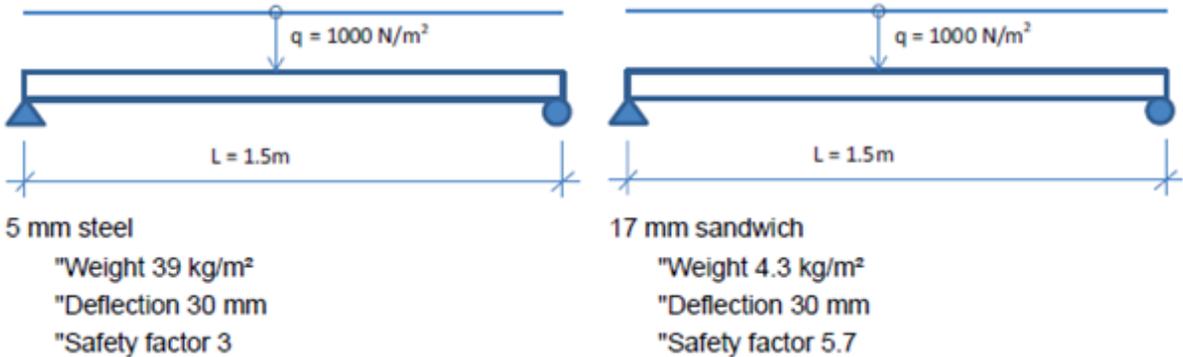


Figure 6. *Comparison of a steel beam to the left, and a sandwich beam to the right [6].*

## 2.3  Materials and the material properties in the sandwich

A sandwich structure has several components. The components in the sandwich, varies where the sandwich was used, the design requirements and the fabrications process. In this chapter the will be given a short description of the facings, core and the adhesive.

### 2.3.1  The facings material

The most important properties for the face materials in the design process, are listed up bellow [9].
- High stiffness giving high flexural rigidity
- High tensile and compressive strength
- Impact resistance
- Surface finish
- Environmental resistance (chemical, UV, heat etc)
- Wear resistance

The face materials are usually divided into two main groups: metallic and non-metallic. The metallic group, contains: steel, stainless steel, and aluminum alloys. The metal has a high Young's modulus and a high tensile strength, but they have also a high density. The non-metallic group, have many different material, and includes: plywood, cement, reinforced plastic and fibre composites [9].

### 2.3.2  Core Material

The core material, have the function to support the skins, so they not buckle, and keep the distance between the facings constant. Shall the core material do this, must the have some properties. The core must be stiff enough to keep the distance between the faces constant. The core must be so rigid in shear, so the faces not slide over each other [6]. In the list below, the main properties of the core material, are listed up [9].

- Low density
- Shear modulus
- Shear strength
- Stiffness perpendicular to the faces
- Thermal insulation

In the generally, the core material can be listed in four groups [14].
- Foams
- Honeycomb
- Corrugated
- Wood

In the sandwich, the foams material, are the most used core material. Foam core, can be manufactured of many different materials. The most used foam material has a density from 40kg/m$^3$ up to more than 200 kg/m$^3$, and the thickness of the foam materials, are often from 5-50mm [14].

Honeycomb cores have been developed and used primarily in the aerospace applications. But cheap honeycomb made from impregnated paper are also used in building applications. The most used cell shapes of the honeycomb cores, is the hexagonal shapes, but other shapes can be used, square shapes, over-expanded hexagonal, flex-core. A sketch of a hexagonal honeycomb, can you see in Figure 7. The material of the honeycomb can be: aluminum alloy, kraft paper, glass/phenolic Nomex [9].
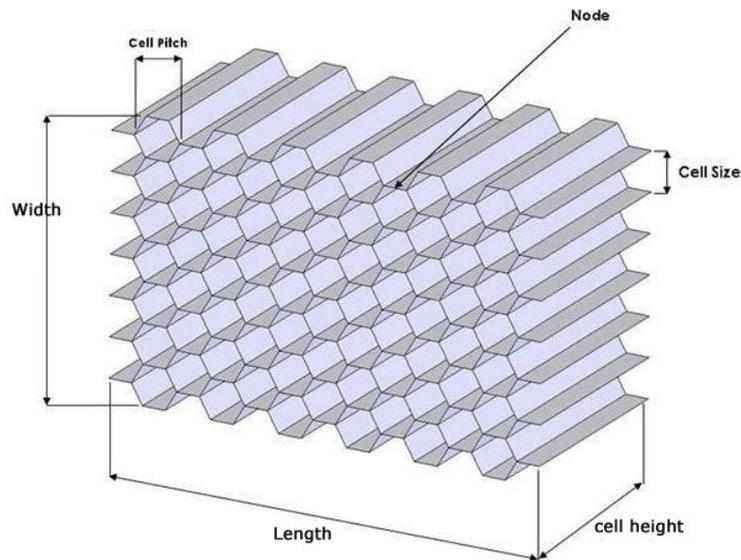


*Figure 7. Hexagonal honeycomb structure [15].*

Corrugated
The corrugated core, are profiled structures. For example triangle profiles and waves profiles. The materials can be: Aluminum, Steel, Stainless Steel, Titanium or any combination [16].

Wood
When you look in a microscope, you can see that the wood has a "honeycomb" structure. The wood has a similar structure that a hexagonal honeycomb, and have therefore a good mechanical property. Wood have a high density, at least $100kg/m^3$, and are only used in large construction [14].

-Balsa Wood
End-gain Balsa, is the most used wood core. Balsa wood have a good compressive property, and was first used in 1940`s, in flying boat hulls, with aluminum facings. The balsa wood, is also a good thermal insulator offering good acoustic.

-Cedar
Cedar is another wood, used as a core material. This material is often used in marine construction.

## 2.3.3  The Adhesive

A very important part in a sandwich construction, is the adhesives. The glued have the task to able the carry of shear and tensile stresses. A concreate demands to the joints, is hard to specify, but a simple rule, is the adhesive should be able to take up the same shear stress as the core [6].

## 2.4 Sandwich Shelters from TAM AS

A sandwich shelters are a lightweight cabin, as you can see in Figure 8. This cabin is very good to use, when you shall move it, because the cabin have a low weight, and therefore can you have more payload in the shelters. The sandwich shelter is used of the Norway army, because the cabin has a low weight and is stiff, and are therefore very easy to move with small helicopters, and good to use in mountain, because the shelters have a high stiffness [3].


*Figure 8.* Sandwich Shelters from TAM AS [3].

### 2.4.1 Materials used in the shelters

In the sandwich shelters from TAM AS, are the facings material aluminum. The most important properties for the facings are listed in Table 2.

| Type | Thickness [mm] | Density [kg/m$^3$] | E-modulus [GPa] | Poissons ratio | Tensile strength [MPa] | Yield strength [MPa] |
|------|----------------|--------------------|-----------------|----------------|------------------------|----------------------|
| Aluminum | 1mm/(1.5mm) | 2780 | 70 | 0.33 | 266 | 219 |

*Table 2. Face materials used in the sandwich shelters Appendix A and Appendix C.*

The core material TAM AS used in the sandwich, are Maciell and H-grade from DIAB (Appendix A). In this project, the are only looked to the core material from DIAB. The most important value for the core material, are listed up in the Table 3.

| Material | Grade | Nominal Density [kg/m$^3$] | Compressive Strength [MPa] | Compressive Modulus [MPa] | Shear Strength [MPa] | Shear Modulus [MPa] |
|----------|-------|-----------------------------|----------------------------|---------------------------|----------------------|---------------------|
| Divinycell | H35 | 38 | 0.5 | 40 | 0.4 | 12 |
| | H45 | 48 | 0.6 | 50 | 0.56 | 15 |
| | H60 | 60 | 0.9 | 70 | 0.76 | 20 |
| | H80 | 80 | 1.4 | 90 | 1.15 | 27 |
| | H100 | 100 | 2.0 | 135 | 1.6 | 35 |
| | H130 | 130 | 3.0 | 170 | 2.2 | 50 |
| | H200 | 200 | 5.4 | 310 | 3.5 | 73 |
| | H250 | 250 | 7.2 | 400 | 4.5 | 97 |

*Table 3. Properties of the core material used in the shelters [17].*

## 2.5  Construction of sandwich panels.

The design of a sandwich construction, is very often a proses of sizing and material selection, to get the optimum value of the weight, strength or the stiffness. All material has both advantages and disadvantages characteristics, and therefore are the difficult to make a general term about the material selection. An optimal design of a sandwich construction, is very difficult to obtain, because the are so many constrains, so the process is complex. But when you find the most important constrains, and using a very simple optimization technique, the can be very useful in the design process. An optimization only on the weight, can give a too low stiffness. In the most of the studies of the optimization of the sandwich, they not take into account all possible failure modes as they should has[14].

To understand a design of a sandwich construction, the are best to first understand design of the sandwich beam. A sketch of a beam, can you see in Figure 9. A beam is classified, as a long thin slender. Because the stiffness of a sandwich plate, are an important factor this project, I will in the chapter 2.5.1 give a short description to find the deflection of a sandwich beam [14].
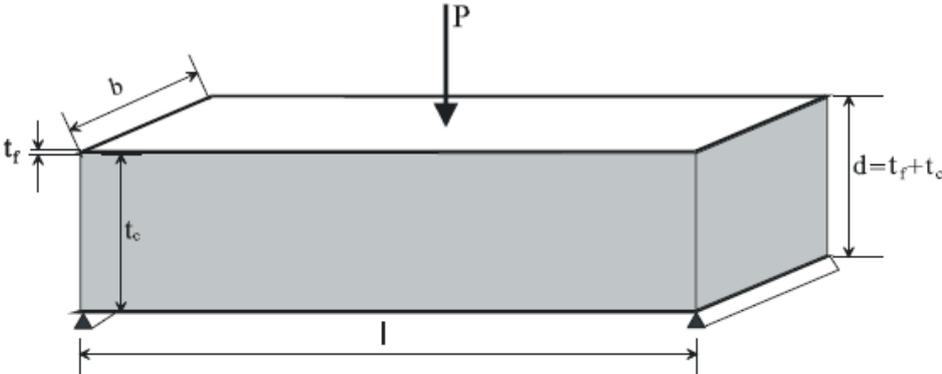


*Figure 9.* Simple supported sandwich construction, with a load P[14].

### 2.5.1  Deflection of a sandwich beam

In this chapter, I will give a short description to find the deflection of a sandwich beam. In the Table 4, you can see some of the coefficients, used in the calculation of the deflection [14].

| Symbol | Name | Unit |
|--------|------|------|
| P | Load | [N], Newton |
| L | Length | [m], meter |
| $E_f$ | Young's modulus of the facings | [MPa], Mega pascal |
| $E_c$ | Young's modulus of the core | [MPa], Mega pascal |
| b | Width | [m], meter |
| $t_f$ | Thickness of the facing | [m], meter |
| $t_c$ | Thickness of the core | [m], meter |
| $G_c$ | Shear modulus of the core | [MPa], Mega pascal |
| $d=t_f + t_c$ | | [m], meter |
| h | Height | [m], meter |
| $B_1$-$B_4$ | Factor depending of the boundary- and load condition, see Table 5. | |

*Table 4. Some coefficients used in the calculation of the deflection.*

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When the cross section is, homogeneous and have the length L and the load P, the deflection of a sandwich beam, can be found by the equation (1):

$$\delta_{Tot} = \delta_b + \delta_s \tag{1}$$

where $\delta_b$ is the deflection from the bending as you can see in equation (2), and $\delta_s$ is the deflection from the shear, equation (4).

$$\delta_b = \frac{PL^3}{B_1(EI)_{eq}} \tag{2}$$

where $(EI)_{eq}$ are the equivalent EI, as you can see in equation (3):

$$(EI)_{eq} = E_f \frac{bt_f^3}{6} + E_f \frac{bt_f d^2}{2} + E_c \frac{bt_c^3}{12} \tag{3}$$

The face in the sandwich, are thin, relative to the core, ($t_f \ll t_c$), and the first term in equation (3), can be neglected, if the first term, is less than 1% of the second term. The first term is less than 1% if:

$$3\left(\frac{d}{t_f}\right)^2 > 100 \ or \ \frac{d}{t_f} > 5.77$$

because

$$\left(\frac{E_f \frac{bt_f^3}{6}}{E_f \frac{bt_f d^2}{2}}\right) 100 < 1$$

If the first term is neglected, the equation can be written as:

$$(EI)_{eq} = E_f \frac{bt_f d^2}{2} + E_c \frac{bt_c^3}{12}$$

If the core is weak, $E_f \ll E_c$, the third term, can also be neglected, because the third term is less than 1% of the second term, if:

$$\frac{6E_f t_f d^2}{E_c t_c^3} > 100$$

because

$$\left(\frac{E_c \frac{bt_c^3}{12}}{E_f \frac{bt_f d^2}{2}}\right) 100 < 1$$

Hence the equation can therefore be write as:

$$(EI)_{eq} = E_f \frac{bt_f d^2}{2}$$

The deformation from the shear can be found by this formula:

$$\delta_s = \frac{PL}{B_2(AG)_{eq}} \tag{4}$$

where $(AG)_{eq}$ equivalent, and can be found of formula (5):

$$(AG)_{eq} = \frac{bd^2 G_c}{t_c} \tag{5}$$

Are the face thin $t_f \ll t_c$ and the core weak $E_c \ll E_f$, the deflection of the sandwich beam can be written as equation (6)

$$\delta_{Tot} = \frac{2PL^3}{B_1 E_f bt_f d^2} + \frac{PLt_c}{B_2 bd^2 G_c} \tag{6}$$

A picture where the different length is marked, can you see in Figure 9.

As you can see from equation (7) this equation have a $L^3$ for the deflection from the bending, but a single L for the shear. This means that the deflection from the bending will be the domineered part, when the L increase.

| Mode of loading, (all beams are of length L) | $B_1$ | $B_2$ | $B_3$ | $B_4$ |
|---|---|---|---|---|
| | $\delta_b = \frac{PL^3}{B_1(EI)_{eq}}$ | $\delta_s = \frac{PL}{B_2(AG)_{eq}}$ | $M_x = \frac{PL}{B_3}$ | $T_x = \frac{P}{B_4}$ |
| Cantilever, end load, P | 3 | 1 | 1 | 1 |
| Cantilever, Uniformly distributed load, $q = P/L$ | 8 | 2 | 2 | 1 |
| Simply supported beam (three-point bend), central load, P | 48 | 4 | 4 | 2 |
| Simply supported beam (three-point bend), Uniformly distributed load, $q = P/L$ | $\frac{384}{5}$ | 8 | 8 | 2 |
| Ends built in, Central load, P | 192 | 4 | 8 | 2 |
| Ends built in, Uniformly distributed load, $q = P/L$ | 384 | 8 | 12 | 2 |

Table 5. Value for B, in different case depending of the boundary condition [14].

# 3 Optimal weight of a sandwich shelters

This project, has the background in the article, "Optimal stiffness design of sandwich plates with variable core densities" [1]. In this chapter the methods described in the article will be use, to calculating the inverse stiffness, weight, and the equation will be verified, with compare the deflection calculated analytical, with the deflection from the numeric solution in ANSYS.

The project has some variable as can be changed, to obtain the lowest weight of the shelters. This variable is listed up in Table 6. In the Table 7, the value of the coefficients used in the calculation, are listed up.

| Free variable |
| --- |
| Thickness of the facings |
| Thickness of the core |
| Density of the core |
| Shear modulus of the core |

*Table 6. Variable as can be changed.*

| Symbol | Name | Value | Unit |
| --- | --- | --- | --- |
| $a_{\text{short side}}$ | Length short side | 2.390 | meter [m] |
| $a_{\text{long side}}$ | Length short side | 6.008 | meter [m] |
| b | Width | 2.398 | meter [m] |
| $v_f$ | Poisson's Ratio facings | 0.33 | |
| $E_f$ | Young's modulus facings | 70*10^9 | Pascal [Pa] |
| $t_f$ | Thickness of the facings | 0.001 | meter [m] |
| $t_c$ | Thickness of the core | 0.04 | meter [m] |
| d | $d=t_f+t_c$ | 0.041 | meter [m] |
| $G_c$ | Shear modulus of the core | 20*10^6 | Pascal [Pa] |
| $v_c$ | Poisson's Ratio of the core | 0.4 | |
| $\rho_f$ | Density of the facings | 2780 | $\frac{kg}{m^3}$ |
| $\rho_c$ | Density of the core | 60 | $\frac{kg}{m^3}$ |

*Table 7. Values used in the calculation.*

## 3.1  Deflection on a simply supported plate

The article, has the base in a rectangular simply supported plate with sides a and b with a uniform disturbed load q(x,y), as you can see in Figure 10.
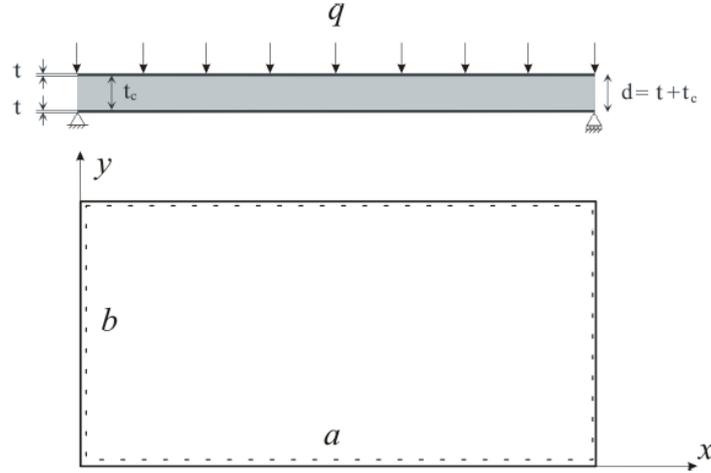


Figure 10. *Rectangular simply supported sandwich plate.*

When the facings thickness $t_f$ is thin with Young`s modulus $E_f$ and Poisson's ratio $v_f$, and the core material is weak $E_c \ll E_f$, with shear modulus $G_c$ and thickness $t_c$. The deflection of the plate, will be find with sum the deflection from the bending and the shear: $W = W_b + W_s$:

$$w_b = \frac{(1 - v_f^2)}{D} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{q_{mn} \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right)}{\left(\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right)^2} \tag{7}$$

$$w_s = \frac{1}{S} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{q_{mn} \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right)}{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \tag{8}$$

where

$$D = \frac{E_f t_f d^2}{2}, \qquad S = \frac{G_c d^2}{t_c} \approx G_c d, \qquad d = t_c + t$$

$q_{mn}$, are given by the loading condition. In case of uniformly load q(x,y) where q>0 is a constant see Figure 10, the value $q_{mn}$, can be written:

$$q_{mn} = \frac{16q}{mn\pi^2}$$

where m and n are odd, otherwise $q_{mn} = 0$. Than we replace m by 2m+1 and n by 2n+1. The equation can then be written as:

$$w_b = \frac{16q(1 - v_f^2)}{D} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\sin\left(\frac{(2m+1)\pi x}{a}\right)\sin\left(\frac{(2n+1)\pi y}{b}\right)}{\pi^2(2m+1)(2n+1)\left(\left(\frac{(2m+1)\pi}{a}\right)^2 + \left(\frac{(2n+1)\pi}{b}\right)^2\right)^2} \quad (9)$$

$$w_s = \frac{16q}{S} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\sin\left(\frac{(2m+1)\pi x}{a}\right)\sin\left(\frac{(2n+1)\pi y}{b}\right)}{\pi^2(2m+1)(2n+1)\left(\left(\frac{(2m+1)\pi}{a}\right)^2 + \left(\frac{(2n+1)\pi}{b}\right)^2\right)} \quad (10)$$

The maximum deflection of the plate, are in the middle of the plate, where x=a/2 and y=b/2. On the midpoint, the deflection can be write as:

$$W_b = \frac{q(1 - v_f^2)b^4}{D} f(a/b) \quad (11)$$

$$W_s = \frac{qb^2}{S} g(a/b) \quad (12)$$

where f(a/b) and g(a/b) are the double Fourier series, as you can see in equation (13) and (14).

$$f(a/b) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{16\sin\left(\frac{(2m+1)\pi}{2}\right)\sin\left(\frac{(2n+1)\pi}{2}\right)}{\pi^6(2m+1)(2n+1)\left(\left(\frac{(2m+1)}{a/b}\right)^2 + \left((2n+1)\right)^2\right)^2} \quad (13)$$

$$g(a/b) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{16\sin\left(\frac{(2m+1)\pi}{2}\right)\sin\left(\frac{(2n+1)\pi}{2}\right)}{\pi^4(2m+1)(2n+1)\left(\left(\frac{(2m+1)}{a/b}\right)^2 + \left((2n+1)\right)^2\right)} \quad (14)$$

The result of the calculation of the double Fourier series, can you see in Table 8. When we look to the book "An introduction to sandwich construction" they said that the summation of m and n, go up to number 27, are a good approximation [9], so the summation go up to 27.

| Walls | Double Fourier series |
|---|---|
| Short walls | $f(a/b) = 4.0352 \times 10^{-3}$ |
| Long walls | $f(a/b) = 1.1507 \times 10^{-2}$ |
| Short walls | $g(a/b) = 7.3426 \times 10^{-2}$ |
| Long walls | $g(a/b) = 0.11996$ |

*Table 8. The values of f(a/b) and g(a/b) for the long- and short walls.*

The inverse stiffness of the plate can be write as the Formula (15):

$$w/q = \frac{(1-v_f^2)b^4}{D}f(a/b) + \frac{b^2}{S}g(a/b) = \frac{2(1-v_f^2)b^4}{E_f t_f d^2}f(a/b) + \frac{b^2}{G_c d}g(a/b)$$

(15)

where the shear moduli of the core, can be found by formula (16):

$$G_c = \frac{g(a/b)b^2}{d\left(w/q - \frac{2(1-v_f^2)b^4}{E t_f d^2}\right)}$$

(16)

The inverse stiffness of the walls, are calculated after the formula (15), and the result can you see in Table 9.

| Walls | Inverse Stiffness |
|---|---|
| Short walls | $w/q = 2535.8 \left[\frac{mm}{MPa}\right]$ |
| Long walls | $w/q = 6604.3 \left[\frac{mm}{MPa}\right]$ |

Table 9. The inverse stiffness of the walls.

## 3.2  Modelling the shear modulus

When the core material belongs to some specific class of cellular materials, where the shear modulus $G_c$ is uniquely determined by the density $\rho$. i.e. $G=G(\rho)$. Then we also assume that the $G_c(0)$ and that the $G_c(.)$ are increasing, continues and piecewise differentiable. This means that the inverse function $\rho(G)$ exist.

The total mass of a sandwich plate, are given by the formula (17):

$$m = 2abt_f\rho_f + abd\rho_c(G)$$

(17)

When the required stiffness is found $(w/q)^{-1}$, the main objective is to find is the density $\rho_c$ $\epsilon[\rho_{min}, \rho_{max}]$, of the core material, and the parameter $t_f$ and $d$, to minimizes the mass of the sandwich plate. The shear stiffness can be approximated by the rational function (18):

$$G(\rho) = \frac{1}{k\rho^{-1} - l}$$

(18)

When man look to DIAB, man find the relation between the $\rho_c$ and $G(\rho)$ as you can see in Table 10.

| $\rho$ [kg/m³] | 38 | 48 | 60 | 80 | 100 | 130 | 160 |
|---|---|---|---|---|---|---|---|
| $G(\rho)$ [MPa] | 12 | 15 | 20 | 27 | 35 | 50 | 73 |

Table 10. Relation between the rho and shear modulus of the core material from DIAB.

The value of k and l, can be calculated by two equation with two unknown. When man take the value when $\rho=100$ $\rho=160$ the function 18, can be written as:

$$G(\rho) = \frac{1}{\dfrac{6080}{1533}\dfrac{s^2}{m^2}\rho^{-1} - \dfrac{17}{1533}\dfrac{1}{MPa}}$$

The graph of the of the function 18 and the value in Table 10 can you see in Figure 11.
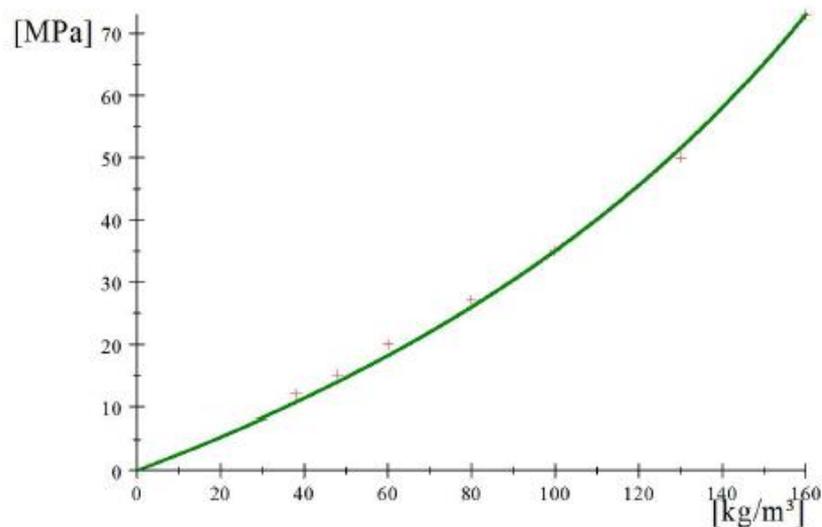


Figure 11. The shear modulus G(ρ), as a function of the core density ρc.

The function (18) is a substantial improvement, compared with other optimization methods. Another function to approximate the shear stiffness by some power of the density, is the function (19):

$$G(\rho) = k\rho^n \tag{19}$$

For some positive constrains k and n. The best approximation for the function (19), with the material with the highest density in Table 10, the function can be written as:

$$G(\rho) = 73 \left(\frac{\rho}{160}\right)^{3/2}$$

In the Figure 12, the corresponding curve to the function (18) and (19) and the table value from Table 10, are sketched.
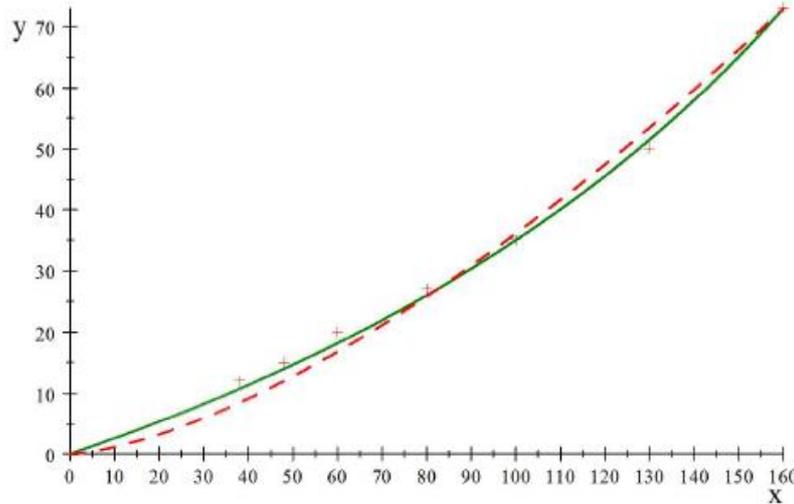


*Figure 12. Comparison of the rational approximation (18) (solid curve) with the best possible power law approximation (19) (dashed curve).*

As you can see from Figure 12, the function (18) is much closer to the point, than the curve for the function (19).

## 3.3  Optimal face thickness

The formula (18), have an even better property then the accuracy. When we set equation (16) equal to (18) the formula can be written as:

$$\frac{1}{k\rho_c^{-1} - l} = \frac{g(a/b)b^2}{d\left((w/q) - \frac{2(1 - v_f^2)b^4}{E_f t_f d^2} f(a/b)\right)} \tag{20}$$

From this equation, the $\rho_c$ are easy to find, and can be written as:

$$\rho_c^{-1} = \frac{d\left((w/q) - \frac{2(1 - v_f^2)b^4}{E_f t_f d^2} f(a/b)\right)}{g(a/b)b^2 k} + \frac{l}{k} \tag{21}$$

The total mass of the plate, has the formula (17)

$$m = 2abt_f\rho_f + abd\rho_c$$

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When man replace the $\rho_c$ in the mass equation with equation (21), the total mass can be written as:

$$m = 2abt\rho_f + abd\left(\frac{d\left((w/q) - \frac{2(1-v_f^2)b^4}{E_f t_f d^2}\right)}{g(a/b)b^2 k} + \frac{l}{k}\right)^{-1} \tag{22}$$

For a given values of a,b,d and the inverse stiffness w/q, the mass can be substitution into the equation 23:

$$m(t) = rt_f + \left(v - \frac{c}{t_f}\right)^{-1} \tag{23}$$

where

$$r = 2ab\rho_f, \qquad v = \frac{(w/q)}{g(a/b)kab^3} + \frac{l}{abdk} \qquad and \qquad c = \frac{2(1-v_f^2)b}{E_f d^2 ak} f(a/b)$$

The derivative of the mass (m) with respect to $t_f$ are given by:

$$m`(t_f) = r - \frac{c}{(vt_f - c)^2} \tag{24}$$

When we set the $m`(t_f)$ to zero, the thickness $t_f = t_0$ can be written as:

$$t_0 = \frac{1}{v}\left(\sqrt{\frac{c}{r}} + c\right) =$$

$$\frac{1}{\frac{(w/q)}{g(a/b)kab^3} + \frac{l}{abdk}}\left(\sqrt{\frac{\frac{2(1-v_f^2)b}{g(a/b)E_f d^2 ak}f(a/b)}{2ab\rho_f}} + \frac{2(1-v_f^2)b}{g(a/b)E_f d^2 ak}f(a/b)\right) \tag{25}$$

$$= \frac{1}{\frac{(w/q)}{g(a/b)kab^3} + \frac{l}{abdk}}\left(\sqrt{\frac{(1-v_f^2)}{g(a/b)E_f d^2 a^2 \rho_f k}f(a/b)} + \frac{2(1-v_f^2)b}{g(a/b)E_f d^2 ak}f(a/b)\right)$$

From the equation (25) the are sketched a function of d and $t_f$, for the long- and short walls, as you can see in Figure 13.
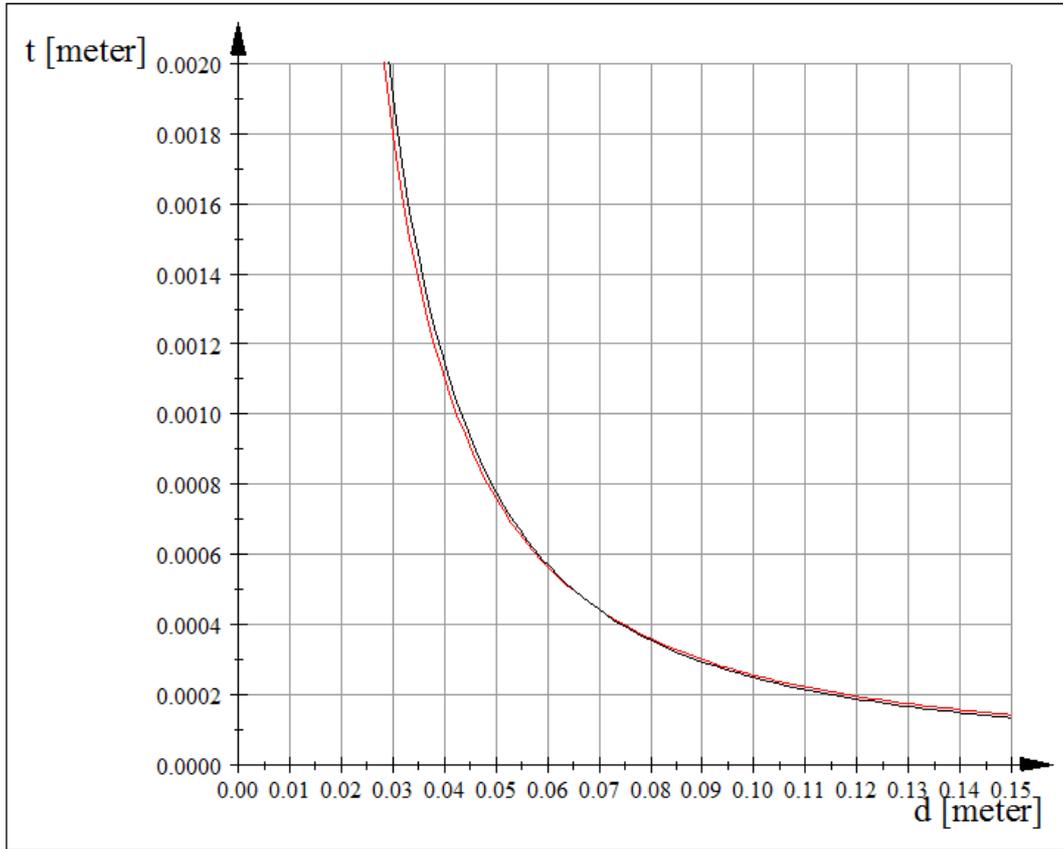


*Figure 13. A graphical context between the $t_f$ and d, for the short- (red) and long walls (black).*

In this article, the $t_0 \ll d$, so the formula is only vailed with thin facings. From the formula (25), can we find the core density, depending of the facings thickness $t_f$.

$$
\rho_c(t_0) = \frac{1}{abd}\left(v - \frac{c}{t_0}\right)^{-1} = \frac{1}{abd}\left(v - \frac{c}{\frac{1}{v}\left(\sqrt{\frac{c}{r}} + c\right)}\right)^{-1}
$$

$$
= \frac{1}{abdv}\left(1 - \frac{1}{\left(\sqrt{\frac{1}{cr}} + 1\right)}\right)^{-1}
$$

$$
= \frac{1}{abdv}\left(1 - \left(\sqrt{\frac{1}{\frac{4\left(1 - v_f^2\right)b^2\rho_f}{g(a/b)E_f d^2 k}f(a/b)}} + 1\right)^{-1}\right)^{-1}
\tag{26}
$$

From the equation (25), the can be sketched a graph, between the relation of d and $\rho_c$ as you can see in Figure 14.
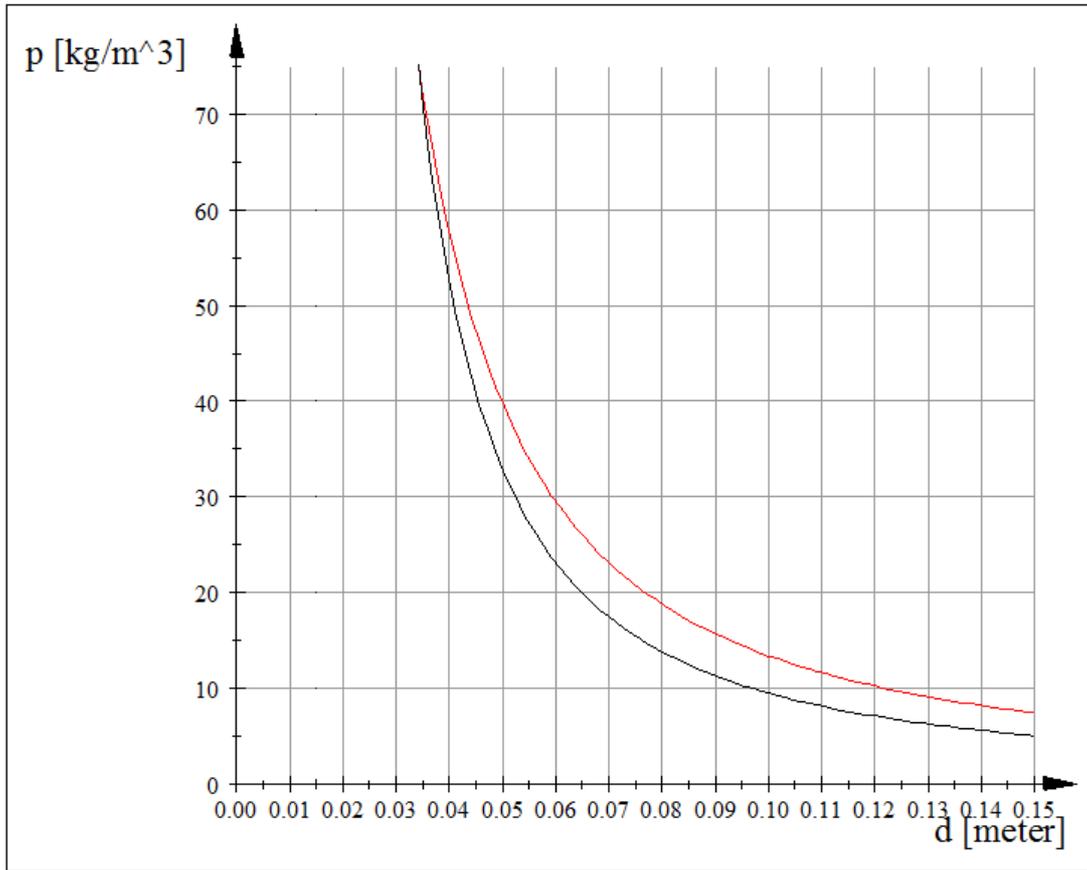


*Figure 14. A graphical context between the $\rho_c$ and d, for the short- (red) and long walls (black).*

In this project, the are only used the H-grade core material from DIAB. H-grade from DIAB, have a density as go from $38\frac{kg}{m^3}$ up to $250\frac{kg}{m^3}$. So, the function $\rho(t_0)$ must be between the lower and upper value of the density.

$$\rho_{min} \leq \rho(t_0) \leq \rho_{max} \tag{27}$$

Based on this, we obtain the following: The optimal value of $t_f=t_{opt}$ is given by:

$$t_{0\rho t}\begin{cases} t_0 & if & \rho_{min} \leq \rho(t_0) \leq \rho_{max} \\ t_- & if & \rho(t_0) < \rho_{min} \\ t_+ & if & \rho_{max} < \rho(t_0) \end{cases} \tag{28}$$

where $t_-$ and $t_+$, are given by

$$w/q = \frac{2(1-v_f^2)b^4}{Ed^2t_-}f(a/b) + \frac{b^2}{G(\rho_{min})d}g(a/b) \tag{29}$$

and

$$w/q = \frac{2(1-v_f^2)b^4}{Ed^2t_+}f(a/b) + \frac{b^2}{G(\rho_{max})d}g(a/b) \tag{30}$$

As we take the mass equation (17), and sets the $\rho_c$ as a function of d, the equation can be written as:

$$m(d) = 2 * f(d) * a * b + a * b * d * \rho(d) \qquad (31)$$

From the equation (31), the graphical relationship between the d and the mass m, are sketched, as you can see in Figure 15.
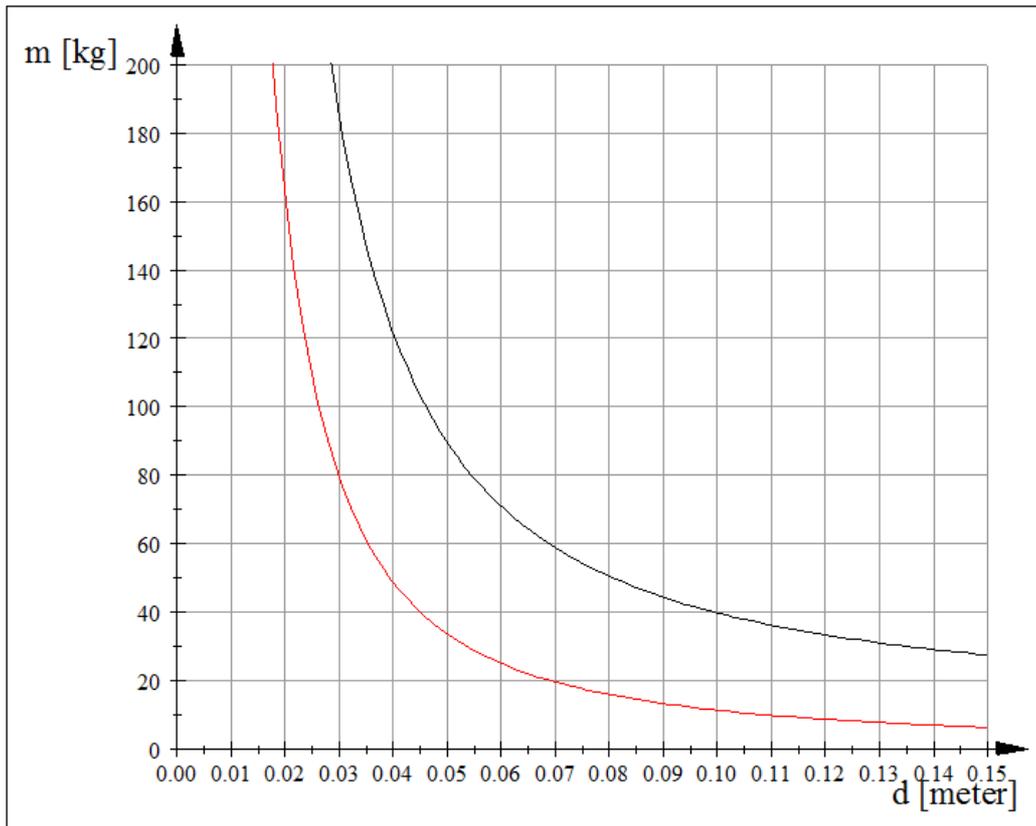


*Figure 15. A graphical context between the mass and d, for the short- (red) and long walls (black).*

In the Figure 15, you can see that the mass of the walls sinking with a higher d. But in this project, the core material is limited to the H-grad from DIAB. When we look to the graph in Figure 14 the density of the core falls with a higher d, but since the lowest density DIAB has to the core are $38 \frac{kg}{m^3}$ [3], the d are selected from this. For the short walls, d is selected to 52mm, and 44mm for the long walls. The exact value of the density, can you see in Table 11. Since the density from DIAB, not have exact the value of density, as calculated here, we take the nearest value to the density, and as you can see, this value is very closed to the calculated value of the density.

| Walls | Density of the core |
|---|---|
| Short walls | $\rho(t_0) = 37.31 \dfrac{kg}{m^3} \approx 38 \dfrac{kg}{m^3}$ |
| Long walls | $\rho(t_0) = 38.43 \dfrac{kg}{m^3} \approx 38 \dfrac{kg}{m^3}$ |

*Table 11. The value of $\rho_c$ for the long- and short walls.*

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The facings thickness obtained from the graph in Figure 13, and the value of $t_f$, can you see in Table 12.

| Walls | Facings thickness |
|---|---|
| Short walls | $t_0 = 0.71mm \approx 0.75mm$ |
| Long walls | $t_0 = 0.97mm \approx 1.00mm$ |

*Table 12. The facings thickness of the walls.*

As you can see, the are an approximation of the facings thickness. This is because what are of aluminum on the marked. For the long walls, 0.97mm is very close to 1mm, TAM used today, and therefore was the facings TAM AS use today, also the facings on the new long walls. For the short walls the nearest aluminum sheet on the marked, is 0.75mm from Astrup [18]. The new value of the changed parameter, can you see in Table 13.

| Changed parameter | New Value | |
|---|---|---|
| | Short walls | Long Walls |
| d | 52mm | 44mm |
| $t_f$ | 0.75mm | 1mm |
| $G_c$ | 12MPa | 12MPa |

*Table 13. The changed parameter for the new design.*

The inverse stiffness of the walls, must be the same before, and after the weight reduction. When man take the equation (15), and calculated the inverse stiffness with the new parameter listed up in Table 13. to check that the inverse stiffness is the same, before and after the weight reduction. The result can you see in Table 14.

| Walls | Inverse Stiffness today | New Inverse Stiffness |
|---|---|---|
| Short walls | $w/q = 2535.8 \left[\dfrac{mm}{MPa}\right]$ | $w/q = 2351.8 \left[\dfrac{mm}{MPa}\right]$ |
| Long walls | $w/q = 6604.3 \left[\dfrac{mm}{MPa}\right]$ | $w/q = 6310.4 \left[\dfrac{mm}{MPa}\right]$ |

*Table 14. The inverse stiffness of the walls.*

As you can see, the inverse stiffness before and after the weight reduction, is not the same. To get this value equal to each other, we take the equation (15), and sets this equation equal to the inverse stiffness today, and solve this equation for d. The new d, and the inverse stiffness for the walls, can you see in Table 15.

| Walls | New d | Inverse stiffness |
|---|---|---|
| Short | $49.75mm$ | $w/q = 2537.3 \left[\dfrac{mm}{MPa}\right]$ |
| Long | $43mm$ | $w/q = 6576.2 \left[\dfrac{mm}{MPa}\right]$ |

*Table 15. New d and inverse stiffness.*

As you can see, the are a deviation in the inverse stiffness. This deviation is small, and coming of in this project, we selected the $t_c$, to nearest whole millimeter.

When all the variable in the equation (15) are calculated, the new weight of the walls can be calculated, with the mass equation (17).

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In the Table 16 you can see the weight of the shelters.

|  | Weight today | Weight New design |
|---|---|---|
| Roof | 138. 1kg | 138. 1kg |
| Floor | 157. 3kg | 157. 3kg |
| Short walls | 2*46kg | 2*34.7kg |
| Long walls | 2*115.6kg | 2*103.7kg |
| Total Weight | 617.4kg | 572.2 |

*Table 16. The weight of the shellteres, the material properties today.*

$$Percent = \frac{Changes * 100\%}{Original\ value}$$
(32)

The changes of the weight in the sandwich shelters are: 45.2kg and the percent changes of weight are calculated after the formula (32) [19], and are 7.3%.

## 3.4  Deflection

To verify the calculation of the inverse stiffness in the sandwich plates, the deflection of the plate was solved, analytical after the formula (11) and (12) and numerical with ANSYS. The was calculated and simulated with four random value of pressure. The random values are selected to see if we get the same answer analytical and numeric.the result can you see in Table 18 and Table 19.

### 3.4.1  Ansys

The objective in this case, is to find the deflection of the sandwich plate, with different loads. The analysis is both for the design today, and the new design. The parameter is listed up in Table 17. Since in datasheets from DIAB, the are only listed up the shear modulus of the core, but in the simulation in ANSYS, we must have the Young`s modulus. When man use the formula (33) [7], it easy to find the Young`s modulus from the shear modulus.

$$G = \frac{E}{2(1 + v)}$$
(33)

|  | Shelters today | | New design | |
|---|---|---|---|---|
| Parameter | Short Walls | Long Walls | Short walls | Long Walls |
| $t_f$ | 1mm | 1mm | 0.75mm | 1mm |
| $E_f$ | 70GPa | 70GPa | 70GPa | 70GPa |
| $v_f$ | 0.33 | 0.33 | 0.33 | 0.33 |
| d | 41mm | 41mm | 49.75mm | 43mm |
| $E_c$ | 56MPa | 56MPa | 33.6MPa | 33.6MPa |
| $v_c$ | 0.4 | 0.4 | 0.4 | 0.4 |

*Table 17. The material parameters used in the simulation.*

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Before the analysis can start, the type of element must be found. ANSYS have a toolbar, where you can search help for the analysis. When you searching on sandwich in the toolbar, you will find guidelines to analysis of a sandwich. In search, I find that the Shell Element 281, is a good element to use in this analysis. I look to the properties of this elements, and 281, was a good element see Appendix E. I have also use 281 in "Modern materials and computations" to analysis a sandwich, and the result was good.

The analysis is a static structural analysis

The model is created with first creating four key points in the active coordinate system, where the points are placed in the following coordinates (x,y,z): (0,0,0), (2.390/6.008,0,0), (2.390/6.008,0,2.398/2.398), (0,0, 2.398/2.398). To form the area of the surfaces of the walls, the are necessary to draw a line between the key points, to form the rectangle.

The generating of the high, was done with the function "Shell-Lay up", there the dimension of the facings and core was selected, and combined with the material parameter.

The plate has the boundary condition with zero deflection in the y-direction on all sides, and in one nodes in x- and z-direction in the two corners, as are black in Figure 16 and Figure 17. The loads are a constant pressure over the whole area.

In this analysis, the size of the element, are the half of the height of the plates, so the plates have exact two elements in the height of the plates. In previous analyzes I have also had two elements in height, and this has yielded a good result.
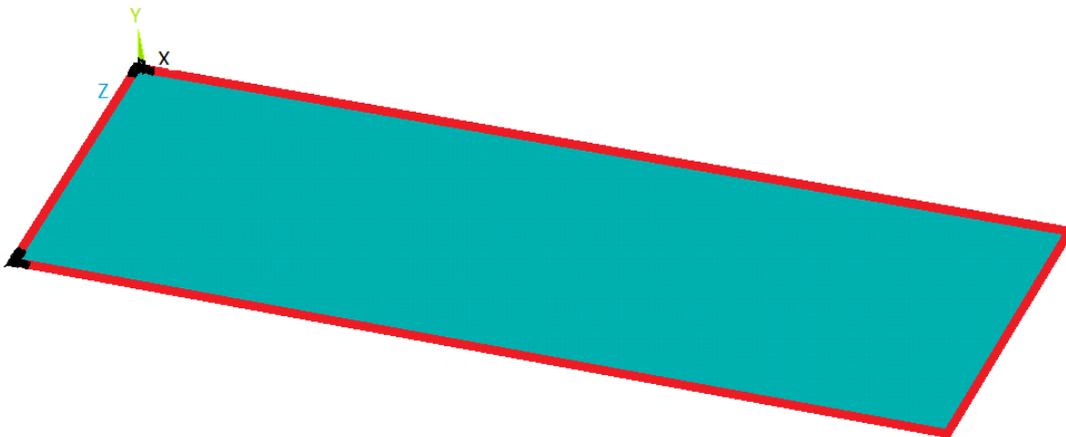


*Figure 16. Boundary condition for the long walls.*

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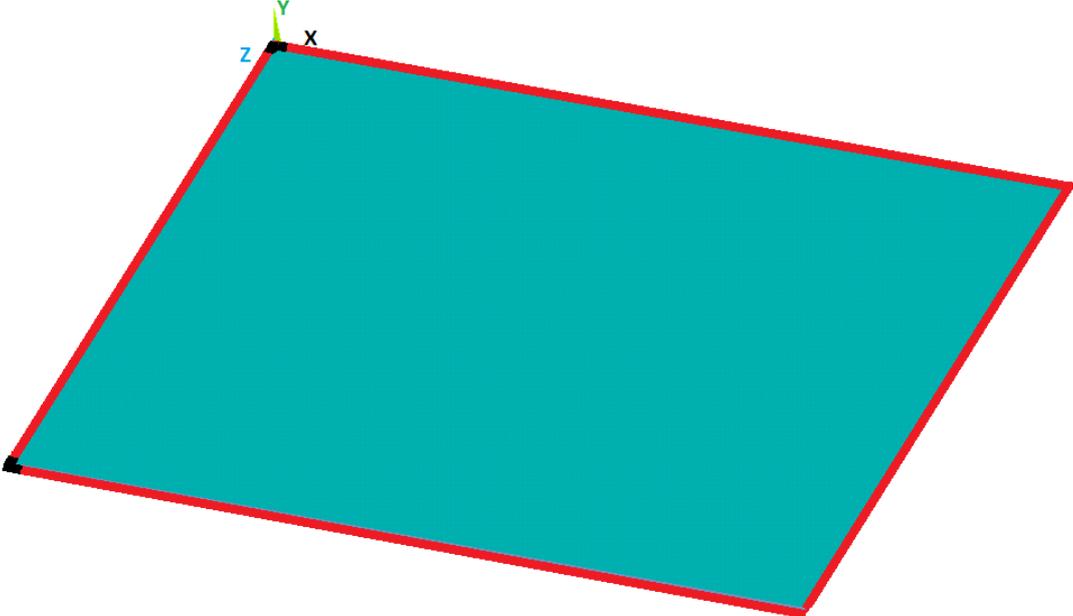


*Figure 17. Boundary condition of the short walls.*

In the Figure 18 and Figure 19 you can see the picture of the analysis. As you can see, the max deflection of the plates, are in the middle of the plates, This is compliance, then stands in the background article for this project. The log-file for the analysis, can you see in appendix D.
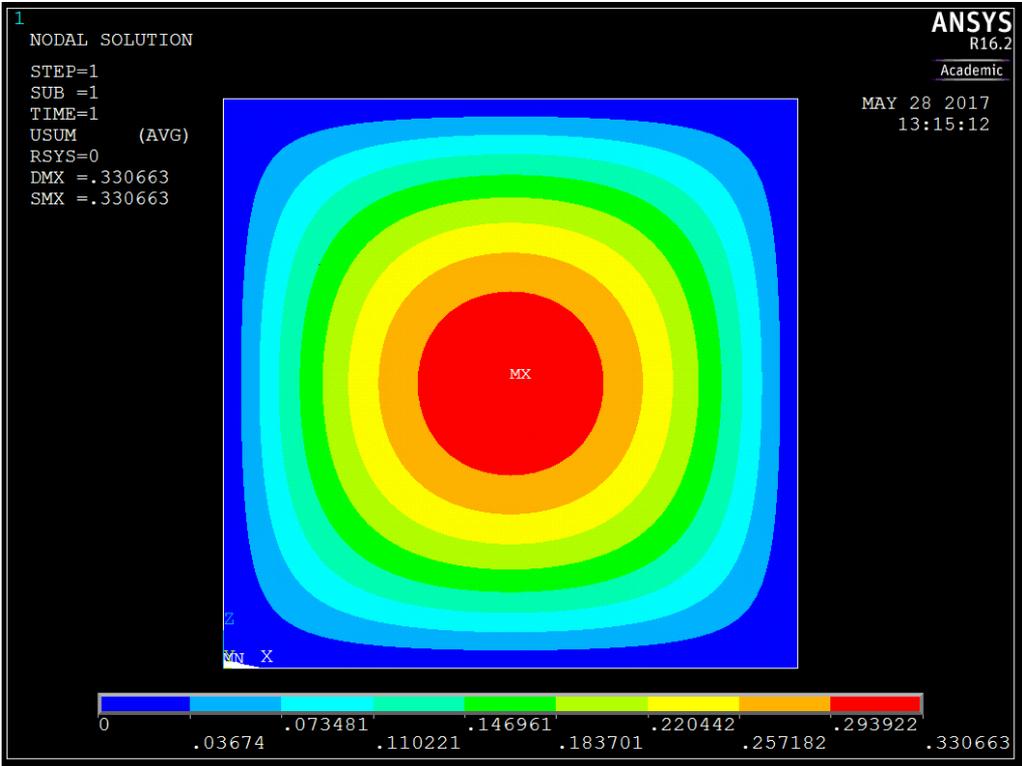


*Figure 18. Deflection of the short walls with a pressure on130000Pa.*
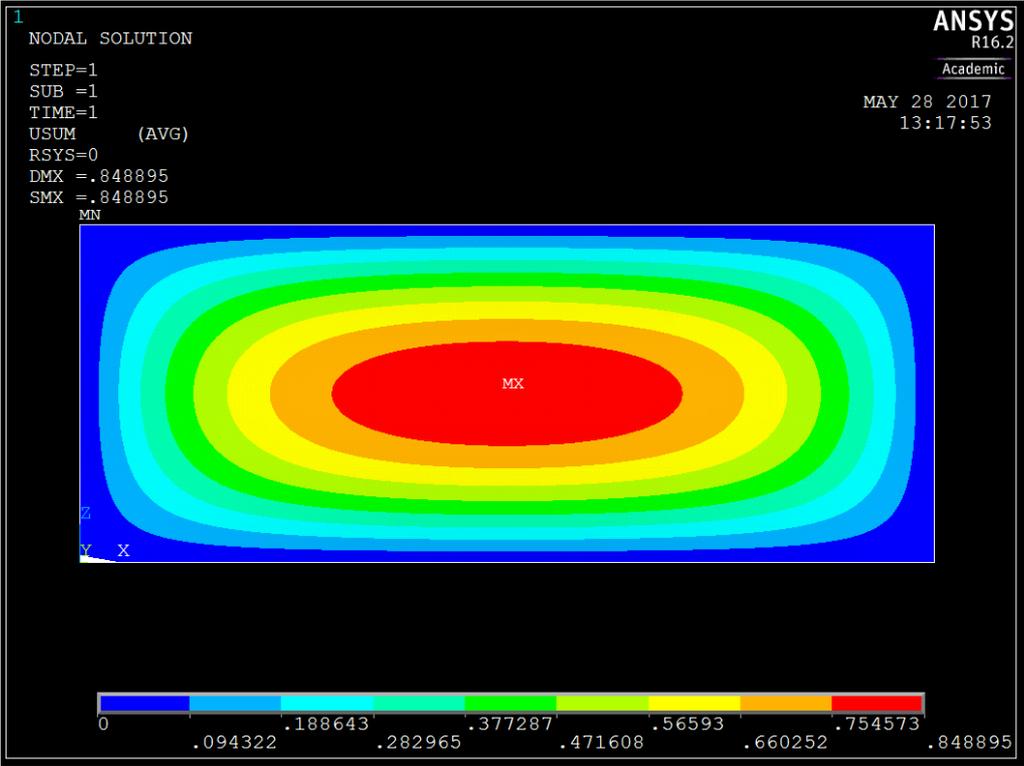
*Figure 19. the deflection of the long walls with a pressure on 130000Pa.*

## 3.4.2 Results

In the Table 18 and Table 19, the result of the analytic and numerical analysis, are listed up.

| Load | Material today | | New material | |
|---|---|---|---|---|
| | Analytic | Numerical | Analytic | Numerical |
| 500Pa | 1.27mm | 1.27mm | 1.27mm | 1.39mm |
| 2000Pa | 5.07mm | 5.09mm | 5.07mm | 5.56mm |
| 50000Pa | 127mm | 127mm | 127mm | 139mm |
| 130000Pa | 330mm | 331mm | 330mm | 362mm |

*Table 18. Deflection of the short walls.*

| Load | Material today | | **New material** | |
|---|---|---|---|---|
| | Analytic | Numerical | Analytic | Numerical |
| 500Pa | 3.30mm | 3.27mm | 3.29mm | 3.29mm |
| 2000Pa | 13.2mm | 13.1mm | 13.2mm | 13.2mm |
| 50000Pa | 330mm | 326mm | 328mm | 329mm |
| 130000Pa | 859mm | 849mm | 855mm | 855mm |

*Table 19. Deflection of the long walls.*

# 4 Evaluation

In this project, the are done some approximation.

- The formula (18), for the shear modulus, is and approximation, and may therefore have a deviation
- In the background article for this project, the are used d instead of $t_c$ to compute the thickness of the core material. This is an approximation, since d $=t_f+t_c$, and the accuracy is therefore not entirely correct
- The values for the selected parameter, are not the exact value from the graph
- The inverse stiffness for the shelters today, and the new design are not quite similar to each other

All this approximation, possible sources of error, and must therefore be studied more carefully.

As you can see, the result in the analytic calculation and numeric analysis, is very close to each other. The largest difference, is 8.8%. The deviation are because that the analytical and numerical formula not identical, the boundary conditions is not absolutely correct, done simplification, and other factors.

# 5 Conclusion

The objective of the project, was to reduce the weight of a sandwich shelters, but have the same stiffness of the shelters. The weight of the shelters was reduce from 617.4kg, to 572.2kg, with change the parameter one the walls. This is a reduction of 45.2kg and approximately 7.3%. A weight reduction of 7.3% by have other parameter for the facings thickness, core thickness and density of the core material is good. This shows that it is possible to reduce the weight of the shelters, by changing a few parameters, and is something and develop on. The objective in the project of the assignment is grace.

## 5.1 Further work

Even though the weight of the shelters was reduce, the are some point, as can be set more on:

- Make a study on whether all approximation can be used
- Find a new algorithms, which can calculate the inverse stiffness of sandwich plates as are not symmetrical, so the weight of the roof and floor can be reduce.
- What happens, when the load is a point load, and not uniformly distributed load?
- See if there are lighter core materials on the market than H-grade from DIAB
- Is it possible to use other facings than aluminum?

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# Appendix A

| Poissonstall, $v_f$ | 0,33 | |
|---|---|---|
| Elastisitetsmodul, $E_{f1}$ | 70 000,00 | [MPa] |
| Densitet, $\rho_{f1}$ | 2 780,00 | [kg/m$^3$] |

Hei,
Vi benytter standard verider på alu, se vedlegg
Bare spør i vei hvis det er noe mer du lurer på.
Mvh
Herman Myrvoll


----- Opprinnelig melding -----
Fra: Arild Røsdal <aro079@post.uit.no>
Til: '"hm@tam.no"' <hm@tam.no>
Kopi: Dag Lukkassen <dag.lukkassen@uit.no>
Dato: Fri, 17 Mar 2017 08:31:50 +0000
Emne: RE: Sandwich-shelter
Beklager alt maset Herman, men du har ikke også Young's modulus og Poisson's ratio tilgjengelig på Aluminiumen, da det er disse verdiene jeg skal bruke i utregningene mine?


Mvh
Arild Røsdal
Tlf: 95 75 76 09
**Fra:** Herman Myrvoll
**Sendt:** tirsdag 14. mars 2017 kl. 09:46
**Til:** 'hm@tam.no; aro079@post.uit.no
**Kopi:** annette.meidell@uit.no; dag.lukkassen@uit.no
**Emne:** Re: Sandwich-shelter
Hei,
Yttremål på container er vist i vedlegget. Målene på selve sandwich bygget er L=6008mm x B=2390mm x H=2398mm
Det er benyttet 1 mm aluminiums skinn limt på kjerne av 40mm H60 divinycell, bortesett fra i gulv, her er det 50mm divinyvell bestående av 10mm H130 innvendig + 40mm H60. Hvis man skal værer 100% korrekt, så er det 1,5mm aluminium innvendig på gulv og utvendig tak. Har lagt ved materialsertifikat for aluminium..
Mvh
Herman Myrvoll
----- Opprinnelig melding -----
Fra: Arild Røsdal <aro079@post.uit.no>
Til: '"hm@tam.no"' <hm@tam.no>
Kopi: Annette Meidell <annette.meidell@uit.no>, Dag Lukkassen <dag.lukkassen@uit.no>
Dato: Fri, 10 Mar 2017 13:33:33 +0000
Emne: RE: Sandwich-shelter
Hei igjen Herman
Jeg har noen flere spørsmål angående dimensjonene til shelterne. Hvis vi tar utgangspunkt i «73VTC. Shelter for video Tele-Conferencing». Da fant jeg ut at en ISO 1496 container har målene: Lengde 5.9m, bredde 2.4m og høyde: 2.4m. Stemmer disse målene? Så lurer jeg også

på hvilket kjernematerialet og facingsmaterialet dere bruker på akkurat disse containerne, og tykkelsen på facingsen?
Mvh
Arild Røsdal
Tlf: 95 75 76 09
**From:** Arild Røsdal
**Sent:** 10. mars 2017 14:32
**To:** Arild Røsdal <aro079@post.uit.no>
**Cc:** Annette Meidell <annette.meidell@uit.no>; Dag Lukkassen <dag.lukkassen@uit.no>
**Subject:** RE: Sandwich-shelter

Hei igjen Herman
Jeg har noen flere spørsmål angående dimensjonene til shelterne. Hvis vi tar utgangspunkt i «73VTC. Shelter for video Tele-Conferencing». Da fant jeg ut at en ISO 1496 container har målene: Lengde 5.9m, bredde 2.4m og høyde: 2.4m. Stemmer disse målene? Så lurer jeg også på hvilket kjernematerialet og facingsmaterialet dere bruker på akkurat disse containerne, og tykkelsen på facingsen?
Mvh
Arild Røsdal
Tlf: 95 75 76 09
**From:** Arild Røsdal
**Sent:** 16. februar 2017 18:30
**To:** Herman Myrvoll <hm@tam.no>
**Cc:** Annette Meidell <annette.meidell@uit.no>; Dag Lukkassen <dag.lukkassen@uit.no>
**Subject:** SV: Sandwich-shelter

Tusen takk for svar. Her var det litt av vært, så her får man sette seg ned å lese å forstå hva som står der.

Mvh
Arild Røsdal
Tlf: 95 75 76 09
**Fra:** Herman Myrvoll <hm@tam.no>
**Sendt:** 16. februar 2017 15:26
**Til:** Arild Røsdal
**Kopi:** Annette Meidell; Dag Lukkassen
**Emne:** Re: Sandwich-shelter


Hei,
Så hyggelig at du vil ta en oppgave med sandwich.
I dag benytter vi kjerne materialer fra Maciell S.r.l (LyCell og MyCell) samt H-grade fra Divinycell. Normal densitet vi benytter er på 60kg/m^3. tykkelse er 40mm.

Stivhet er vanskelig å definere og det foreligger ikke noen direkte krav annet enn at det skal fungere. Kravet til de små hyttene er at de skal kunne transporteres på lukket bil dvs bredde 2,4m og høyde 2,5m, Når man nærmer seg størrelser som tilsvarer ISO-container mål er ønsket at disse følger standarden. Krav til innfesting av utstyr innvendig er at ved transport med tog og bil etc. er kravet 3-5g og med fly opp til 7g. Utstyr som monters inn er vanligvis 19" rack som står på gulv 4 punkt og 2 i vegg. Et slikt rack veier fra 80 til 400 kg avhengig

2

av utstyr. Vedlagt finnes bilder av monterte rack.

Dersom shelteret imøtekommer ISO standard er det kravene som stilles i Iht. SO 1496 her er det mange last bilder som kan brukes i oppgaven. Forslag kan være test nr. 1 og 7 i standarden.

Vet ikke hvor mye klokere du ble av dette.

Mvh
Herman Myrvoll

----- Opprinnelig melding -----
Fra: Arild Røsdal <aro079@post.uit.no>
Til: "hm@tam.no" <hm@tam.no>
Kopi: Dag Lukkassen <dag.lukkassen@uit.no>, Annette Meidell <annette.meidell@uit.no>
Dato: Wed, 15 Feb 2017 13:29:06 +0000
Emne: Sandwich-shelter

Hei Herman

Jeg holder på å skrive masteroppgave ved UiT-Narvik, og har fått en oppgave, der jeg skal prøve å redusere vekten på en sandwich-shelter, men at den er like stiv, fordi om vekten reduseres. Derfor lurer jeg på hvilket kjernematerialet dere bruker i sandwichen-platene dere bruker i shelteren, og hvilken stivhet disse skal ha? Samtidig lurer jeg på om det stilles noen krav til størrelse fra forsvaret på shelteren. Innvendig/utvendig høyde, lengde, bredde, veggtykkelse osv?
Når det gjelder lastfordelingen på en shelter, så lurer jeg på om dere tar utgangspunkt i en jevnt fordelt last, punktlast, eller en kombinasjon av disse to lastene?
Håper du kan svare på dette.

Mvh
Arild Røsdal
Tlf: 95 75 76 09

# Appendix B
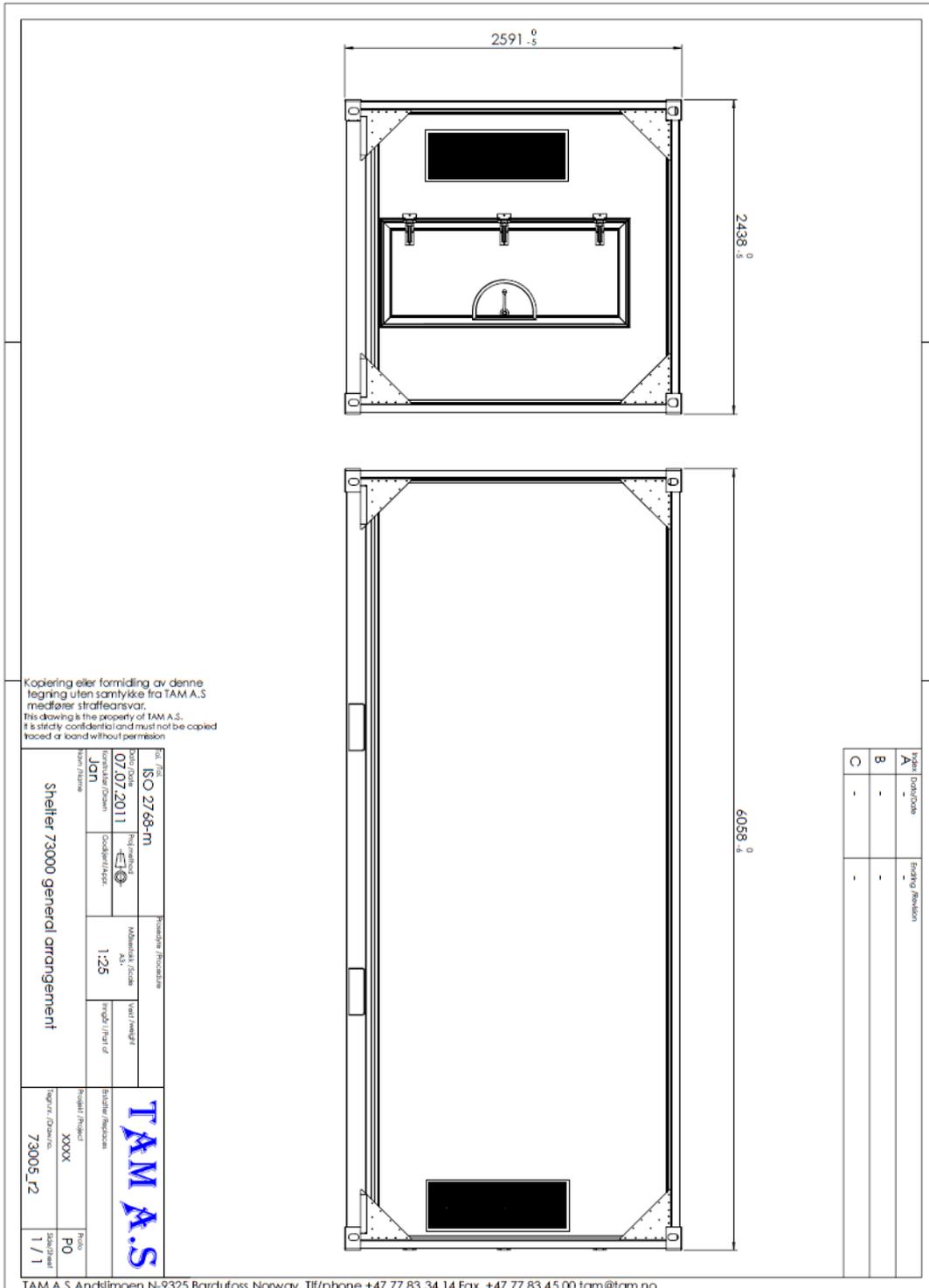
TAM A.S Andslimoen N-9325 Bardufoss Norway, Tlf/phone +47 77 83 34 14 Fax. +47 77 83 45 00 tam@tam.no

Shelter 73000 general arrangement

4

# Appendix C



**TEST REPORT / WERKSZEUGNIS**
EN.10204 JAN.2005

ALCAN

Usine d'Issoire
LABORATOIRE de CONTROLE
B.P 42 – 63502 ISSOIRE CEDEX
TEL : 04 73 55 50 50
TELECOPIE : 04 73 55 50 60

NUMERO-Number-Nummer : **012331**

| COMMANDE CLIENT-Customer Order - Undenbestellung | DESTINATAIRE – Consignee - Empfänger | COMMANDE ALCAN |
|---|---|---|
| 82479 **TAM NORVEG** | **TAM AS ANDSLIMOEN 9325 BARDU FOSS NORVEGE** | 289284/01 AVIS D'EXPEDITION – Dispatch.Note - Lieferschein 0080497836 DU 21/10/05 |

BANDE LAQUEE (RECTO T:14B R:SP
B:60 E:30) VERNIE (VERSO T:08F
R:EP B:00 E:04) PST EN.AW.5052 H46
EN.1396.ORIG.03.97
(CONF1:IS.5087.ISSUE.6)
DIM 2500 /1,50
PU=1500 KG PU MAXI=2000 KG PV

EN10204.2.2
LIVRAISON PLAST. ADH. 1F

3 UNITES

| CAISSE Case Kiste | LOT CONTROLE Inspection lot Los | QUANTITE Quantity Menge | PLATEAU Slab Walztafel | ETAT Temper Zustand | SENS Direction Richtung | ESSAIS DE TRACTION (MOYENNE) Tensile Tests (Average) Zugversuche (Mittelwerte) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | R Tensile Strength MPA | R 0,2 Yield Strength MPA | A % Elongation % |
| 8900/1 | 289284/011 | 1 | 14027293/04 | H46 | TL | 266 | 219 | 8 |
| 8901/1 | | 1 | | | | | | |
| 8902/1 | | 1 | | | | | | |

| COULEE – Castings Schmelze | COMPOSITION CHIMIQUE – Chemical Composition - Zusammensetzung | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SI | FE | CU | MN | MG | CR | NI | ZN | TI | ZR | | |
| 14027293 | 0,03 | 0,15 | 11* | 0,09 | 2,5 | 0,16 | 30* | 0,01 | 70* | 10* | | |

* en ppm

We certify that subject to the exceptions and engineering departures above mentioned the present supply has been manufactured to the technical specifications of customer contract, order or sub-order, and that it complies in EVERY ASPECT with the particular specifications which are there attached with the drawings and all the relative standards and regulations in force.

Chef de service Métallurgie Qualité    24/10/05
Metallurgy Quality Manager                    R. DIF
Leiter der Qualitätsicherung

AFAQ
ISO 9001
VERSION 2000

OBSERVATIONS DE LA
SURVEILLANCE
Remarks of official inspector
Bemerkungen von der
Beaufsichtigung

PAGE : 1 DERNIERE PAGE
Masque PV md. 1 du 01-05-2005

PECHINEY RHENALU
SOCIETE ANONYME AU CAPITAL DE 123.547.875 € – 672 014 081 R.C.S. PARIS – CODE APE 741 J
SIEGE SOCIAL : 7, PLACE DU CHANCELIER ADENAUER – 75116 PARIS - FRANCE

# RELEVE DE CONTROLE
## TEST REPORT / WERKSZEUGNIS
EN.10204 JAN.2005

**ALCAN**

| NUMERO-Number-Nummer | 012332 |
|---|---|

| COMMANDE CLIENT-Customer Order - Underbestilling | DESTINATAIRE – Consignee - Empfänger | COMMANDE ALCAN |
|---|---|---|
| 82479<br>**TAM NORVEG** | **TAM AS<br>ANDSLIMOEN<br>9325 BARDU FOSS<br>NORVEGE** | 289284/02<br><br>AVIS D'EXPEDITION – Dispatch Note - Lieferschein<br><br>**0080497836 DU 21/10/05** |

| | | |
|---|---|---|
| **BANDE LAQUEE (RECTO T:14B R:SP<br>B:60 E:30) VERNIE (VERSO T:08F<br>R:EP B:00 E:04) PST EN.AW.5052 H46<br>EN.1396.ORIG.03.97<br>(CONF1:IS.5087.ISSUE.6)<br>DIM 2500 /1<br>PU=1500 KG PU MAXI=2000 KG PV** | **EN10204.2.2<br>LIVRAISON PLAST. ADH. 1F** | **3 UNITES** |

| CAISSE<br>Case<br>Kiste | LOT CONTROLE<br>Inspection lot<br>Los | QUANTITE<br>Quantity<br>Menge | PLATEAU<br>Slab<br>Walzstol | ETAT<br>Temper<br>Zustand | SENS<br>Direction<br>Richtung | ESSAIS DE TRACTION (MOYENNE)<br>Tensile Tests (Average)<br>Zugversuche (Mittelwerte) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | R<br>Tensile<br>Strength<br>MPA | R 0,2<br>Yield<br>Strength<br>MPA | A %<br>Elongation<br>% |
| 8861/1 | 289284/021 | 1 | 14027294/03 | H46 | TL | 266 | 219 | 8 |
| 8861/2 | | 1 | | | | | | |
| 8861/3 | | 1 | | | | | | |

| COULEE – Castings<br>Schmelze | COMPOSITION CHIMIQUE – Chemical Composition - Zusammensetzung | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SI | FE | CU | MN | MG | CR | NI | ZN | TI | ZR | | | |
| 14027294 | 0,03 | 0,15 | 14* | 0,05 | 2,6 | 0,19 | 30* | 0,01 | 60* | 10* | | | * en ppm |

We certify that subject to the exceptions and engineering departures above mentioned the present supply has been manufactured to the technical specifications of customer contract, order or sub-order, and that it complies in EVERY ASPECT with the particular specifications which are there attached with the drawings and all the relative standards and regulations in force.

Chef de service Métallurgie Qualité    24/10/05
Metallurgy Quality Manager      R. DIF
Leiter der Qualitätsicherung

OBSERVATIONS DE LA
SURVEILLANCE
Remarks of official inspector
Bemerkungen von der
Beaufsichtigung

**AFAQ**
ISO 9001
**VERSION 2000**

# Appendix D Log-File ANSYS

```
/BATCH
/NOPR
KEYW,PR_SET,1
KEYW,PR_STRUC,1
KEYW,PR_THERM,0
KEYW,PR_FLUID,0
KEYW,PR_ELMAG,0
KEYW,MAGNOD,0
KEYW,MAGEDG,0
KEYW,MAGHFE,0
KEYW,MAGELC,0
KEYW,PR_MULTI,0
/GO
/PREP7
ET,1,SHELL281
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,1,,7e10
MPDATA,PRXY,1,,0.33
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,2,,33.6e6
MPDATA,PRXY,2,,0.4
sect,1,shell,,
secdata, 0.00075,1,0.0,3
secdata, 0.04975,2,0.0,3
secdata, 0.00075,1,0.0,3
secoffset,MID
seccontrol,,,, , , ,
K,1,0,0,0,
K,2,2.390,0,0,
K,3,2.39,0,2.398,
K,4,0,0,2.398,
FLST,2,4,3
FITEM,2,1
FITEM,2,2
FITEM,2,3
FITEM,2,4
A,P51X
ESIZE,0.025625,0,
MSHAPE,0,2D
MSHKEY,0
CM,_Y,AREA
ASEL, , , ,     1
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
AMESH,_Y1
CMDELE,_Y
```

```
CMDELE,_Y1
CMDELE,_Y2
FLST,2,4,4,ORDE,2
FITEM,2,1
FITEM,2,-4
/GO
DL,P51X, ,UY,0
FLST,2,2,1,ORDE,2
FITEM,2,3
FITEM,2,378
/GO
D,P51X, ,0, , , ,UX,UZ, , , ,
FLST,2,26885,1,ORDE,2
FITEM,2,1
FITEM,2,-26885
/GO
SF,P51X,PRES,130000
FINISH
/SOL
SOLVE
FINISH
/POST1
```

# Appendix E
SHELL281

*8-Node Structural Shell*

SHELL281 Element Description

SHELL281 is suitable for analyzing thin to moderately-thick shell structures. The element has eight nodes with six degrees of freedom at each node: translations in the x, y, and z axes, and rotations about the x, y, and z-axes. (When using the membrane option, the element has translational degrees of freedom only.)

SHELL281 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. The element accounts for follower (load stiffness) effects of distributed pressures.

SHELL281 may be used for layered applications for modeling composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first-order shear-deformation theory (usually referred to as Mindlin-Reissner shell theory).

The element formulation is based on logarithmic strain and true stress measures. The element kinematics allow for finite membrane strains (stretching). However, the curvature changes within a time increment are assumed to be small.

See SHELL281 in the *Mechanical APDL Theory Reference* for more details about this element.

SHELL281 Input Data

The following figure shows the geometry, node locations, and the element coordinate system for this element. The element is defined by shell section information and by eight nodes (I, J, K, L, M, N, O and P).

Midside nodes may not be removed from this element. See *Quadratic Elements (Midside Nodes)* in the *Modeling and Meshing Guide* for more information about the use of midside nodes.

A triangular-shaped element may be formed by defining the same node number for nodes K, L and O.

**Figure 281.1: SHELL281 Geometry**

$x_o$ = Element x-axis if element orientation (**ESYS**) is not provided.

$x$ = Element x-axis if element orientation is provided.

## Single-Layer Definition

To define the thickness (and other information), use section definition, as follows:

**SECTYPE**,,SHELL

**SECDATA**,*THICKNESS*, ...

A single-layer shell section definition provides flexible options. For example, you can specify the number of integration points used and the material orientation.

## Multilayer Definition

The shell section commands allow for layered shell definition. Options are available for specifying the thickness, material, orientation, and number of integration points through the thickness of the layers.

You can designate the number of integration points (1, 3, 5, 7, or 9) located through the thickness of each layer when using section input. When only one, the point is always located midway between the top and bottom surfaces. If three or more points, two points are located on the top and bottom surfaces respectively and the remaining points are distributed at equal distances between the two points. The default number of integration points for each layer is three; however, when a single layer is defined and plasticity is present, the number of integration points is changed to a minimum of five during solution.

The following additional capabilities are available when defining shell layers:

- SHELL281 accepts the preintegrated shell section type (**SECTYPE**,,GENS).

  When the element is associated with the GENS section type, thickness or material definitions are not required.

- You can use the function tool to define thickness as a function of global/local coordinates or node numbers (**SECFUNCTION**).

- You can specify offsets (**SECOFFSET**).

**Other Input**

The default orientation for this element has the S1 (shell surface coordinate) axis aligned with the first parametric direction of the element at the four in-plane integration points:

Where element geometry [20] is given as follows:

$(s,r)$ = two isoparametric element coordinates

$h^I(s,r)$ = shape functions associated with eight element nodes (see *Mechanical APDL Theory Reference* for more details)

$[20]^i$ = global coordinates of eight element nodes

For undistorted elements, the default orientation is the same as described in *Coordinate Systems* (the first surface direction is aligned with the IJ side).

The first surface direction $S_1$ can be rotated by angle θ (in degrees) for the layer via the **SECDATA** command. For an element, you can specify a single value of orientation in the plane of the element. Layer-wise orientation is supported.

You can also define element orientation via the **ESYS** command. For more information, see *Coordinate Systems*.

The element supports degeneration into a triangular form. For better accuracy, however, ANSYS, Inc. recommends quadrilateral shaped elements. The triangle form is generally more robust when using the membrane option with large deflections.

To evaluate stresses and strains on exterior surfaces, use KEYOPT(1) = 2. When used as overlaid elements on the faces of 3-D elements, this option is similar to the surface stress option (described in the *Mechanical APDL Theory Reference*), but is more general and applicable to nonlinear analysis. The element used with this option does not provide any stiffness, mass, or load contributions. This option should only be used in single-layer shells. Irrespective of other settings, SHELL281 provides stress and strain output at the four in-plane integration points of the layer.

SHELL281 uses a penalty method to relate the independent rotational degrees of freedom about the normal (to the shell surface) with the in-plane components of displacements. The program chooses an appropriate penalty stiffness by default. A drill stiffness factor can be specified via the **SECCONTROL** command.

Element loads are described in *Nodal Loading*. Pressures may be input as surface loads on the element faces as shown by the circled numbers in *Figure 281.1: SHELL281 Geometry*. Positive pressures act into the element. Because shell edge pressures are input on a per-unit-length basis, per-unit-area quantities must be multiplied by the shell thickness.

Temperatures may be input as element body loads at the corners of the outside faces of the element and at the corners of the interfaces between layers. The first

corner temperature T1 defaults to TUNIF. If all other temperatures are unspecified, they default to T1. If KEYOPT(1) = 0 and if exactly NL+1 temperatures are input, one temperature is used for the four bottom corners of each layer, and the last temperature is used for the four top corner temperatures of the top layer. If KEYOPT(1) = 1 and if exactly NL temperatures are input, one temperature is used for the four corners of each layer. That is, T1 is used for T1, T2, T3, and T4; T2 (as input) is used for T5, T6, T7, and T8, etc. For any other input pattern, unspecified temperatures default to TUNIF.

SHELL281 includes the effects of transverse shear deformation. The transverse shear stiffness of the element is a 2x2 matrix as shown below:

To define transverse shear stiffness values, issue the **SECCONTROL** command.

Transverse shear-correction factors k are calculated once at the start of the analysis for each section. The material properties used to evaluate the transverse shear correction factors are at the current reference temperature during solution. User-field variables and frequency are all set to zero when evaluating the material properties used to calculate the transverse shear correction factors.

In the above matrix, shear-correction factor k = 5/6, G = shear modulus, and h = thickness of the shell.

SHELL281 can be associated with linear elastic, elastoplastic, creep, or hyperelastic material properties. Only isotropic, anisotropic, and orthotropic linear elastic properties can be input for elasticity. The von Mises isotropic hardening plasticity models can be invoked with BISO (bilinear isotropic hardening), MISO (multilinear isotropic hardening), and NLISO (nonlinear isotropic hardening) options. The kinematic hardening plasticity models can be invoked with BKIN (bilinear kinematic hardening), MKIN and KINH (multilinear kinematic hardening), and CHABOCHE (nonlinear kinematic hardening). Invoking plasticity assumes that the elastic properties are isotropic (that is, if orthotropic elasticity is used with plasticity, the program assumes the isotropic elastic modulus = EX and Poisson's ratio = NUXY).

Hyperelastic material properties (2, 3, 5, or 9 parameter Mooney-Rivlin material model, Neo-Hookean model, polynomial form model, Arruda-Boyce model, and user-defined model) can be used with this element. Poisson's ratio is used to specify the compressibility of the material. If less than 0, Poisson's ratio is set to 0; if greater than or equal to 0.5, Poisson's ratio is set to 0.5 (fully incompressible).

Both isotropic and orthotropic thermal expansion coefficients can be input using **MP**,ALPX. When used with hyperelasticity, isotropic expansion is assumed.

Use the **TREF** command to specify the global value of reference temperature. If **MP**,REFT is defined for the material number of the element, it is used for the element instead of the value from the **TREF** command. But if **MP**,REFT is defined for the material number of the layer, it is used instead of either the global or element value.

SHELL281 uses an advanced shell formulation that accurately incorporates initial curvature effects. The calculation for effective shell curvature change accounts for both shell-membrane and thickness strains. The new formulation generally offers improved accuracy in curved shell structure simulations, especially when thickness strain is significant or the material anisotropy in the thickness direction cannot be ignored.

KEYOPT(8) = 2 stores midsurface results in the results file for single or multi-layer shell elements. If you use **SHELL**,MID, you will see these calculated values, rather than the average of the TOP and BOTTOM results. Use this option to access these correct midsurface results (membrane results) for those analyses where averaging TOP and BOTTOM results is inappropriate; examples include midsurface stresses and strains with nonlinear material behavior, and midsurface results after mode combinations that involve squaring operations such as in spectrum analyses.

KEYOPT(9) = 1 reads initial thickness data from a user subroutine.

The effects of pressure load stiffness are automatically included for this element. If an unsymmetric matrix is needed for pressure load stiffness effects, use **NROPT**,UNSYM.

A summary of the element input is given in *"SHELL281 Input Summary"*. A general description of element input is given in *Element Input*.

SHELL281 Input Summary
**Nodes**

> I, J, K, L, M, N, O, P

**Degrees of Freedom**

> UX, UY, UZ, ROTX, ROTY, ROTZ if KEYOPT(1) = 0
>
> UX, UY, UZ if KEYOPT(1) = 1

**Material Properties**

> **TB** command: See *Element Support for Material Models* for this element.
>
> **MP** command: EX, EY, EZ, (PRXY, PRYZ, PRXZ, or NUXY, NUYZ, NUXZ), ALPX, ALPY, ALPZ (or CTEX, CTEY, CTEZ *or* THSX, THSY, THSZ), DENS, GXY, GYZ, GXZ, ALPD
>
> Specify BETD, ALPD, and DMPR for the element (all layers) by issuing the **MAT** command to assign the material property set. REFT may be specified once for the element, or may be assigned on a per-layer basis. See the discussion in *"SHELL281 Input Summary"* for more information.

**Surface Loads**
> **Pressures --**
>
> face 1 (I-J-K-L) (bottom, in +N direction),
>
> face 2 (I-J-K-L) (top, in -N direction),
>
> face 3 (J-I), face 4 (K-J), face 5 (L-K), face 6 (I-L)

**Body Loads**
> **Temperatures --**

### For KEYOPT(1) = 0 (Bending and membrane stiffness):

T1, T2, T3, T4 (at bottom of layer 1), T5, T6, T7, T8 (between layers 1-2); similarly for between next layers, ending with temperatures at top of layer NL(4*(NL+1) maximum). Hence, for one-layer elements, eight temperatures are used.

### For KEYOPT(1) = 1 (Membrane stiffness only):

T1, T2, T3, T4 for layer 1, T5, T6, T7, T8 for layer 2, similarly for all layers (4*NL maximum). Hence, for one-layer elements, four temperatures are used.

## Special Features

Birth and death

Element technology autoselect

Initial state

Large deflection

Large strain

Linear perturbation

Nonlinear stabilization

Section definition for layered shells and preintegrated general shell sections for input of homogeneous section stiffnesses

## KEYOPT(1)

Element stiffness:

**0 --**

Bending and membrane stiffness (default)

**1 --**

Membrane stiffness only

**2 --**

Stress/strain evaluation only

## KEYOPT(8)

Specify layer data storage:

**0 --**

Store data for bottom of bottom layer and top of top layer (multi-layer elements) (default)

**1 --**

Store data for TOP and BOTTOM, for all layers (multi-layer elements). (The volume of data may be considerable.)

**2 --**

Store data for TOP, BOTTOM, and MID for all layers; applies to single- and multi-layer elements

**KEYOPT(9)**

User thickness option:

**0 --**

No user subroutine to provide initial thickness (default)

**1 --**

Read initial thickness data from user subroutine `UTHICK`

For more information, see *Subroutine UTHICK (Getting User-Defined Initial Thickness)* in the *Guide to User-Programmable Features*.

SHELL281 Output Data

The solution output associated with the element is in two forms:

- Nodal displacements included in the overall nodal solution

- Additional element output as shown in *Table 281.1: SHELL281 Element Output Definitions*

Several items are illustrated in *Figure 281.2: SHELL281 Stress Output*.

KEYOPT(8) controls the amount of data output to the results file for processing with the **LAYER** command. Interlaminar shear stress is available as SYZ and SXZ evaluated at the layer interfaces. KEYOPT(8) must be set to either 1 or 2 to output these stresses in the POST1 postprocessor. A general description of solution output is given in *Solution Output*. See the *Basic Analysis Guide* for ways to review results.

The element stress resultants (N11, M11, Q13, etc.) are parallel to the element coordinate system, as are the membrane strains and curvatures of the element. Such generalized strains are available through the SMISC option at the element centroid only. The transverse shear forces Q13, Q23 are available only in resultant form: that is, use SMISC,7 (or 8). Likewise, the transverse shear strains, $\gamma_{13}$ and $\gamma_{23}$, are constant through the thickness and are only available as SMISC items (SMISC,15 and SMISC,16, respectively).

The program calculates moments (M11, M22, M12) with respect to the shell reference plane. By default, the program adopts the shell midplane as the reference plane. To offset the reference plane to any other specified location, issue the **SECOFFSET** command. When there is a nonzero offset (L) from the reference plane to the midplane, moments with respect to the midplane (      ) can be recovered from stress resultants with respect to the reference plane as follows:

SHELL281 does not support extensive basic element printout. POST1 provides more comprehensive output processing tools; therefore, it is good practice to issue the **OUTRES** command to ensure that the required results are stored in the database.

**Figure 281.2:  SHELL281 Stress Output**

$x_o$ = Element x-axis if ESYS is not provided.

$x$ = Element x-axis if ESYS is provided.

**The Element Output Definitions table uses the following notation:**

A colon (:) in the Name column indicates that the item can be accessed by the Component Name method (**ETABLE**, **ESOL**). The O column indicates the availability of the items in the file **Jobname.OUT**. The R column indicates the availability of the items in the results file.

In either the O or R columns, "Y" indicates that the item is *always* available, a number refers to a table footnote that describes when the item is *conditionally* available, and "-" indicates that the item is *not* available.

**Table 281.1: SHELL281 Element Output Definitions**

| Name | Definition | O | R |
|---|---|---|---|
| EL | Element number and name | Y | Y |
| NODES | Nodes - I, J, K, L | - | Y |
| MAT | Material number | - | Y |
| THICK | Average thickness | - | Y |
| VOLU: | Volume | - | Y |
| XC, YC, ZC | Location where results are reported | - | *4* |
| PRES | Pressures P1 at nodes I, J, K, L; P2 at I, J, K, L; P3 at J,I; P4 at K,J; P5 at L,K; P6 at I,L | - | Y |
| TEMP | T1, T2, T3, T4 at bottom of layer 1, T5, T6, T7, T8 between layers 1-2, similarly for between next layers, ending with temperatures at top of layer NL(4*(NL+1) maximum) | - | Y |
| LOC | TOP, MID, BOT, or integration point location | - | *1* |
| S:X, Y, Z, XY, YZ, XZ | Stresses | *3* | *1* |
| S:1, 2, 3 | Principal stresses | - | *1* |
| S:INT | Stress intensity | - | *1* |
| S:EQV | Equivalent stress | - | *1* |
| EPEL:X, Y, Z, XY | Elastic strains | *3* | *1* |
| EPEL:EQV | Equivalent elastic strains [*7*] | - | *1* |
| EPTH:X, Y, Z, XY | Thermal strains | *3* | *1* |
| EPTH:EQV | Equivalent thermal strains [*7*] | - | *1* |
| EPPL:X, Y, Z, XY | Average plastic strains | *3* | *2* |

| Name | Definition | O | R |
|---|---|---|---|
| EPPL:EQV | Equivalent plastic strains [7] | - | 2 |
| EPCR:X, Y, Z, XY | Average creep strains | 3 | 2 |
| EPCR:EQV | Equivalent creep strains [7] | - | 2 |
| EPTO:X, Y, Z, XY | Total mechanical strains (EPEL + EPPL + EPCR) | 3 | - |
| EPTO:EQV | Total equivalent mechanical strains (EPEL + EPPL + EPCR) | - | - |
| NL:SEPL | Plastic yield stress | - | 2 |
| NL:EPEQ | Accumulated equivalent plastic strain | - | 2 |
| NL:CREQ | Accumulated equivalent creep strain | - | 2 |
| NL:SRAT | Plastic yielding (1 = actively yielding, 0 = not yielding) | - | 2 |
| NL:PLWK | Plastic work/volume | - | 2 |
| NL:HPRES | Hydrostatic pressure | - | 2 |
| SEND:ELASTIC, PLASTIC, CREEP | Strain energy densities | - | 2 |
| N11, N22, N12 | In-plane forces (per unit length) | - | Y |
| M11, M22, M12 | Out-of-plane moments (per unit length) | - | 8 |
| Q13, Q23 | Transverse shear forces (per unit length) | - | 8 |
| $\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{12}$ | Membrane strains | - | Y |
| $k_{11}, k_{22}, k_{12}$ | Curvatures | - | 8 |
| $\gamma_{13}, \gamma_{23}$ | Transverse shear strains | - | 8 |
| LOCI:X, Y, Z | Integration point locations | - | 5 |
| SVAR:1, 2, ... , N | State variables | - | 6 |
| ILSXZ | SXZ interlaminar shear stress | - | Y |
| ILSYZ | SYZ interlaminar shear stress | - | Y |
| ILSUM | Magnitude of the interlaminar shear stress vector | - | Y |
| ILANG | Angle of interlaminar shear stress vector (measured from the element x-axis toward the element y-axis in degrees) | - | Y |
| Sm: 11, 22, 12 | Membrane stresses | - | Y |
| Sb: 11, 22, 12 | Bending stresses | - | Y |
| Sp: 11, 22, 12 | Peak stresses | - | Y |
| St: 13, 23 | Averaged transverse shear stresses | - | Y |

1.  The following stress solution repeats for top, middle, and bottom surfaces.

2. Nonlinear solution output for top, middle, and bottom surfaces, if the element has a nonlinear material, or if large-deflection effects are enabled (**NLGEOM**,ON) for SEND.

3. Stresses, total strains, plastic strains, elastic strains, creep strains, and thermal strains in the element coordinate system are available for output (at all section points through thickness). If layers are in use, the results are in the layer coordinate system.

4. Available only at centroid as a **\*GET** item.

5. Available only if **OUTRES**,LOCI is used.

6. Available only if the `UserMat` subroutine and **TB**,STATE command are used.

7. The equivalent strains use an effective Poisson's ratio: for elastic and thermal this value is set by the user (**MP**,PRXY); for plastic and creep this value is set at 0.5.

8. Not available if the membrane element option is used (KEYOPT(1) = 1).

*Table 281.2: SHELL281 Item and Sequence Numbers* lists output available through **ETABLE** using the Sequence Number method. See Creating an Element Table in the *Basic Analysis Guide* and *The Item and Sequence Number Table* in this document for more information. The following notation is used in *Table 281.2: SHELL281 Item and Sequence Numbers*:

**Name**

output quantity as defined in the *Table 281.1: SHELL281 Element Output Definitions*

**Item**

predetermined *Item* label for **ETABLE**

**E**

sequence number for single-valued or constant element data

**I,J,K,L**

sequence number for data at nodes I, J, K, L

**Table 281.2: SHELL281 Item and Sequence Numbers**

| Output Quantity Name | ETABLE and ESOL Command Input | | | | | |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| | Item | E | I | J | K | L |
| N11 | SMISC | 1 | - | - | - | - |
| N22 | SMISC | 2 | - | - | - | - |
| N12 | SMISC | 3 | - | - | - | - |
| M11 | SMISC | 4 | - | - | - | - |
| M22 | SMISC | 5 | - | - | - | - |

| Output Quantity Name | ETABLE and ESOL Command Input | | | | | |
|---|---|---|---|---|---|---|
| | Item | E | I | J | K | L |
| M12 | SMISC | 6 | - | - | - | - |
| Q13 | SMISC | 7 | - | - | - | - |
| Q23 | SMISC | 8 | - | - | - | - |
| $\varepsilon_{11}$ | SMISC | 9 | - | - | - | - |
| $\varepsilon_{22}$ | SMISC | 10 | - | - | - | - |
| $\varepsilon_{12}$ | SMISC | 11 | - | - | - | - |
| $k_{11}$ | SMISC | 12 | - | - | - | - |
| $k_{22}$ | SMISC | 13 | - | - | - | - |
| $k_{12}$ | SMISC | 14 | - | - | - | - |
| $\gamma_{13}$ | SMISC | 15 | - | - | - | - |
| $\gamma_{23}$ | SMISC | 16 | - | - | - | - |
| THICK | SMISC | 17 | - | - | - | - |
| P1 | SMISC | - | 18 | 19 | 20 | 21 |
| P2 | SMISC | - | 22 | 23 | 24 | 25 |
| P3 | SMISC | - | 27 | 26 | - | - |
| P4 | SMISC | - | - | 29 | 28 | - |
| P5 | SMISC | - | - | - | 31 | 30 |
| P6 | SMISC | - | 32 | - | - | 33 |
| P1 | SMISC | - | 18 | 19 | 20 | 21 |
| P2 | SMISC | - | 22 | 23 | 24 | 25 |
| P3 | SMISC | - | 27 | 26 | - | - |
| P4 | SMISC | - | - | 29 | 28 | - |
| P5 | SMISC | - | - | - | 31 | 30 |
| P6 | SMISC | - | 32 | - | - | 33 |
| Sm: 11 | SMISC | 34 | - | - | - | - |
| Sm: 22 | SMISC | 35 | - | - | - | - |
| Sm: 12 | SMISC | 36 | - | - | - | - |
| Sb: 11 | SMISC | 37 | - | - | - | - |
| Sb: 22 | SMISC | 38 | - | - | - | - |
| Sb: 12 | SMISC | 39 | - | - | - | - |
| Sp: 11 (at shell bottom) | SMISC | 40 | - | - | - | - |
| Sp: 22 (at shell bottom) | SMISC | 41 | - | - | - | - |

| Output Quantity Name | ETABLE and ESOL Command Input | | | | | |
|---|---|---|---|---|---|---|
| | Item | E | I | J | K | L |
| Sp: 12 (at shell bottom) | SMISC | 42 | - | - | - | - |
| Sp: 11 (at shell top) | SMISC | 43 | - | - | - | - |
| Sp: 22 (at shell top) | SMISC | 44 | - | - | - | - |
| Sp: 12 (at shell top) | SMISC | 45 | - | - | - | - |
| St: 13 | SMISC | 46 | - | - | - | - |
| St: 23 | SMISC | 47 | - | - | - | - |

| Output Quantity Name | ETABLE and ESOL Command Input | | |
|---|---|---|---|
| | Item | Bottom of Layer i | Top of Layer NL |
| ILSXZ | SMISC | 8 * (i - 1) + 51 | 8 * (NL - 1) + 52 |
| ILSYZ | SMISC | 8 * (i - 1) + 53 | 8 * (NL - 1) + 54 |
| ILSUM | SMISC | 8 * (i - 1) + 55 | 8 * (NL - 1) + 56 |
| ILANG | SMISC | 8 * (i - 1) + 57 | 8 * (NL - 1) + 58 |

SHELL281 Assumptions and Restrictions

- ANSYS, Inc. recommends against using this element in triangular form, except as a filler element. Avoid triangular form especially in areas with high stress gradients.

- Zero-area elements are not allowed. (Zero-area elements occur most often whenever the elements are numbered improperly.)

- Zero thickness elements or elements tapering down to a zero thickness at any corner are not allowed (but zero thickness layers are allowed).

- If multiple load steps are used, the number of layers may not change between load steps.

- When the element is associated with preintegrated shell sections (**SECTYPE**,,GENS), additional restrictions apply. For more information, see _Considerations for Using Preintegrated Shell Sections_.

- No slippage is assumed between the element layers. Shear deflections are included in the element; however, normals to the center plane before deformation are assumed to remain straight after deformation.

- Transverse shear stiffness of the shell section is estimated by an energy equivalence procedure (of the generalized section forces and strains vs. the material point stresses and strains). The accuracy of this calculation may be adversely affected if the ratio of material stiffnesses (Young's moduli) between adjacent layers is very high.

- The calculation of interlaminar shear stresses is based on simplifying assumptions of unidirectional, uncoupled bending in each direction. If

accurate edge interlaminar shear stresses are required, shell-to-solid submodeling should be used.

- The section definition permits use of hyperelastic material models and elastoplastic material models in laminate definition. However, the accuracy of the solution is primarily governed by fundamental assumptions of shell theory. The applicability of shell theory in such cases is best understood by using a comparable solid model.

- The layer orientation angle has no effect if the material of the layer is hyperelastic.

- The through-thickness stress, SZ, is always zero.

- This element works best with full Newton-Raphson solution scheme (**NROPT**,FULL,,ON).

- Stress stiffening is always included in geometrically nonlinear analyses (**NLGEOM**,ON). Prestress effects can be activated via the **PSTRES** command.

- In a nonlinear analysis, the solution process terminates if the thickness at any integration point that was defined with a nonzero thickness vanishes (within a small numerical tolerance).

- If a shell section has only one layer and the number of section integration points is equal to one, or if KEYOPT(1) = 1, then the shell has no bending stiffness, a condition that can result in solver and convergence problems.

SHELL281 Product Restrictions

## ANSYS Professional

- The only special features allowed are stress stiffening and large deflections.