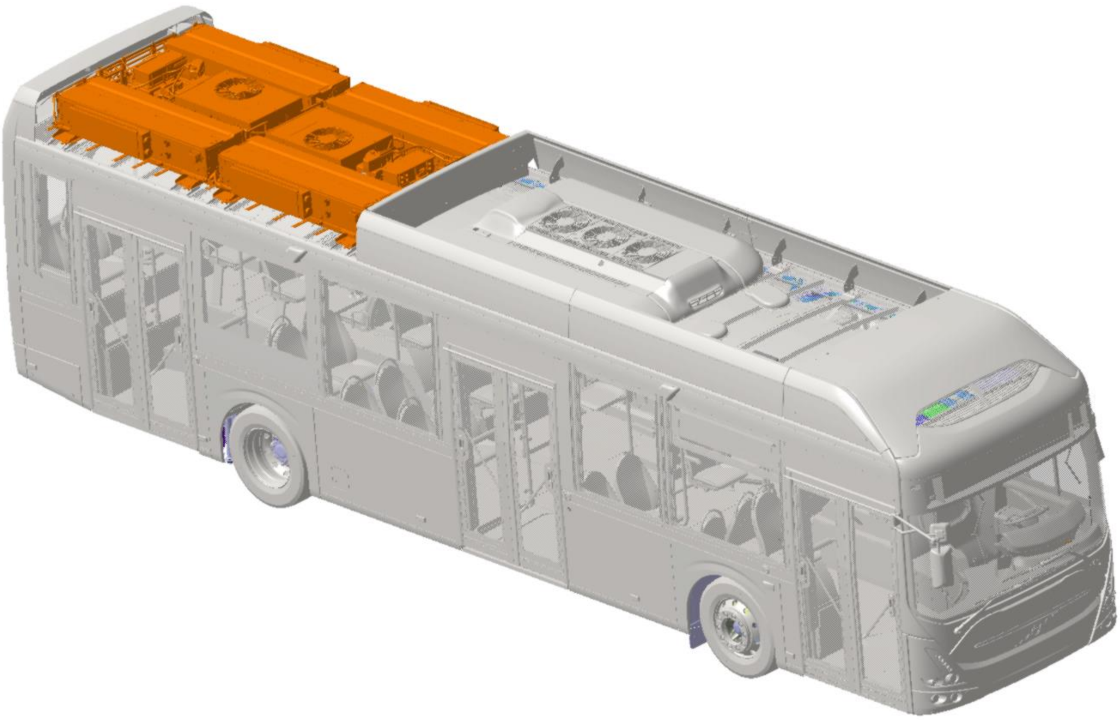

Fastening methods for Energy Storage systems

Infästningsmetoder för energilagringssystem

Bachelor thesis in Bachelor Mechanical enginering

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Gothenburg, Sweden 2016

Preface

This thesis work is written as the last stage in the mechanical engineering program, a three-year education (180 hp) at Chalmers technical university. The thesis is written at the department of product and production development. The work has been done at Volvo bus corporation and was completed between February and June of 2016 and corresponds to 15 hp.

We would like to thank the following persons for their help, support and contributions to the work: Kjell Melkersson, supervisor at Chalmers technical university, Martin Åslund, supervisor at Volvo bus corporation and David Lantz, strength analysis engineer at Volvo bus corporation.

Eric Eriksson & Filip Jönsson
Göteborg 11-05-16

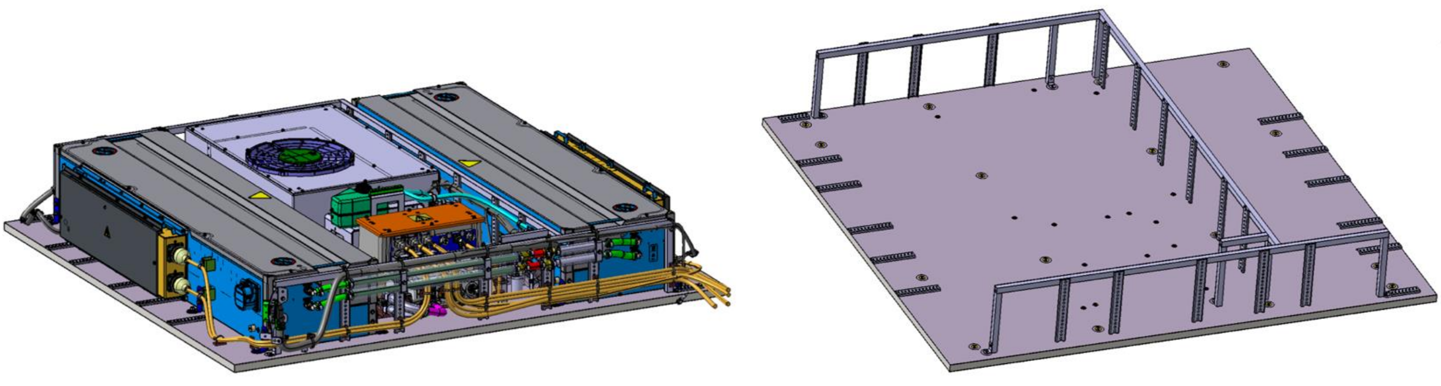
Abstract

By reducing the weight of a bus the passenger capacity can increase. The electric and hybrid buses from Volvo have an energy storage system mounted in a steel rack on top of the bus. Volvo Buses wants to replace the steel rack which is heavy, with a lightweight sandwich panel.

The great advantage of sandwich panels, is its superior stiffness-to-weight ratio. Its disadvantage is its low capacity to carry concentrated loads. The main objective of this project was to find ways to transfer loads from components in the energy storage system to the sandwich panel. Secondarily a new system to attach cables, pipes and tubes to the sandwich panel were to be developed.

In order to transfer a concentrated load into a sandwich panel it has been widely adopted to use potted inserts to spread the load into the sandwich panel.

With the knowledge of the current design and potted insert theory, concepts were made and a final concept was chosen. The new design meets all the demands of the current design with a weight reduction of 62% relative the current design. It has been shown in FE-analysis that the new design is able to carry the loads which a bus during operation is subjected to. The new design utilizes so called through the thickness inserts to transfer concentrated loads from components in the energy storage system to the sandwich panel. Furthermore, in the new design a system to attach cables, pipes and tubes to the sandwich panel was developed. In the figure below the new design of the energy storage system can be seen. To the left in the figure all of the components have been mounted in the new design. To the right the new design can be seen without any components mounted.



New design of the energy storage system

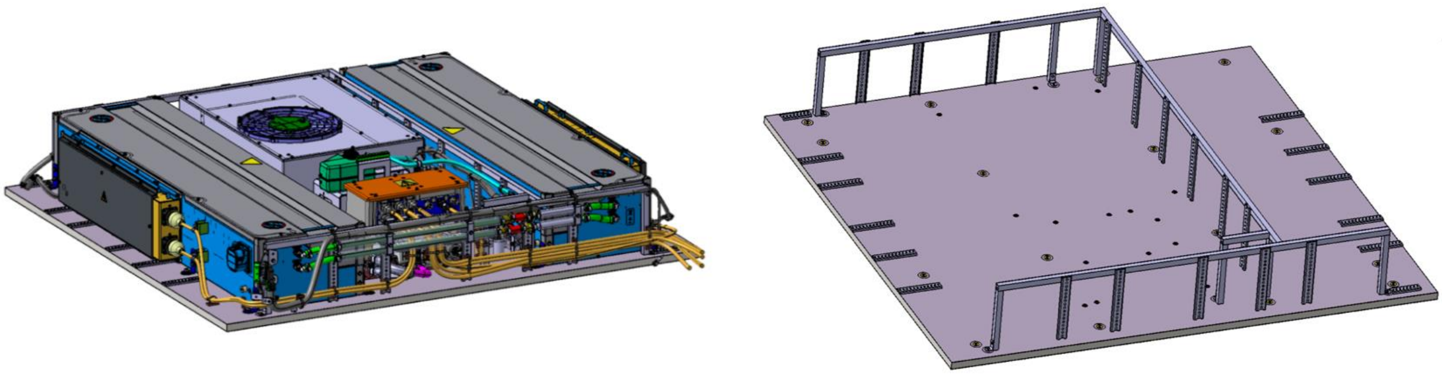
Sammanfattning

Genom att minska vikten på en buss kan bussens passagerarkapacitet ökas. Volvos hybrid- och elbussar har ett energilagringssystem monterat i ett ramverk av stål på bussens tak. Volvo bussar vill minska bussens vikt genom att ersätta detta stålramverk, som är tungt, med en panel i ett lätt sandwich material.

Den största fördelen med sandwich material är dess överlägset höga styvhethet per viktenhet förhållande. Dess största nackdel är dess oförmåga att bära koncentrerade laster. Projektets primära mål är att finna en metod för att överföra laster från komponenterna i energilagringssystemet till sandwichpanelen. Projektets andra del består i att ta fram ett system för att fästa kablar, rör och slangar hos energilagringsystemet på sandwichpanelen.

En allmänt vedertagen metod för att överföra koncentrerade laster till en sandwichpanel är användandet av så kallade ingjutna insatser.

Med kunskapen om teorin kring ingjutna insatser och den nuvarande konstruktionen av energilagringsystemet togs ett antal koncept fram och ett slutgiltigt koncept valdes. I den nya konstruktionen har en viktminskning på 62 % erhållits relativt den nuvarande konstruktionen. I FE-analyser har det visats att den nya konstruktionen har förmågan att bära lasterna som en buss utsätts för under drift. I den nya konstruktionen används så kallade genomgående insatser för att överföra lasterna från komponenterna i energilagringsystemet till sandwichpanelen. Ett system för att fästa kablar, rör och slangar togs också fram. I figuren nedan visas den nya konstruktionen av energilagringssystemet. Till vänster syns den nya konstruktionen med alla dess ingående komponenter monterade och till höger ses den nya konstruktionen utan några komponenter monterade.



Den nya konstruktionen av energilagringssystemet.

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Abbreviations

CSU – Charging switch unit
ESS – Energy storage system
FP - Fully potted
HJB – Hybrid junction box
PP - Partially potted
SWP - Sandwich panel
TTT - Trough the thickness

1. Introduction

In this chapter the reader will take part of the background of the project, objectives and delimitations in the project as well as deliveries during the course of this project.

1.1 Background

When implementing hybrid and electric technology in busses one of the major challenges is that the energy storage system for the electric motor will require a lot of space and add a significant amount of weight to the bus. This extra weight will among other negative side effects primarily decrease the bus passenger capacity.

In Volvos hybrid and full electric busses, the energy storage system (ESS) is a battery module containing battery, cooling systems, electrical components, cabling and tubing that is mounted in a steel rack. The components are mounted on brackets that are welded on to the rack. This module is used in several different buses and adjusted for the requirement for each bus. In figure 1.1 a bus with two units of ESS highlighted in orange is shown.

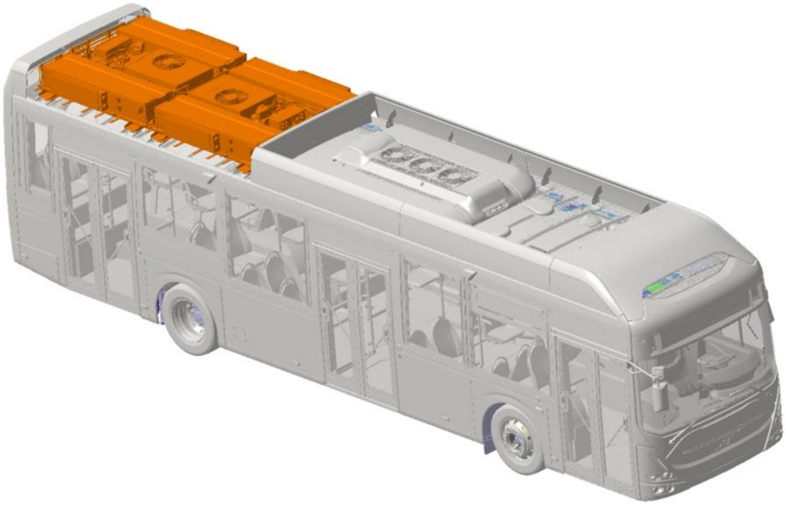

Figure 1.1 – ESS mounted on buss

The current steel rack is heavy. By replacing this rack with a design made out of a lightweight sandwich material the weight could be decreased. Engineers at Volvo has decided that the new lightweight rack will be designed as a flat rectangular sandwich panel. It is estimated that the sandwich panel will weigh 70% less than the steel rack. 70% corresponds to approximately 70 kg in this case which is the general weight of a passenger when the bus passenger capacity is analysed. If this weight reduction could be achieved the bus passenger capacity would increase by one passenger.

In the process of replacing steel with a sandwich panel, you will not be able to fasten the components to the new sandwich panel in the same way as in the case with the steel rack. This leads to the objective of this project.

1.2 Objective

This project aims to find ways to use sandwich material instead of steel and thereby decrease weight. The main objective of this project is to find ways to fasten components to the sandwich panel in a way that meets all the demands.

By the end of this project, a concept on methods of fastening components on the sandwich panel that meets TRL 4 standard (Technical readiness level 4, see appendix D) is presented. The results will form the basis for upcoming projects in this field.

1.3 Clarification of objectives

To clarify the objectives, the current design needs to be further explained. The steel rack is holding the energy storage system (ESS) with all its components. In figure 1.2 the steel rack on its own can be seen. Figure 1.3 shows a complete ESS mounted on the steel rack. It contains two batteries (1), a cooling system (2) and a junction box (3), hereafter named main components, and cables, pipes and tubes (4), hereafter named media, and media holders (5) in the form of steel profiles welded directly on the steel rack for holding the media.

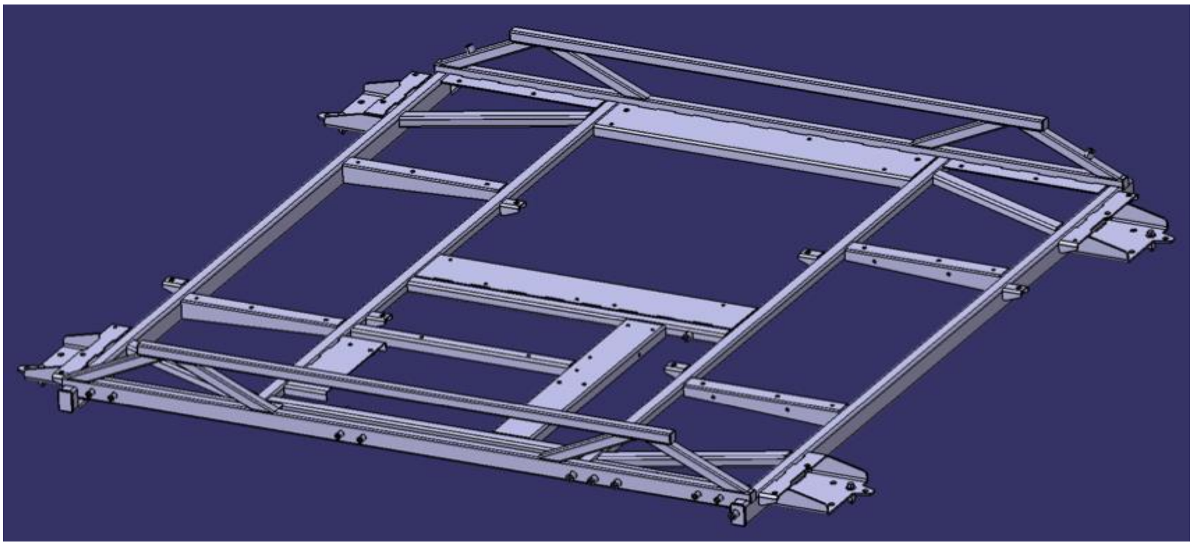

Figure 1.2 – Steel rack

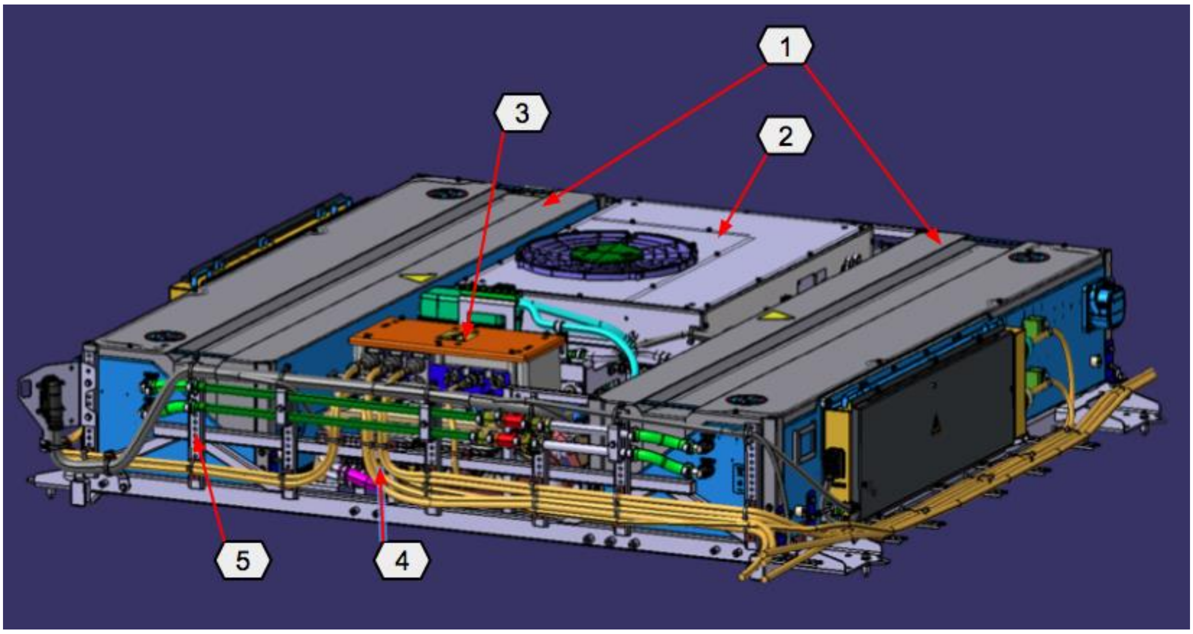

Figure 1.3 – Overview of steel rack and complete ESS

Figure 1.4 is a schematic representation of the ESS and its mounting on the bus.

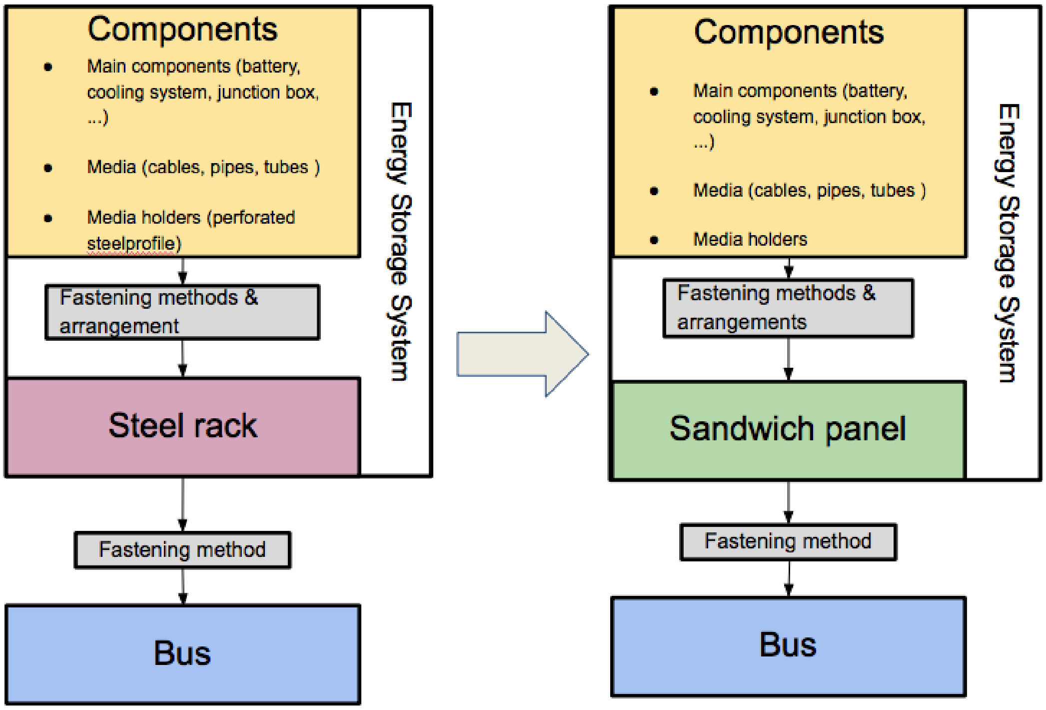

Figure 1.4 - Overview of the energy storage system, today (left) and new design (right).

1.3.1 Backwards compatibility

It is desired to minimize changes in the production and thereby keeping the production cost down. Today the main components are fastened with bolts to the steel rack from above with a screwdriver equipped with an extender and a socket of required size. When the bolt is tightened no counter torque is applied. It is demanded to keep this method in the production when components are mounted to the sandwich panel, hereafter referred to as SWP. It is demanded to keep the arrangement of main components and media intact. The arrangement of media holders can be adjusted.

Before the ESS is mounted on the roof of the bus all the main components, media and media holders shall be mounted on the SWP. Main components, media and media holders shall be mounted in such a way that they can easily be removed for service on the battery module.

Attached components, cables, pipes and hoses.
On the steel rack steel brackets, also known as media holders, are welded to the rack. The media holders have different length and have 7-10 holes for mounting media. Depending on the media different inserts are mounted in the holes and then media is fastened by bolts and/or cable ties, hereafter named media fasteners.

On the new rack all the components and media shall be arranged precisely as on the steel rack. The ways to mount the inserts can be modified but the inserts together with bolts and cable ties shall be used.

Methods to fasten components to SWP
By its nature SWP cannot carry concentrated load well. The main objective of this project is to find the best way to distribute the loads from the components to SWP during use.

Weight reduction
To achieve weight reduction, it is necessary to find a method for fastening components in the SWP. Since the use of a SWP instead of steel rack is motivated by reduction of weight it is important that the method of fastening that this project aims to develop does not add an unnecessary amount of weight to the final product.

Ensure demanded requirements.
For safety reason the energy storage system (ESS) must be able to resist different kinds of loads. Below follows a breakdown of the components and their critical loads

<u>Main components</u>
Due to the weight of the main components it is assumed that shock loads will be a critical aspect. Except shock loads the stress caused by vibrations will cause fatigue which the fastening method must be dimensioned for. Which one of the aspects that will be the most critical will depend on which hardware component that is analysed.

<u>Media</u>
Media components must also resist shock loads and resist fatigue. The fatigue will probably be the critical case. Media components must be mounted in a way that tubes, pipes and cables will not be worn down or damaged during operation and thereby cause leakage or short circuit.

Media holders
The current design of media holders will be reused and thereby it is ensured that the demands for media holders are fulfilled.

1.4 Delimitations

In this project there are some delimitations that won't be processed.

- The SWP has a core of foam with an aluminium face sheet. It is assumed that the SWP will be strong and stiff enough to carry the overall load. This project aims to analyse how the loads are distributed in the near region of the inserts.

- This project will not include designing new media holders. The media holders will be reused by its positions and weights.

- The project will not deal with the grounding problem that occurs when the steel rack who served as ground is replaced by the SWP.

- The project will not deal with the issue of mounting the SWP with components included on the roof of the bus.

- Components cannot be modified to work with the method used to fasten them to the SWP.

2. Theoretical reference frame

In this chapter theories and methods for sandwich panels and inserts are described.

2.1 Sandwich structure theory

The following section is based on the book “Insert design handbook” by ECSS 2011 [11] and “The handbook of sandwich construction” By Dan Zenkert [1]*.

A sandwich material is composed of two face sheets and a core illustrated in figure 2.1. The Faces are thin, stiff and strong and the core is thick, light and weaker. The three components are adhesively bonded to each other to enable loads to be transferred between them. In that way the properties of each component can be utilised to a structural advantage of the whole assembly.

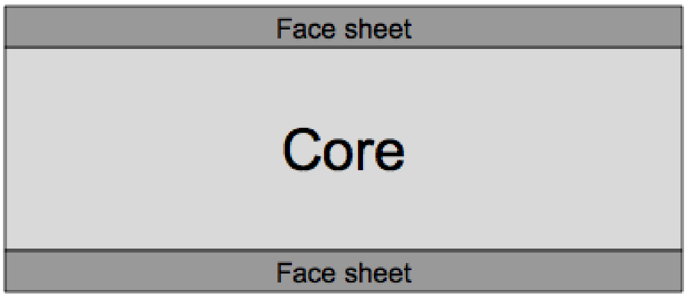

Figure 2.1 - Overview of sandwich panel

The great advantage of a sandwich structure is comparable to the I-beam where the large part of the material is placed on the flanges as far away as possible from the neutral axis.
The difference is that in a SWP the core is of another material and not concentrated in the middle as a narrow web but a continuous support under all of the face sheet. Because of this the primary load must be carried by the face sheet. The core primary acts as a stabilizer.

The faces make the sandwich structure resist external loads such as bending moment and the core resist shear and provides stability to the sheets for avoiding them to wrinkle and buckle. The shear modulus of the core affects how the load is distributed between the core and the face sheets. The higher the stiffness of the face sheets compared to the core stiffness is, the higher the load contribution to the core is and conversely.

The adhesive bonding has to be strong enough to resist shear and tensile stresses.

* Numbers in square brackets [ ] designates references

2.1.1 Advantages and disadvantages

The big advantage of sandwich material is the ability to utilize the properties of each component to the structural advantage of the whole assembly. When doing this correct you achieve superior strength-to-weight ratio. Figure 2.2 tells you how stiffness, flexural strength and weight is affected when a core is added between two sheets.

	Solid Material (t)	Core Thickness t (2t)	Core Thickness 3t (4t)
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Figure 2.2 – Relative comparison of stiffness, flexural strength and weight of SWP [11]

The big challenge with sandwich materials is how to transmit load to it. By its nature sandwich materials are not very good at carrying concentrated loads since the face sheets are thin and the core is too weak to distribute the loads effectively.

With this in mind, when transferring load onto a sandwich material it is of its highest importance to avoid concentrated loads, see figure 2.3. Thereby it is of highest importance to choose an appropriate insert.

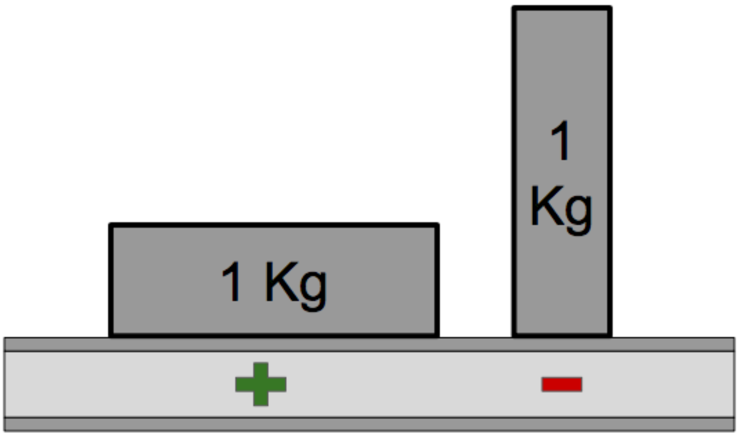

Figure 2.3 - Loads on SWP

2.2 Insert theory

The following section is based on the book “Insert design handbook” by ECSS 2011 [11] and “The handbook of sandwich construction” By Zenkert Dan [1].

“An insert is a local change in stiffness and strength of the sandwich panel, the purpose of which is to distribute a localised load in an appropriate manner to the sandwich panel”
- *Dan Zenkert* [1]

An insert is a component whose purpose is to distribute a local load from e.g. a bolt down to the sandwich panel as figure 2.4 shows.

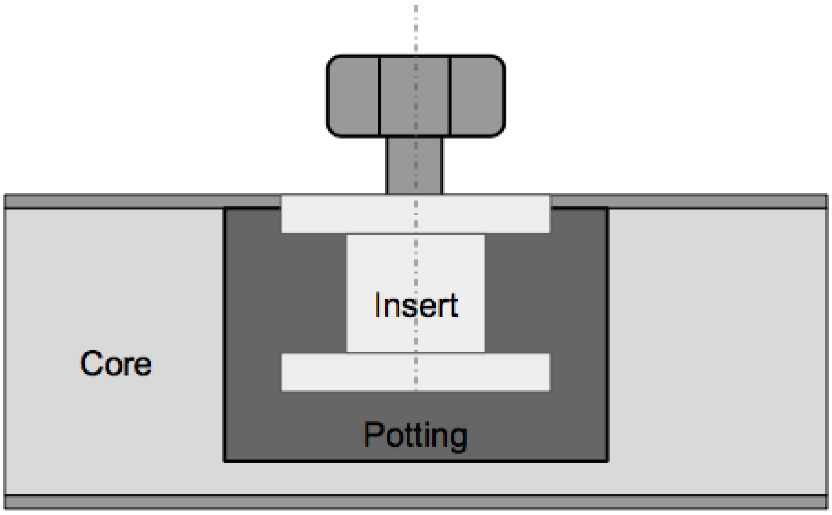

Figure 2.4 – Insert with internal threads in SWP

It is to be noted that theories and calculations of insert capacity are primarily based on empirical studies. The theories that have been used is widely spread and approved by many reliable organisations, for example European Cooperation for Space Standardisation and Boeing [8].

When using SWP´s it is of the highest importance to know about the load carrying mechanisms and understanding of the structural principles of inserts. Compared to the old steel rack which is quite tolerant for how the inserts are mounted on the rack (nuts welded on to the rack), the SWP requires a deliberate design of inserts to distribute loads.

Basically there are two types of insert, mechanical insert and moulded-in inserts, see figure 2.5. The mechanical inserts work like a screw joint where the insert is threaded and building in compression because of the deformation when tightening the insert. The moulded in insert are placed in a hole in the SWP and then moulded usually with epoxy-resin called potting.

The moulded-in insert is preferred because the plurality of advantages. The biggest of them is the ability to bound insert, potting, core and face sheets together which increase the ability to distribute loads.

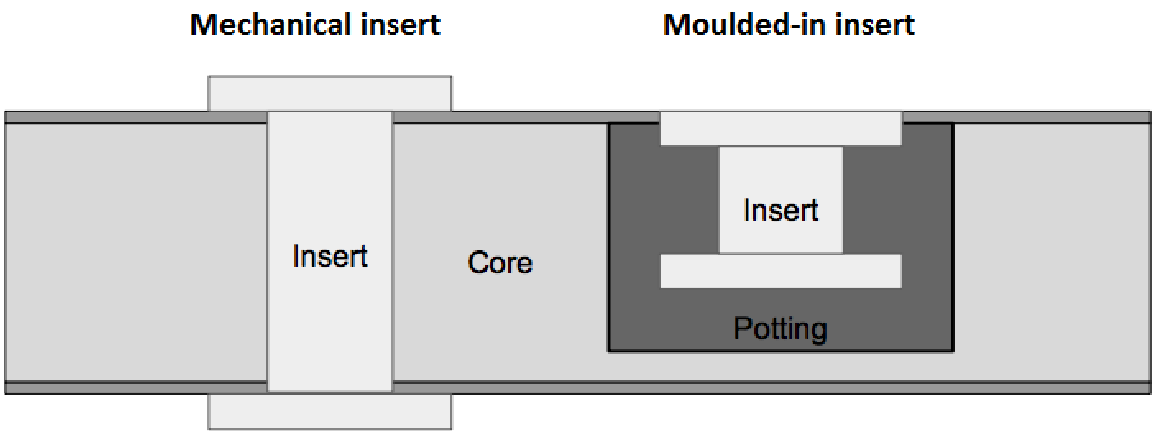

Figure 2.5 - Different types of inserts

There are three type of potted insert, which is shown in figure 2.6.

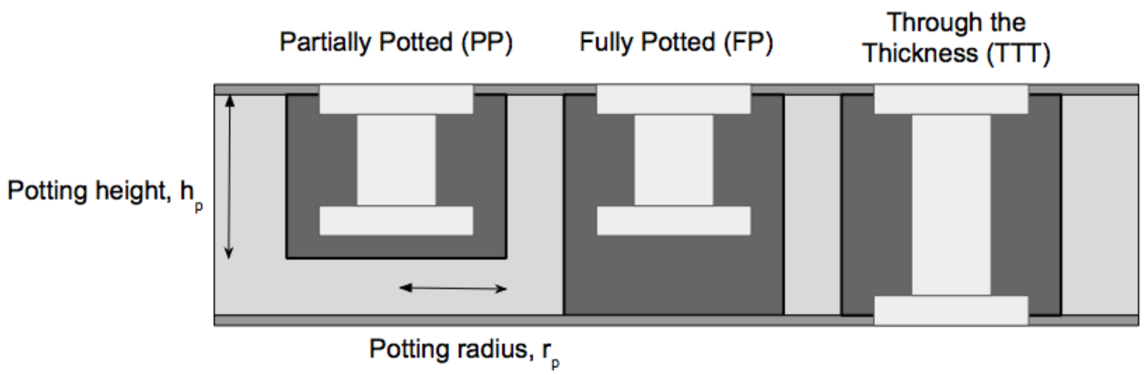

Figure 2.6 - Different types of inserts

The through the thickness (TTT) insert transfers pull and pressure forces to the core and it transfers moments and shear forces directly to the face sheets, which gives distinctly advantages. This makes the TTT-inserts superior for significant loads.

The fully potted (FP) insert transfer the different types of loads from the insert to one face sheet and/or the core. Partially potted (PP) insert are desirable when one face sheet is to be not damaged e.g. at shipbuilding. PP inserts shall be avoided when having a bending moment and shear forces.
The PP insert works like the fully potted insert but has lower weight and can carry smaller loads due to the decrease of surface area compared to a FP insert.

In order to transfer a concentrated load into a SWP it has been widely adopted to use TTT inserts to spread the load to both sheets and core.

2.2.1 Affected area under concentrated load

Consider a concentrated load *P* on the surface of the panel, see figure 2.7. At any closed circle around *P* equilibrium must be fulfilled. This yields that the reaction force per unit length $T = P/(2\pi r)$ at the enclosed path Π decreases by *r*. This means that the reaction force needed to resist locally concentrated load is inversely proportional to *r* and that reaction force needed to resist a concentrated moment is inversely proportional to r^2. This also indicates that the affected area under a concentrated load is small and for further calculations and simulations there is generally no need for calculation models for the entire panel.

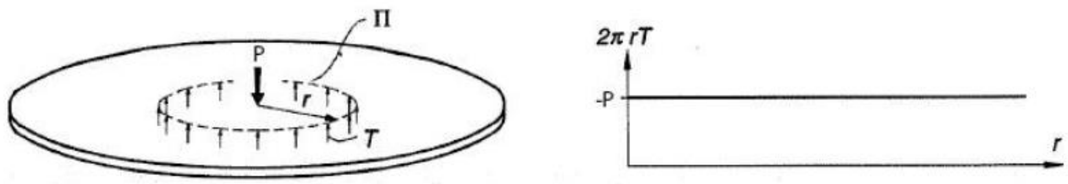

Figure 2.7 – Distribution of loads to surface [1]

In addition to the SWP's structural elements, two other elements are of interest: the insert and the potting compound. Since the young's modulus is much higher for both insert and potting compound than the core reasoning's and calculations usually are to be made under the assumption that the insert and potting is infinitely rigid and the interesting parameter is the potting radius r_{p}, see figure 2.6.

2.2.2 Load analysis

There are four kinds of loads, illustrated in figure 2.8, that have to be considered. Out-of-plane (or tension/compression) load *P*, in-plane-load (or shear load) *Q*, bending moment *M* and torsional moment *T*.

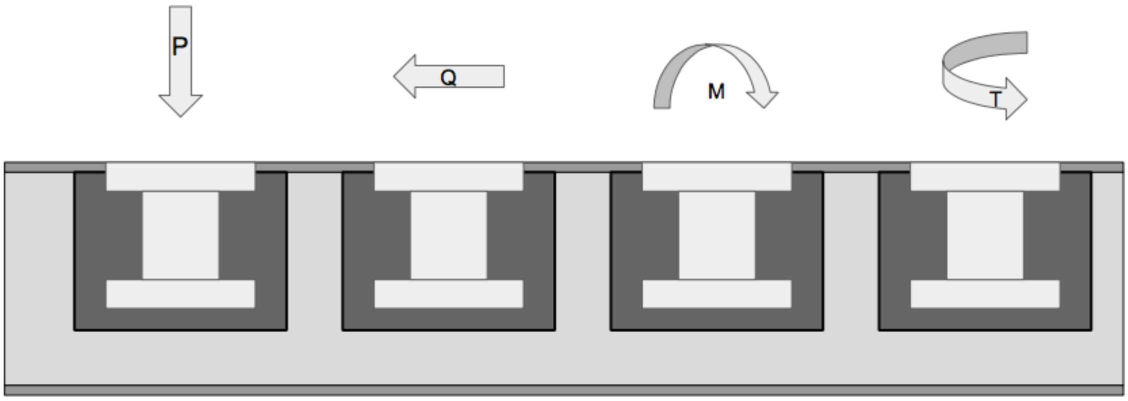

Figure 2.8 - Types of loads

Both bending moment and torsional moment on single inserts should be avoided because of the low strength and stiffness. On single inserts bending moments tends to "submarine" the insert into the core, see C in figure 2.9.

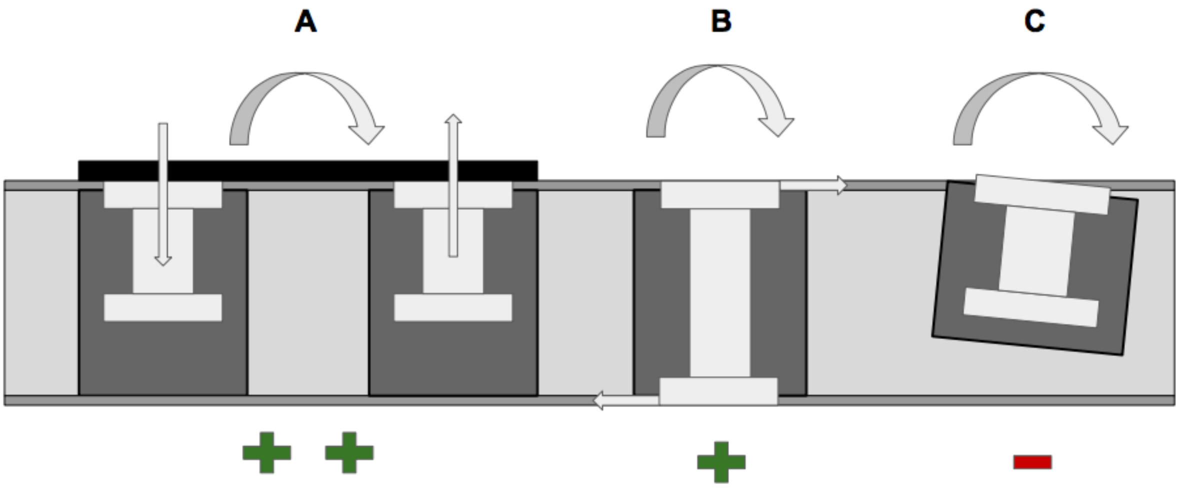

Figure 2.9 - Different load cases

A good design practice is to carry the bending moment by two or more inserts (coupled inserts) and "convert" the loads to normal out-of-plane loads which is a much more favourably load case, see A in figure 2.9. If double inserts are not possible, a TTT-insert is preferred. This enables the moment to be transferred directly to the face sheets, see B in figure 2.9. When using this design-practice only the preferred out-of-plane and in-plane loads remains.

Summary: Of the available inserts TTT-inserts is the superior insert when having great loads. If the design-practices cannot be utilized TTT-inserts has great advantages over the rest of the inserts when carrying bending moment. From now on, the assumptions made have TTT-inserts in mind if nothing else is mentioned.

2.2.3 Failure modes

Depending on which kind of load an insert is exposed to the highest levels of stress will appear in some different areas and result in damage. In figure 2.10 the most critical areas of stress are marked with a red line.

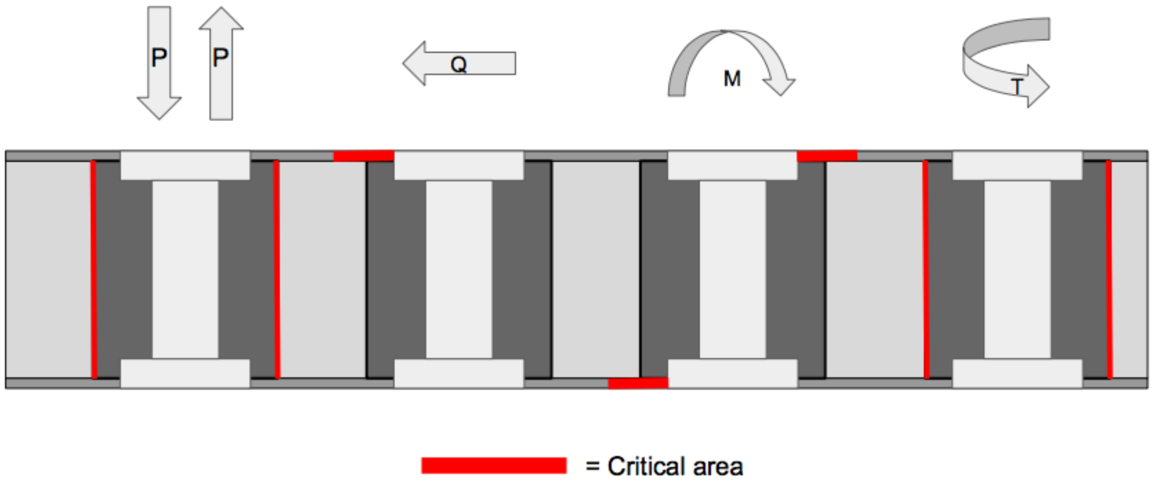

Figure 2.10 - Critical areas at different loads on an insert.

Variables mentioned in the text below can be found in figure 2.11.

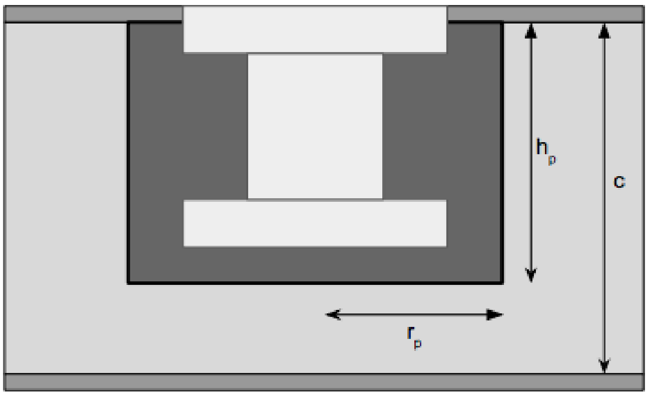

Figure 2.11 - Variables for inserts

The following arguments are true for sandwich panels with thin face sheets of metal with a thick, weak, isotropic core and where core or face sheets will fail before insert and potting which in this case is regarded as rigid.

<u>Out-of-plane tensile load *P*</u>
For a TTT insert with an out-of-plane loading fail will occur by shear rupture in the core surrounding the potting. The stress levels are decreasing when increasing the radius r_p . The rupture fail appears in the weaker core next to the stiffer potting. The limiting property in this case is the core shear strength $\tau_{c,crit}$ and the insert capability increases with the core height c and potting radius r_p.

For PP inserts, the same theory is valid but tensile rupture under the potting is possible if c-h_p reaches a certain value.

Out-of-plane compressive load *P*

The statements in out-of-plane tensile load are valid for an out-of-plane compressive load with some exceptions. For PP inserts tensile strength of the core is replaced by compressive strength and other than shear rupture in the core surrounding the potting fail due to compression under the potting is possible if c-h_p reaches a certain value.

In-plane loading *Q*

For in-plane loading the capability of the insert is limited by the yield strength of the face sheets $\boldsymbol{\sigma}_{fy}$. The core is weak compared to the face sheets. As a result of that, in plane loads are carried by the face sheets. The face sheets can also fail by compressive buckling around the insert. Other failure modes are possible but when having aluminium face sheets this is the most common. For PP-inserts only one face sheet is loaded which reduces the critical load. “Submarining” can occur due to the compressed core, see figure 2.9.

Bending load *M*

Bending moment on single inserts should be avoided. Using couple inserts, see figure 2.9 A, the load “converts” to out-of-plane, which makes the inserts significantly stronger. If coupled inserts are not possible a single insert can be used. When using a single insert for bending loads TTT insert is advantageous. Then the load case visualised in figure 2.9 - B are “converted” to in-plane loads. Bending moment on a single PP insert is not recommended for significant loads. This design will fail due to shear rupture or compressed core at small loads, see figure 2.9 -C).

Torsional load *T*

Just like bending loads, torsional load on single insert is to be avoided by using coupled inserts. If this is not possible, TTT or PP insert shall be used. For at TTT insert failure will occur due to shear rupture around the potting. The limiting property in this case is core shear strength $\tau_{c,crit}$ and the insert capability increases with the core height c and potting radius r_p. For PP inserts, the same theory is valid but shear rupture under the potting is possible if c-h_p reaches a certain value.

Summary: Depending on the type of load, different components in the SWP structure contributes with different amount of load bearing capability. Figure 2.12 below summarizes the different types of loads and provides an indication where the highest level of stress will appear.

Load type	Contribution of sandwich component to insert load-bearing capability		
	Core	Face sheet	Core/face bond
Tension	High	Medium	Very low (1)
Compression	High	Medium	Low
Shear	Low	High	Very low (1)
Bending	High	Medium	Low
Torsion	High	Low	Low

Figure 2.12 - Contributions of sandwich component to insert load-bearing capability [8]

2.2 Mounting of potted inserts

The stages of the mounting procedure of potted inserts are visualized in figure 2.13.
The first step is to drill a hole in both sheets and core. In step 2, the insert is placed in the SWP with a circular adhesive plastic part (a) that ensures the right position of the insert and maintain that position during the potting process. The plastic part has two holes (b). Potting compound is injected in one of the holes and the other hole permits venting. As an effect of the potting the inserts is well sealed and is resistant to the operating environment described in appendix B. After the curing process, the plastic part (a) is removed and step 3, the insert is ready to be used.

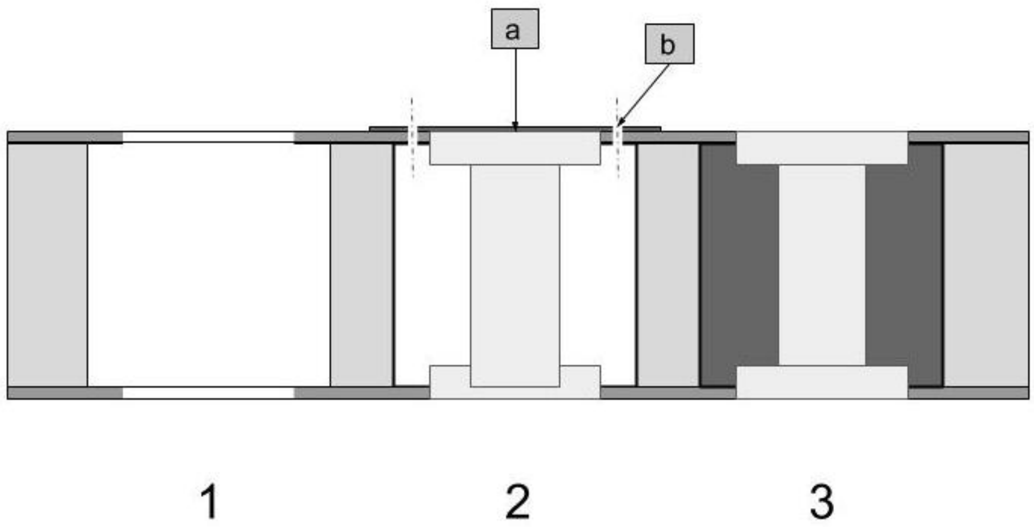

Figure 2.13 – Mounting procedure for potted inserts

3. Method

The work in this thesis started with an initiative phase where the project was defined and planned. Using reverse engineering [13] the product with all its functions was analysed which resulted in a specification of demands.

A Literature study was made on sandwich panels and inserts. Previously written texts and thesis about theory, experimental studies and calculations/simulations, and information from manufacturers and from Volvo uses in this field were studied.

Simplified load cases were made and numerical calculations determined approximate solutions. The model for numerical calculations was compared to experimental studies to validate the results.

From these approximations, a CAD-model was made and formed the basis for an FE-model. In-house experts at Volvo Buses performed FEM analysis.

4. Current design

In this chapter the current design with all its functions are described. The ESS is mounted on the roof of the bus in the rear end. There can be one or two ESS's on a bus. In figure 4.1, the complete ESS with all its components can be seen.

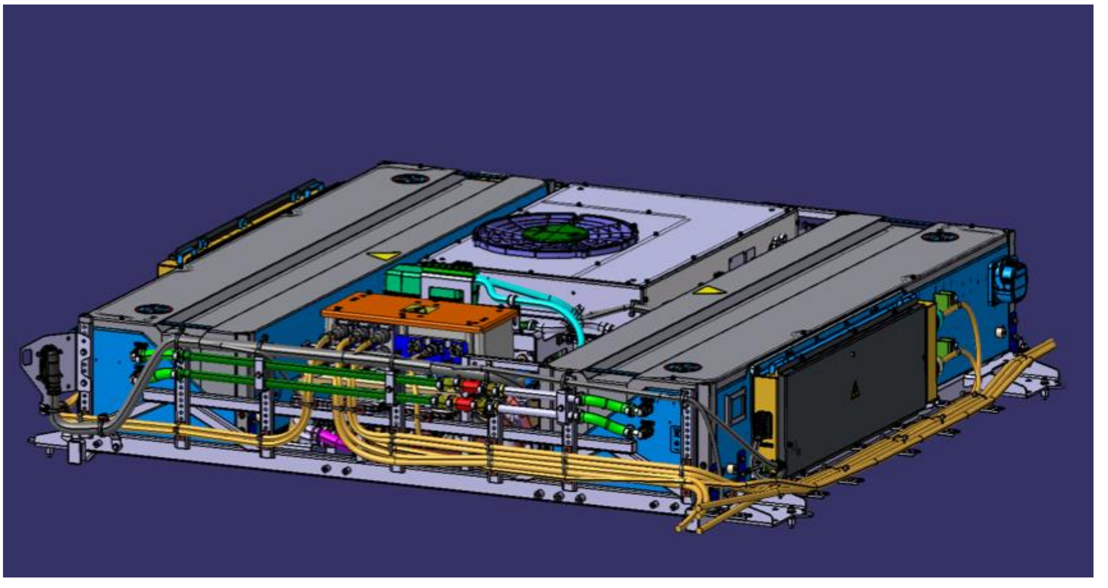

Figure 4.1 - Complete ESS

The current design of the ESS used in Volvo hybrid buses consists of a steel rack on which the components in the energy storage system are mounted. The steel rack is primarily made of 35 mm square steel profiles that are welded together. The total mass of the steel rack is approximately 93 kg, including media holders. In figure 4.2 the steel rack without any components mounted can be seen.

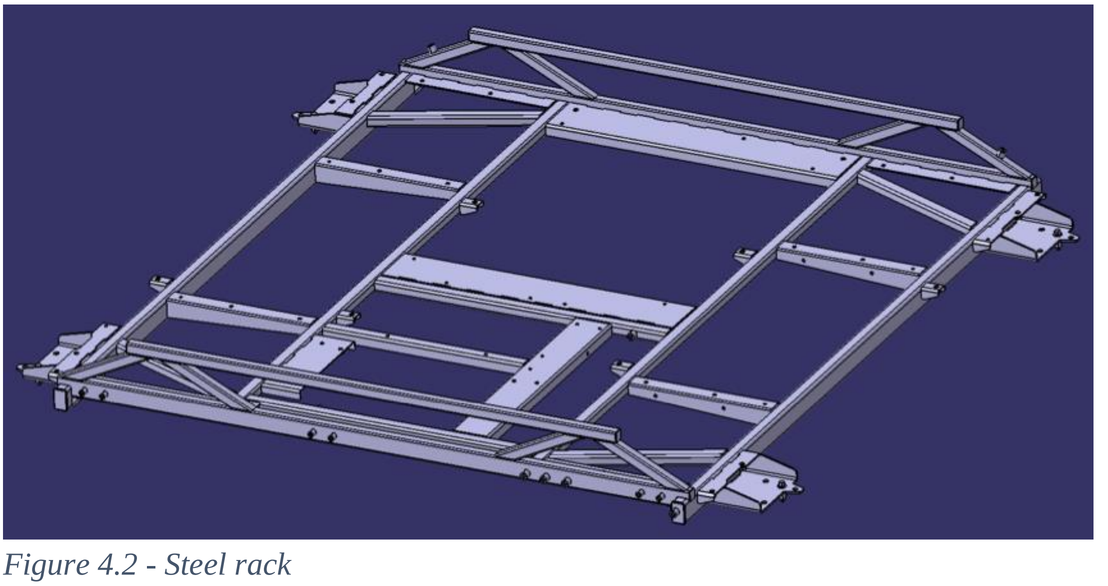

Figure 4.2 - Steel rack

4.1 Components included in the ESS

The included components have been divided into three groups based on their function and properties. The three groups are main components, media and media holders.

4.1.1 Main components

Components in this group are the main components in the ESS. In figure 4.3 below, the main components can be seen mounted in the rack. Note that no media can be seen in figure 4.3.

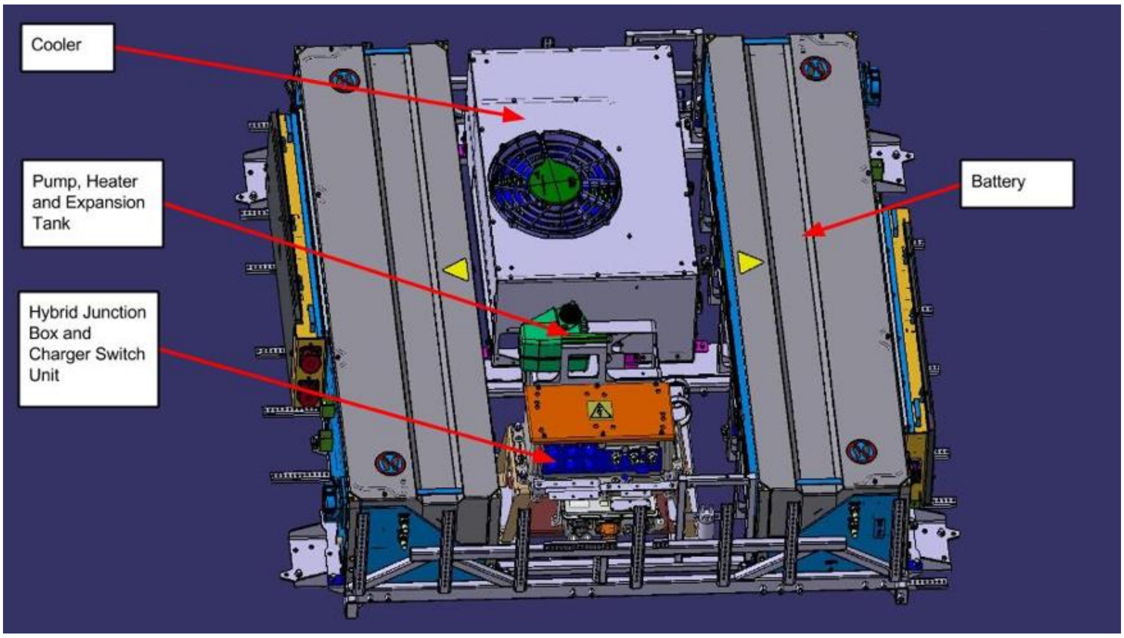

Figure 4.3 - Description of main components

The batteries are mounted directly onto the steel rack with eight M12 bolts for each battery. The cooler is fastened to the rack with six M8 bolts. For each fastening point for the batteries and cooler, a nut is welded on the bottom face of the steel rack. By welding a nut on the bottom face of the steel rack no counter torque is needed when the bolt is tightened. All bolts used to fasten the main components are tightened from above with a screwdriver equipped with an extender and a socket of required size. An L-shaped steel profile connects battery and steel rack. A similar L-shaped steel profile is also used to connect the steel rack and cooler. Figure 4.4 shows how the battery is fastened to the steel rack. The cooler is fastened using the same method shown in figure 4.4 with the only difference being the use of M8 bolts instead of M12 bolts.

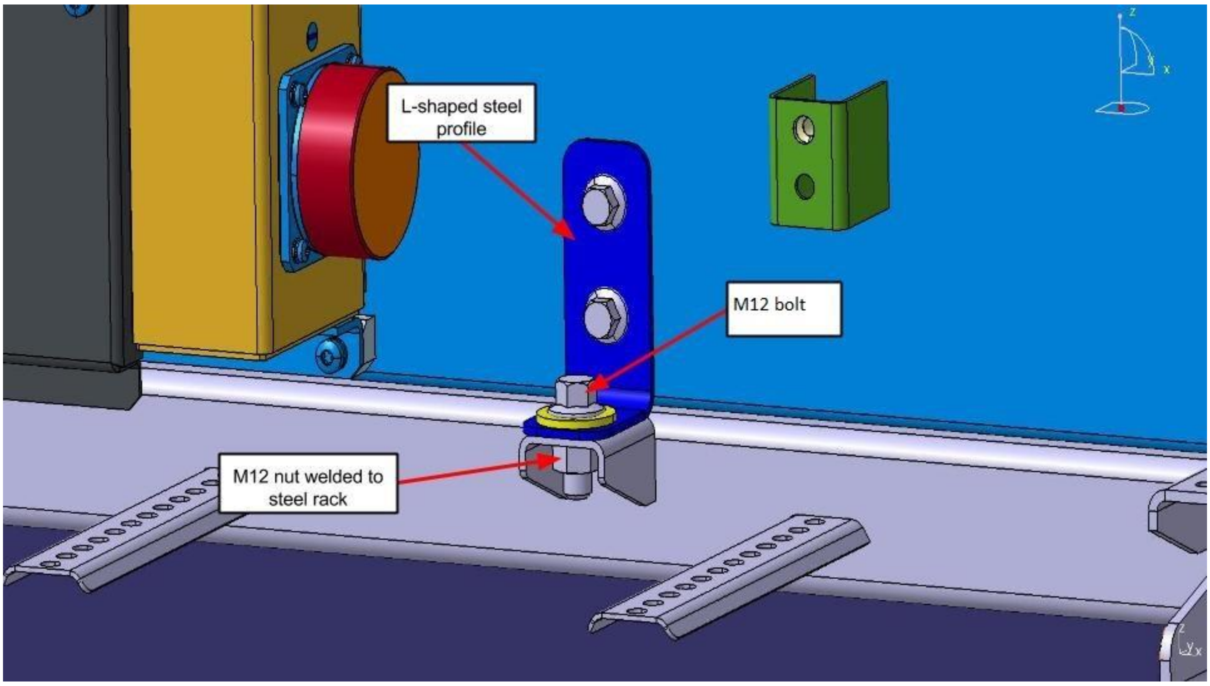

Figure 4.4 – Current fastening of the battery

The pump, heater and expansion tank are mounted together in a sub-rack as shown in figure 4.5. This pump sub-rack is then mounted onto the steel rack with six M8 bolts.

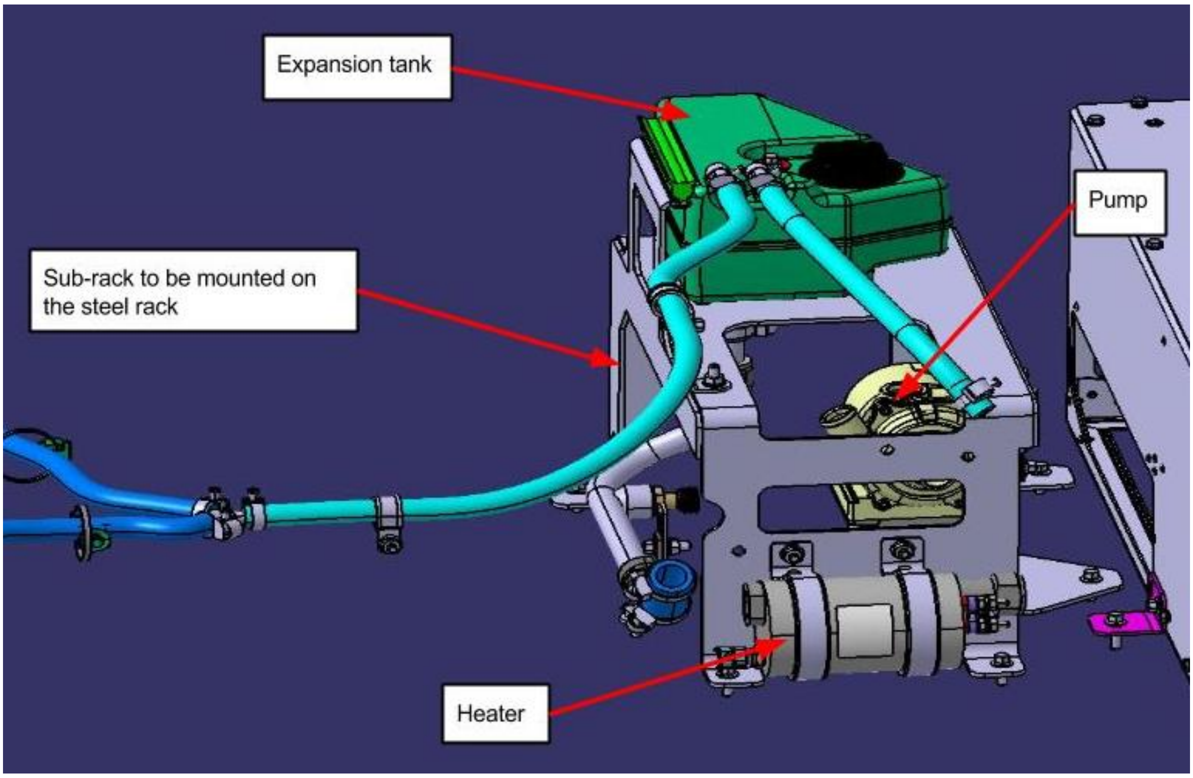

Figure 4.5 – Sub-rack with pump, heater and expansion tank

The hybrid junction box (HJB) is placed above the charging switch unit (CSU) as shown in figure 4.6. The HJB is mounted in the HJB sub-rack that is then mounted on to the steel rack with four M10 bolts. The CSU is mounted on the CSU-sub rack with four M10 bolts.

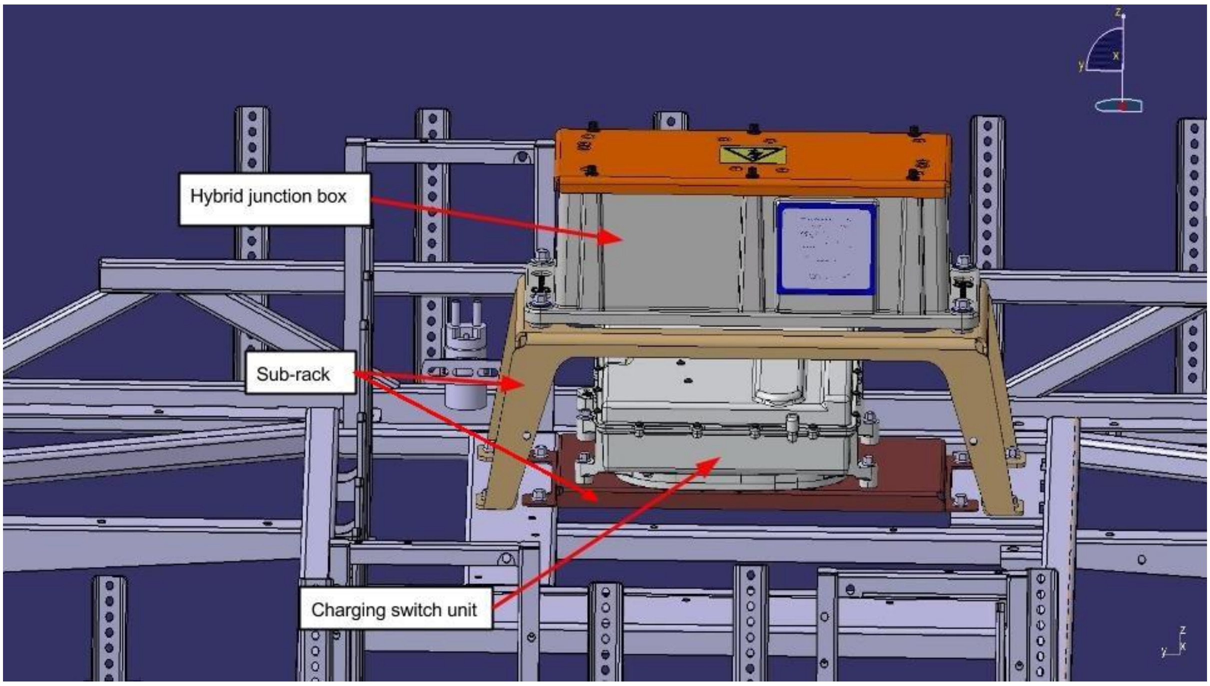

Figure 4.6 - Hybrid junction box and charging switch unit attached to sub-racks

In figure 4.7 below the main components and sub racks mounted on the steel rack is listed with quantity and total mass.

Main Components		
Component	Quantity	Mass [kg]
Battery	2	350
Cooler	1	53
Pump sub rack	1	6
HJB sub rack	1	19
CSU sub rack	1	17

Figure 4.7 - Table of main components

4.1.2 Media

Main components in the ESS are connected to each other and to other parts of the bus by various types of pipes, hoses and cables. These pipes, hoses and cables make up the group called media. In figure 4.8 two examples of media have been marked.

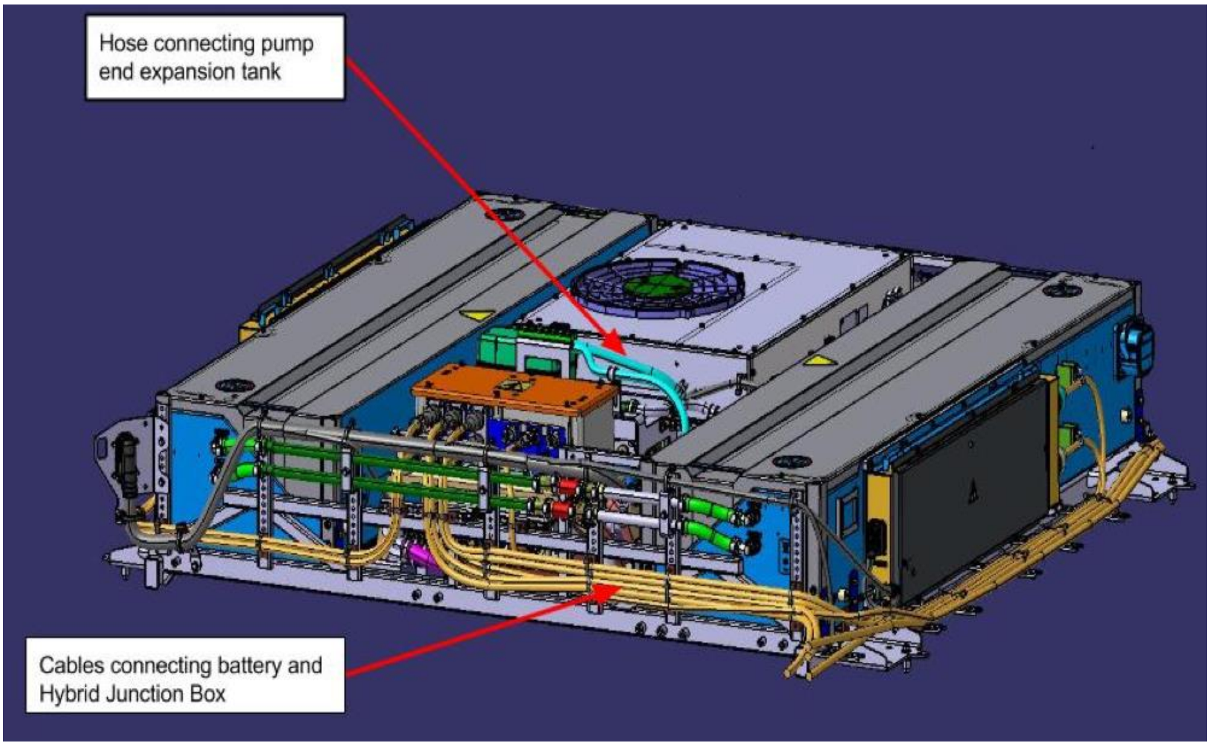

Figure - 4.8 - ESS with media

4.1.3 Media holders

The function of media holders is to hold media in place in the ESS. Media holders are made out of steel and are welded directly onto the steel rack with a minimum distance of 300 mm between each other. Media is fastened to media holders by the use of media fasteners. On each media holder there are 5 to 18 holes for fastening media with media fasteners. Media holders can be mounted on the steel rack either standing vertically or lying horizontally. The media holder group also contains two steel supports that holds up a covering plate which protects the entire ESS. These supports and the media holders have similar design and both are welded on to the steel rack; hence the reason for placing them in the same group. In figure 4.9 a vertical and horizontal media holder as well as a support for the covering plate has been marked.

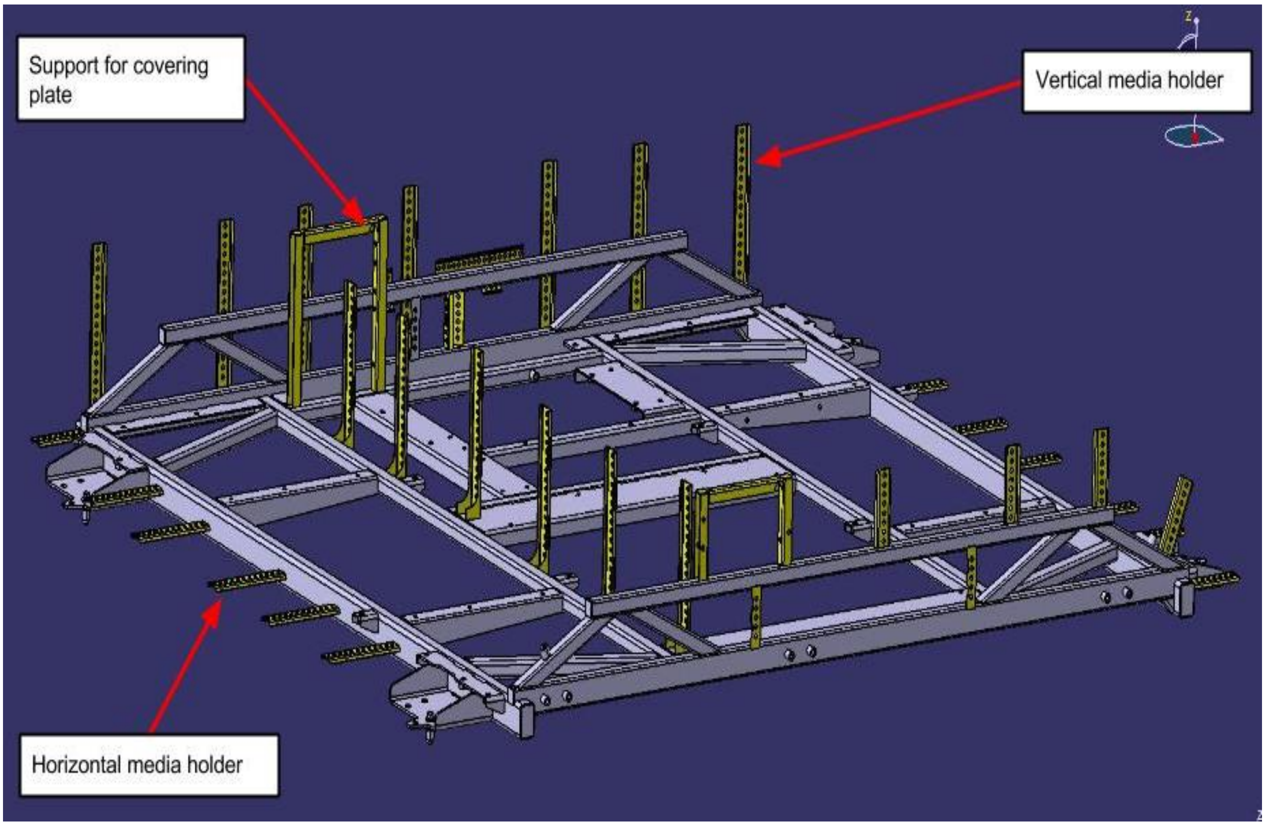

Figure 4.9 - Media holders marked at steel rack

Figure 4.10 below shows an example on how media is fastened to media holders using media fasteners.

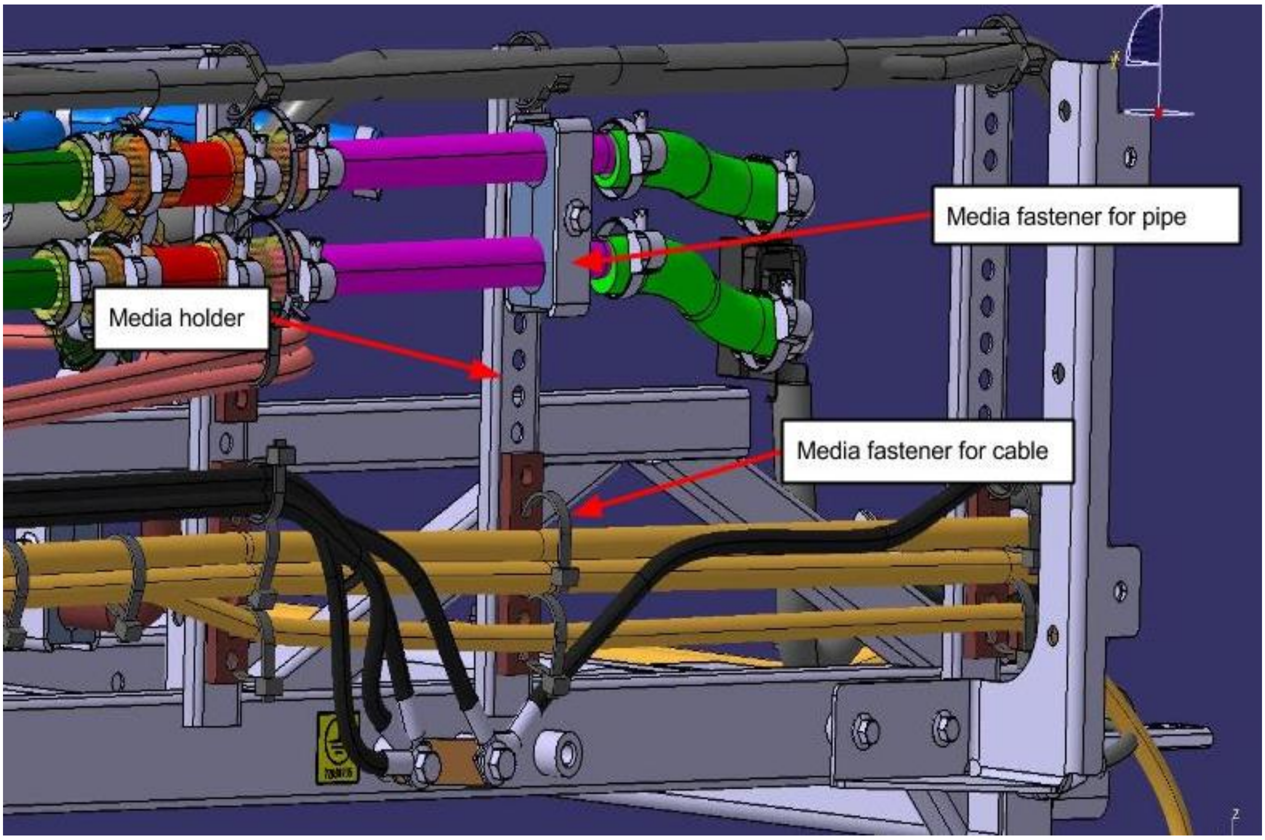

Figure 4.10 - Fastening methods for media

4.2 Design guidelines

Volvo buses uses design guidelines. The purpose of the design guidelines is to be a tool in the work of product development.

By means of these guidelines, you are assisted in the selection of product requirements, materials, methods and processes. In addition, you are advised on the design and installation of various types of machine elements and parts. Some design guidelines are relevant for this project and found below.

4.2.1 Clamping length

When designing a screw joint appropriate clamping length is needed, see figure 4.11. To ensure that the joint is working well the clamping length should exceed 1.5 times the diameter of the screw joint.

For the battery it means that the clamping length for the M12 screw must be 1.5x12 = 18 mm. The current design only has a clamping length of 9.5 mm which is less than desired. When designing the inserts for the new design the minimum clamping length easily will be fulfilled if the threaded part of the inserts is placed at the bottom, see figure 4.11.

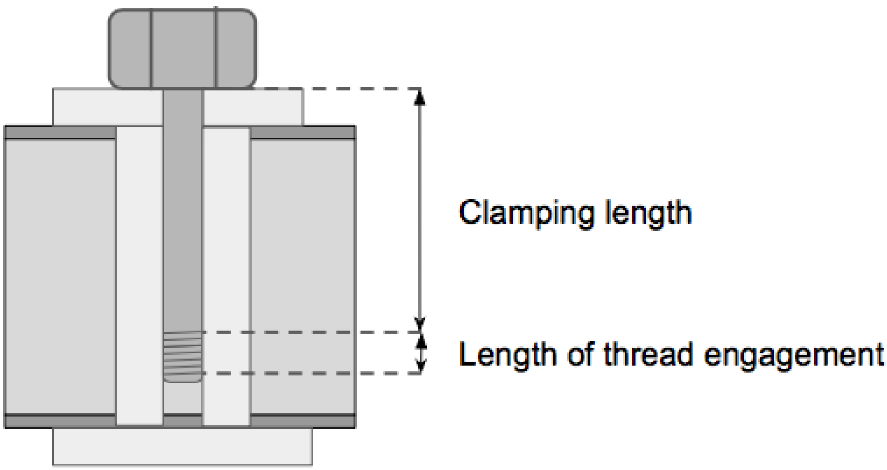

Figure 4.11 - Clamping length

4.2.2 Length of threaded engagement

When designing a screw joint an appropriate length of thread engagement is needed, see figure 4.11. To ensure that the joint is working well the length of thread engagement should exceed the diameter of the screw joint.

5. Dimensioning loads

Components in the ESS must be fastened in such a way that they can withstand certain loads without failing. A fastening method for a certain component must be able to withstand a maximum static load as well as a fatigue load. Components on the ESS must also be fastened in such a way that they have sufficiently high natural frequency.

5.1 Standard loads

Volvo supplies standard loads for components on a bus. Standard loads are the general loads, which a bus is exposed to during operation. All loads listed in Volvo standard loads includes safety factors. All components in the ESS will be dimensioned for these loads.

The components in the ESS are to be regarded as "other equipment on flexible support" when choosing load case in Volvo standard loads. By choosing this load case, it is ensured that components in the ESS will meet a minimum requirement on strength.

Volvo standard loads for "other equipment on flexible supports" states that:

1. Components must have a sufficiently high natural frequency to avoid resonance in components*.
2. Components must be able to withstand the maximum static loads presented in figure 5.1 below*.

Direction of Load	Maximum Static Load
Vertical	-X g
Lateral	0.5X g
Longitudinal	0.5X g

Figure 5.1 - Table of standard loads

5.2 Battery loads

Due to the batteries chemical nature it is desired to dimension the fastening method for the batteries against a greater static maximum load than other components. The maximum static load will be replaced with a shock load. Values for the shock load are presented in figure 5.2*.

*Due to secrecy, loads have been censored.

Direction of Load	Shock Load
Lateral	1.3X g
Longitudinal	1.7X g
Vertical	–X g

Figure 5.2 - Table of battery loads

These increased loads are preventing batteries from come lose. That is, a fastening design is not meant to manage these increased loads multiple times without breakage, only ensure that batteries will not come off.

6. New Design

In the new design, the steel rack will be replaced with a SWP. The main reason being weight reduction. When replacing the steel rack with a SWP it is no longer possible to keep the current method of fastening. When fastening main components on the steel rack nuts are welded to its bottom face and bolts fastens the main components from above. This method will no longer be compatible with a SWP since it is not possible to weld a nut to the bottom face of the SWP. Media holders are currently welded directly onto the steel rack, this will also not be possible with a SWP. This means that in the new design, new methods of fastening main components and media holders has to be found, which is the main objective of this project. The new design is presented in figure 6.1 and figure 6.2 below. The vertical media holders are connected through a framework, which is fastened to the SWP with seven TTT inserts. The horizontal media holders are glued on to the SWP along two of the edges of the SWP. All the main components are fastened with TTT inserts, which has been potted with a sufficient potting radius. The total mass of the new design amounts to 35 kg, which corresponds to a weight reduction of 62%. In FE-analysis stress levels in the SWP has shown to be low. From here on the workflow that resulted in this design will be presented.

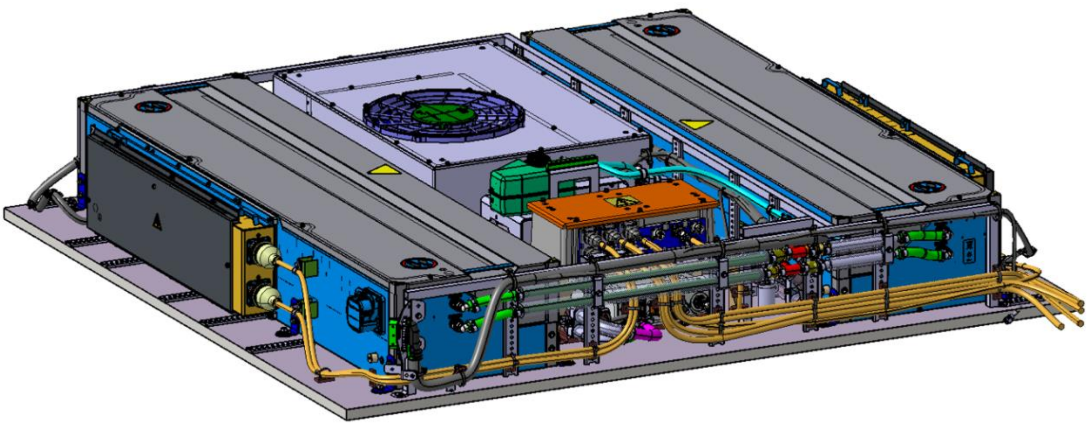

Figure 6.1 – Final concept in the complete ESS

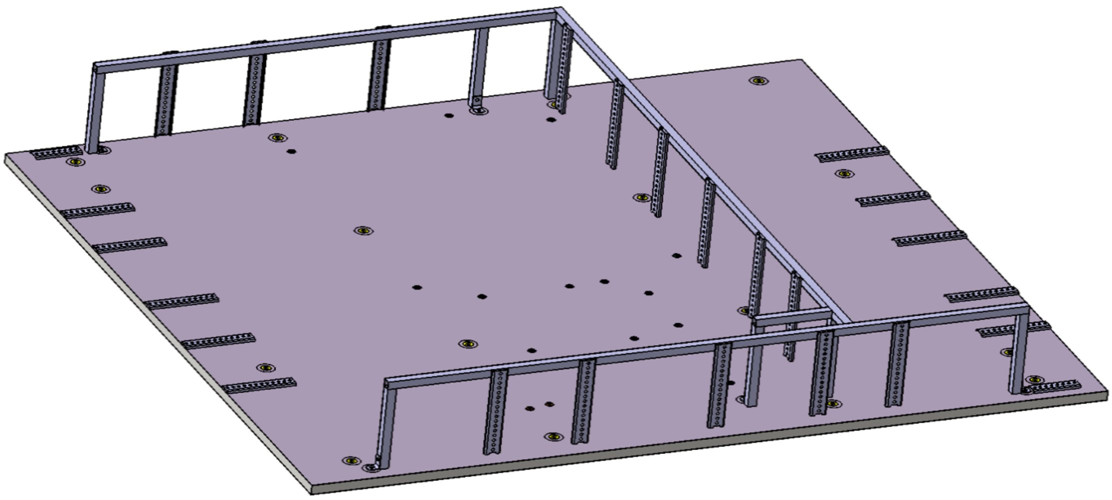

Figure 6.2 – Final concept.

6.1 Backwards compatibility

When replacing the steel rack with a SWP it is desirable to minimize changes in production and the aftermarket of the ESS, this will hence be defined as backwards compatibility. Backwards compatibility can be achieved by considering a number of aspects in the new design of the ESS. These aspects are the following:

- Keeping the components in the same arrangement as in the current design.
- Ensure that the same tools can be used when fastening components to the SWP.
- The components will be mounted from above without the need of applying counter torque when the screws are tightened.
- Main components cannot be modified to be compatible with a fastening method.
- It will be possible to mount a complete ESS separately, which then later can be mounted on a bus.
- It will be possible to remove an individual component in the ESS for maintenance purposes and then either replace it with a new identical component or, after maintenance, remount the same component.
- It is demanded that media can be fastened to media holders with the same method in the new design as in the current design, that is by the means of media fasteners, see section 4.1.3.
- To match the height of the current steel rack which is primarily made up of 35 mm square steel profiles, see chapter 4. Therefore the SWP together with the fastening method, components excluded, is not allowed to have a height greater than 35 mm.

The above aspects are also listed in the specification of demands in appendix B.

New media holders
Since the current media holders are welded directly onto the steel rack a redesign of media holders will have to be necessary for them to be compatible with a new fastening method.

Operating environment
Beyond these aspects the new design also has to be able to withstand impact from the environment in which the bus will operate in. Such impacts from the operating environment are presented in the specification of demands in appendix B.

Loads
The new design will also be able to withstand the loads it will be subjected to during production and operation. These loads were presented in chapter 5.

Sandwich panel
Due to limited space on the roof of the bus outer dimensions of the SWP has been defined as the outer dimensions of the steel rack. By making sure that the SWP is no larger than the steel rack it can be assumed that the SWP will fit into the space reserved for the ESS on the roof of the bus. It shall be noted that this project is delimited from the issue of mounting the ESS to the roof of the bus. This assumption on dimensions is made for the reason to find out if components can be mounted on the limited area that the SWP constitutes.

When replacing the steel rack with a SWP the change will have some effect on the serviceability of the batteries. Bolts on the side of the battery, that in the current design can be reached from below will no longer be possible to reach from below in the new design, see figure 6.3 and 6.4. This problem occurs because the batteries are designed to be used on a steel rack. Solving the problem would require a redesign of the batteries which is beyond the objective of this project.

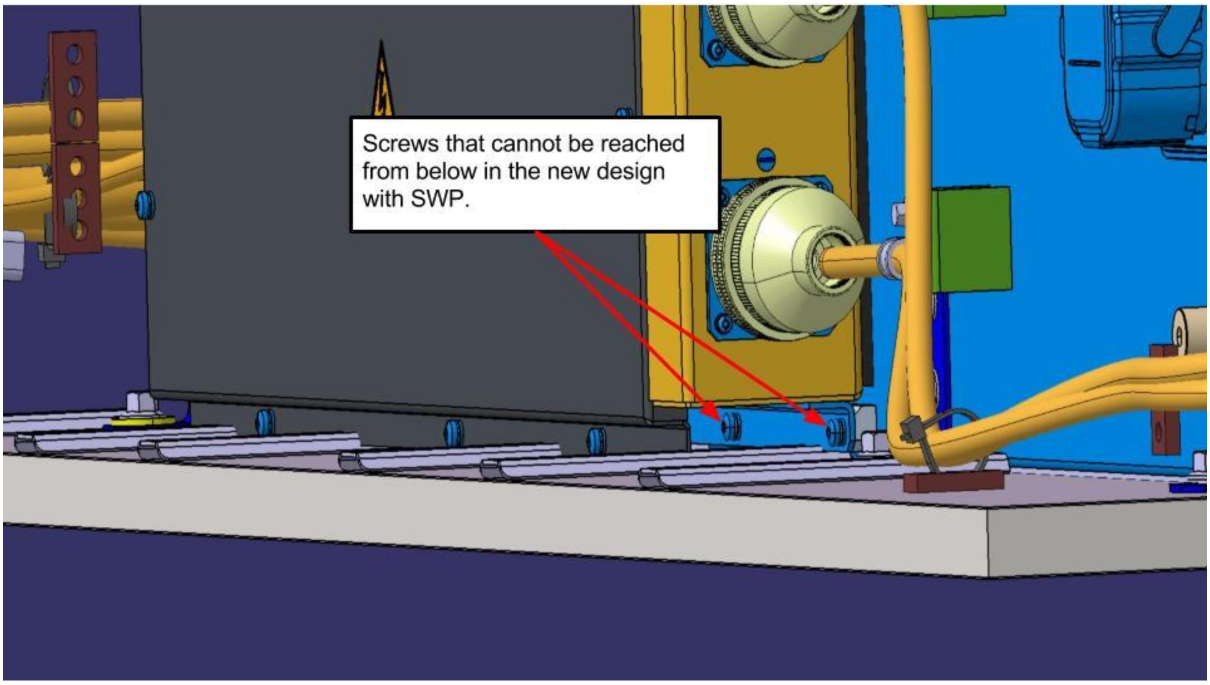

Figure 6.3 - Screws that cannot be reached in the new design.

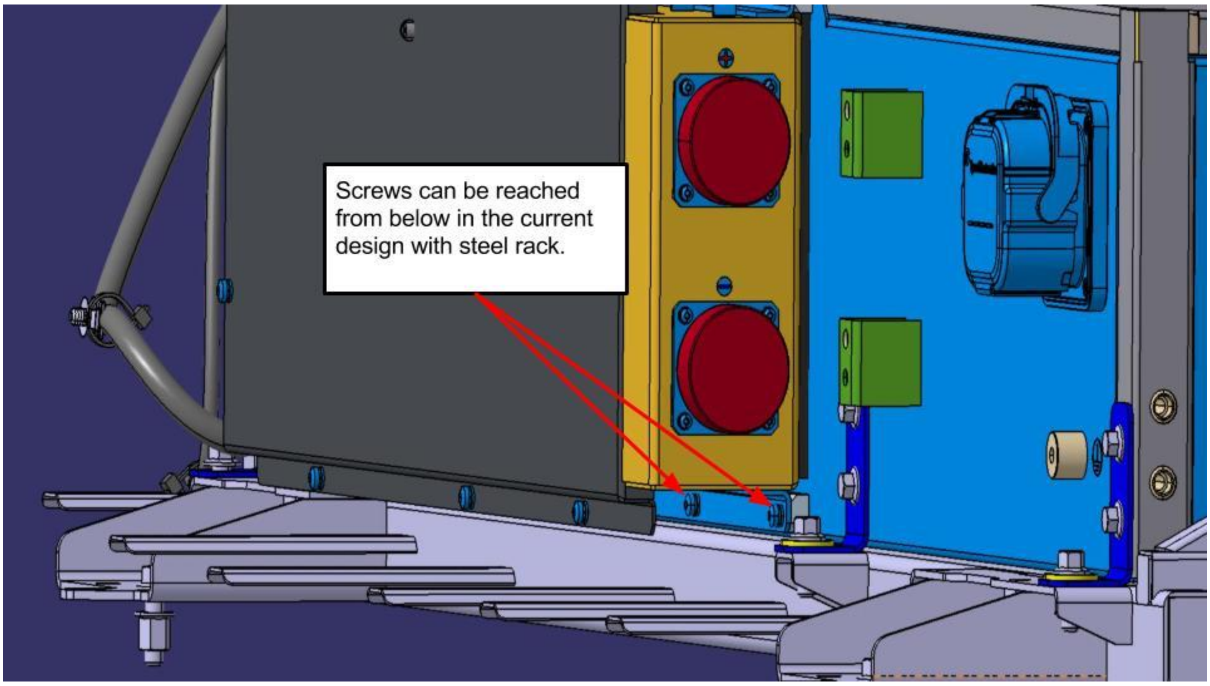

Figure 6.4 - Screws that can be reached in the current design.

In figure 6.5, a surface representing the SWP has been placed under the steel rack so that the outer dimensions of the SWP can be defined as the outer dimensions 2244x2063 mm, of the steel rack.

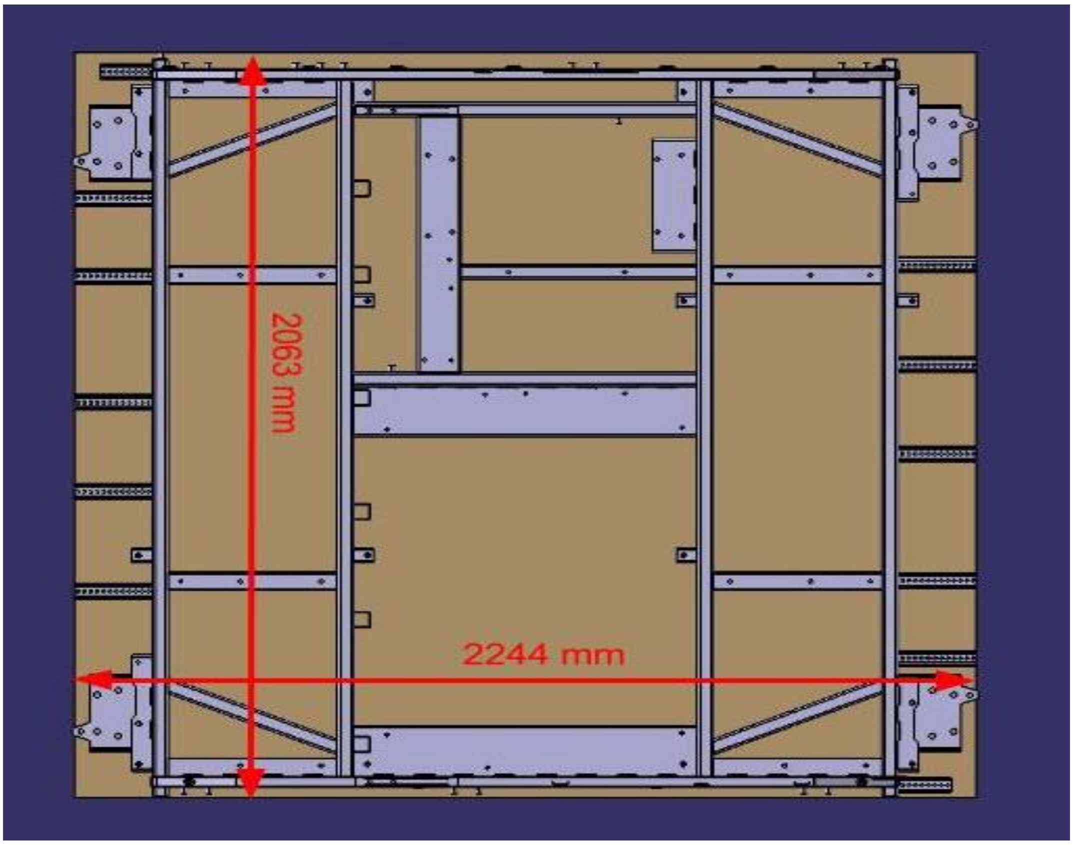

Figure 6.5 - SWP outer dimensions

To get an overview of the fastening points for all components figure 6.6 was made. In the upper left every fastening element for each main component and every media holder has been marked on the steel rack. In the upper right the same markings have been done on a surface representing the SWP. Lastly, in the bottom every fastening element for each main component and every media holder has been marked with a circle on a surface representing the SWP.

In the centre of every circle in figure 6.6, a method for fastening the component corresponding to that circle has to be found. Multiple circles could be covered by a single method of fastening.

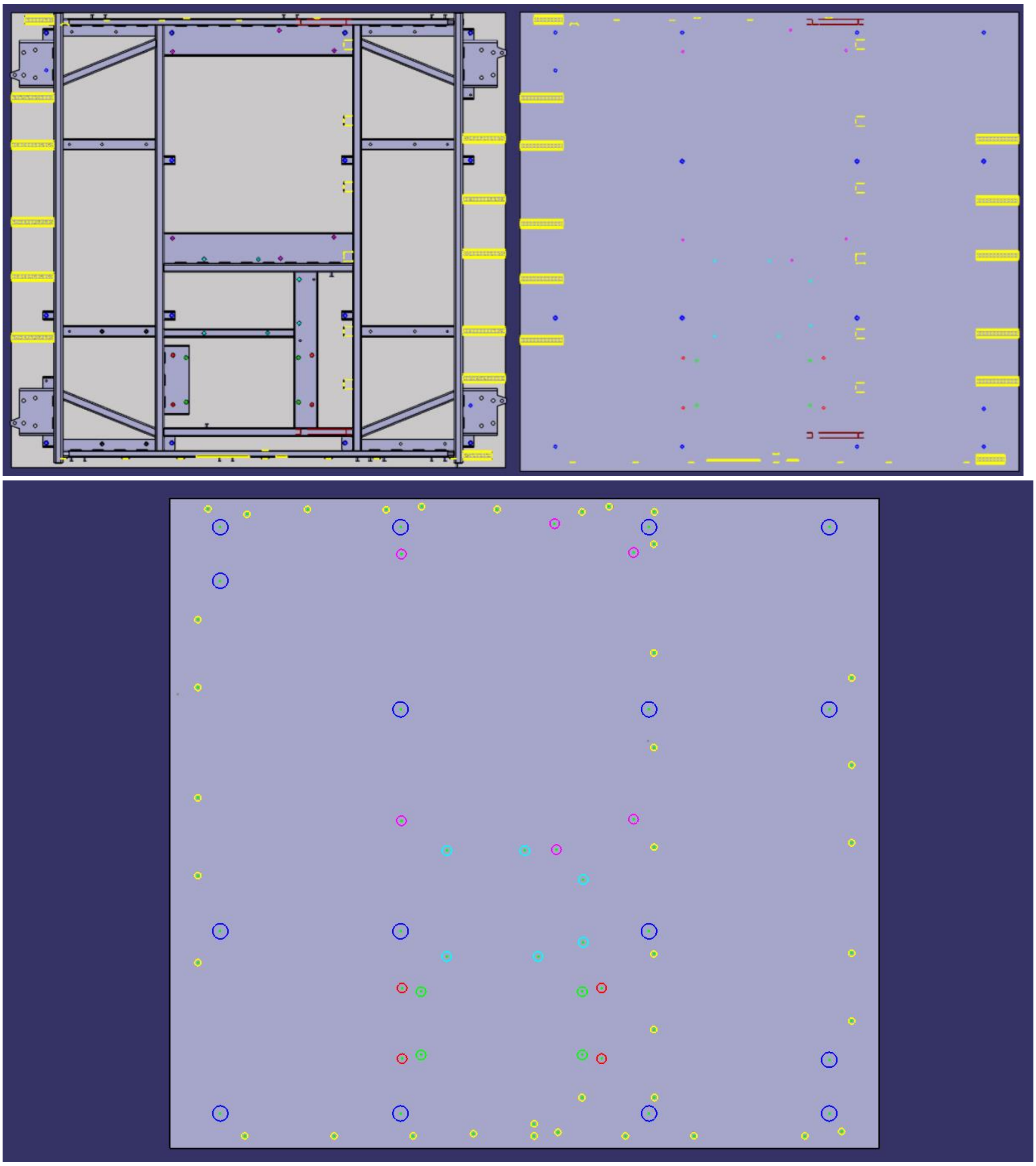

Figure 6.6 – Fastening points on SWP

The size of the circles corresponds to the magnitude of the loads. The 16 large blue circles correspond to the fastening point of the two batteries, 8 for each battery. The batteries are the heaviest components and thereby generates the most critical loads. The purple, turquoise, green and red correspond to the fastening point of the cooler, pump and heater, CSU and HJB. The weight of each of these components is approximately a tenth of the weight of one battery and therefore generates a smaller load. The yellow circles corresponds to the media holders and generate even smaller loads.

6.2 Dimensioning of SWP

To further analyse the strength of a fastening method in the SWP it must be given certain properties. These properties include:

- Core material
- Core height
- Face sheet material
- Face sheet thickness

The project delimitates itself from specifying analysing the SWP. However it would be impossible to evaluate the performance of any fastening method without the properties of the SWP, because any given reasonable method of fastening would be dependent on these properties. To not specify these properties would simply give too many free variables.

Load carrying capability is defined as the amount of load the SWP can carry without malfunction. When the SWP is subjected to load through fastening points of the components stress will occur both locally around the fastening point as well as globally due to displacement of the SWP. Figure 6.7 shows a SWP being subjected to load P through a component fastening point.

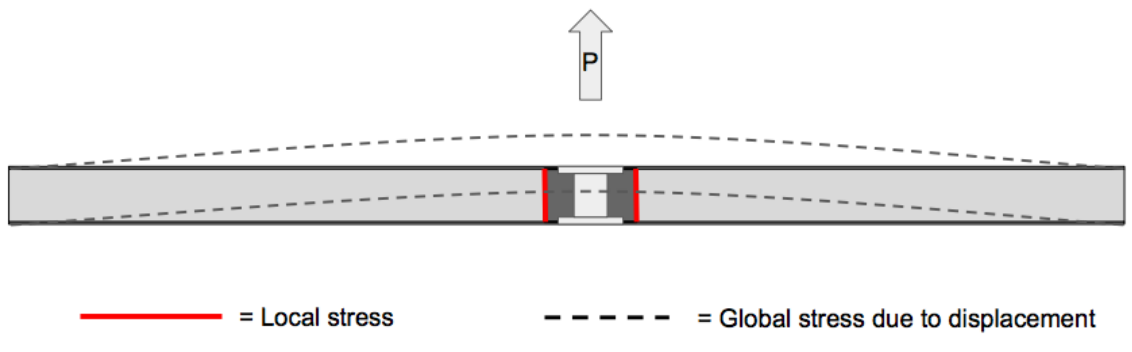

Figure 6.7 - Local stress and global displacement

This project is mainly oriented to analyse the local stress around the fastening points in the SWP. Therefore, a SWP was chosen that is assumed to be able to withstand the global stress. The project members consulted in house experts at Volvo Buses to conclude that a core height of c = 30 mm and a face sheet thickness of 0.8 mm should be sufficient enough to comply with the demand of having sufficiently high natural frequency and withstand global displacement and stress without malfunction. The fastening method will then be designed with respect to the strength of this SWP as more fully described below.

Core height

Core height: *c* was primarily specified with respect to the demand of having a sufficiently high natural frequency. A greater core height makes the SWP stiffer and thereby increasing the natural frequency of the SWP. To achieve a higher load carrying capability of the SWP the core height c could be increased.

Core Material

A core material used previously by Volvo Buses in similar applications was chosen. This material is the Divinycell H45 [6]. Products in the Divinycell H-series are presented in figure 6.8.
From figure 6.8 it can be concluded that Divinycell H45 has relatively low strength and density compared to most other products in the H-series. To achieve higher load carrying capability of the SWP, a core material ranging from H60 to H250 could be chosen.

Mechanical properties Divinycell® H

Property	Test Procedure	Unit		H35	H45	H60	H80	H100	H130	H200	H250
Compressive Strength[1]	ASTM D 1621	MPa	Nominal	0.5	0.6	0.9	1.4	2.0	3.0	5.4	7.2
			Minimum	0.3	0.5	0.7	1.15	1.65	2.4	4.5	6.1
Compressive Modulus[1]	ASTM D1621-B-73	MPa	Nominal	40	50	70	90	135	170	310	400
			Minimum	29	45	60	80	115	145	265	350
Tensile Strength[1]	ASTM D 1623	MPa	Nominal	1.0	1.4	1.8	2.5	3.5	4.8	7.1	9.2
			Minimum	0.8	1.1	1.5	2.2	2.5	3.5	6.3	8.0
Tensile Modulus[1]	ASTM D 1623	MPa	Nominal	49	55	75	95	130	175	250	320
			Minimum	37	45	57	85	105	135	210	260
Shear Strength	ASTM C 273	MPa	Nominal	0.4	0.56	0.76	1.15	1.6	2.2	3.5	4.5
			Minimum	0.3	0.46	0.63	0.95	1.4	1.9	3.2	3.9
Shear Modulus	ASTM C 273	MPa	Nominal	12	15	20	27	35	50	73	97
			Minimum	9	12	16	23	28	40	65	81
Shear Strain	ASTM C 273	%	Nominal	9	12	20	30	40	40	45	45
Density	ISO 845	kg/m³	Nominal	38	48	60	80	100	130	200	250

All values measured at +23°C

1. Properties measured perpendicular to the plane

Nominal value is an average value of a mechanical property at a nominal density
Minimum value is a minimum guaranteed mechanical property a material has independently of density

Figure 6.8 - Table of mechanical properties of Divynicell H [6]

Face sheet material

The most probable choice of material for the face sheets of a SWP is aluminium. Aluminium is the material most common at Volvo Buses and is currently used in SWP’s in similar applications at Volvo Buses.

Face sheet thickness
The face sheet has to be thick enough to resist loads on the SWP, mainly shear load. Furthermore, the face sheet has to be durable enough to withstand handling in production, for example a tool being dropped on the SWP. It has been assumed that a face sheet thickness of $f = 0.8$ mm will be sufficient. To achieve a higher load carrying SWP a face sheet thickness of $f = 1.0$ mm could be chosen. $f = 0.8$ mm and $f = 1.0$ mm are standard aluminium sheet thicknesses at Volvo Buses. A face sheet thickness of $f > 1.0$ mm is considered to add too much mass to the SWP.

6.3. Fastening methods

When the SWP, the fastening points for all components and the loads on each component are defined it is possible to draw conclusions about possible and suitable fastening methods.

6.3.1 Circular single inserts

Regarding section 2.2 Insert theory it can be concluded that circular TTT inserts are generally accepted as the most suitable fastening method without inhibiting the SWP’s lightweight nature, so also in this project.

6.3.2 Moulded in profile

In case of great loads TTT insert may be insufficient and result in torn out insert. In that case a moulded in profile can be used. If a number of fastening points with great loads are in a row or close to each other in a way that single inserts can´t be used, a profile (or plate) with several fastening points can be used, see figure 6.9. In figure 6.9 two potential moulded in profiles are sketched as yellow marked area. In each profile there are 4 inserts points with heavy loads (blue circles) and 4 fastening points close to each other (next to the top). In this case a moulded in profile may be suitable.

As stated before, a moulded in profile take advantage of it's much bigger area which provides a better distribution of loads. In figure 6.9 three types of profiles (or plates) are shown. A TTT (A) or a PP (B) T-track profile with self-locking hex-head bolts could be used. The third type (C) is a flat profile with threaded holes. Moulded in profiles has disadvantages too, with its larger area comes a larger potting and a higher weight.

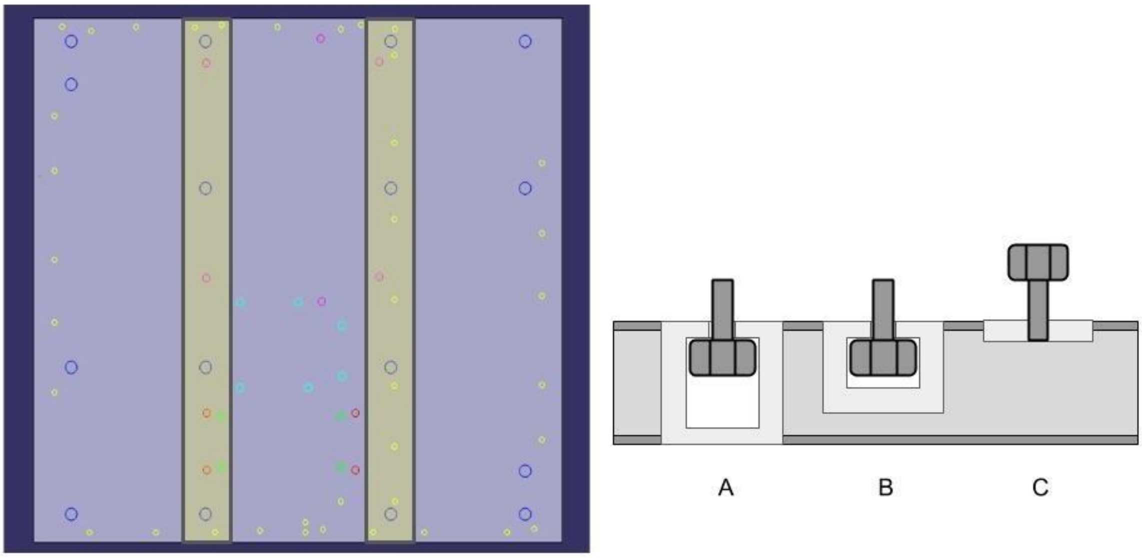

Figure 6.9 - Moulded in profiles in SWP.

In case of heavy loads and several fastening points close to each other a moulded in plate may be necessary. But if possible circular inserts with a single fastening point are more suitable when maximising strength to weight ratio. A real case comparison of a moulded in profile and TTT-inserts can be seen in section. 6.4.4.

6.3.3 On-surface glued inserts

When having small loads, it may be unnecessary to break the sheets and weaken the SWP. In that case on-surface glued inserts can be used, see figure 6.10.

The insert is threaded and glued to the sheets of the SWP. This fastening method is simple and cheap but can only bear small loads compared to the potted inserts who distributes the loads to both sheets and core.

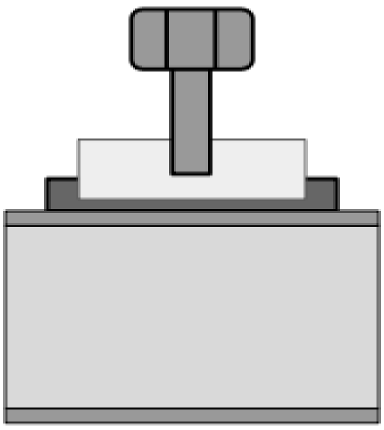

Figure 6.10 - On-surface glued insert

6.4 Fastening method for main components

In this section the process of dimensioning the fastening method for main components are described.

6.4.1 Simplified load case for main components

When loads are applied to the main components on the SWP they cause statically indeterminate load cases. To be able to determine the reaction forces that act on a fastening point a number of simplifications are made. These simplifications intend to form a basis for a rough approximation of the forces acting on each fastening point. With these approximations a first preliminary design of fastening method can be made.

Out of plane load *P*

By considering P evenly distributed on the number of fastening points the vertical load case can be simplified to the load case shown in figure 6.11.

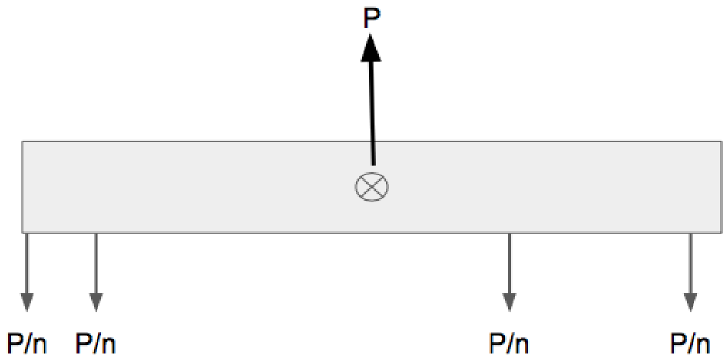

Figure 6.11 - Simplified vertical load case where n is the number of fastening points

In plane load *Q*

By considering Q evenly distributed on the number of fastening points the horizontal load case can be simplified to the load case shown in figure 6.12.

Figure 6.12 - Simplified horizontal load case where n is the number of fastening points

6.4.2 Simplified analysis of insert capacity

When analysing insert capacity, theories and equations from reference [11] are used. In these analyses the SWP is considered to be large, meaning that influence on insert capacity from edges and corners of the SWP can be neglected. Furthermore, by considering the inserts to be far away from each other it can be assumed that the inserts have no influence on one another.

In the analytical analyse it is also assumed that the material of the SWP surrounding the insert and potting will break before the insert itself breaks.

The load that each insert is subjected to, both in-plane and out of plane, are given by the assumptions made in section 6.4.1- simplified load case. Design guidelines in reference [11] recommend that loads are increased by 1.5 times the load to achieve a safety factor. This safety factor will be applied to all loads in the analytical analyse of the insert capacity.

It should be noted that the theories and equations are mainly based on empirical studies of inserts in a SWP. These theories and equations are presented in appendix A. The calculations are intended to result in a first rough approximation of an insert design that is to be analysed more thoroughly.

It should also be noted that the inserts should be dimensioned not to break lose when batteries are exposed to the shock loads described in section 5.2. This model can only handle yield strength and not the tensile strength. Thus, this model calculates inserts that would endure a shock load without exceeding the yield strength, i.e. conservative.

6.4.3 Results of simplified calculations

In this section results of the analytical calculations on the main components are presented.

Results of simplified calculations for the battery

When using the theories from appendix A for the battery with the loads from section 5.2 and the properties for the SWP found in section 6.2 the following result was obtained:

The red line in the figure 6.13 is the shock load from the battery acting on a TTT-insert. The red dotted line is the load given by the battery including the safety factor 1.5. The green and the blue line is the critical load from antiplane theory and extended antiplane theory. To achieve a sufficient strength a potting radius of 24 mm is needed.

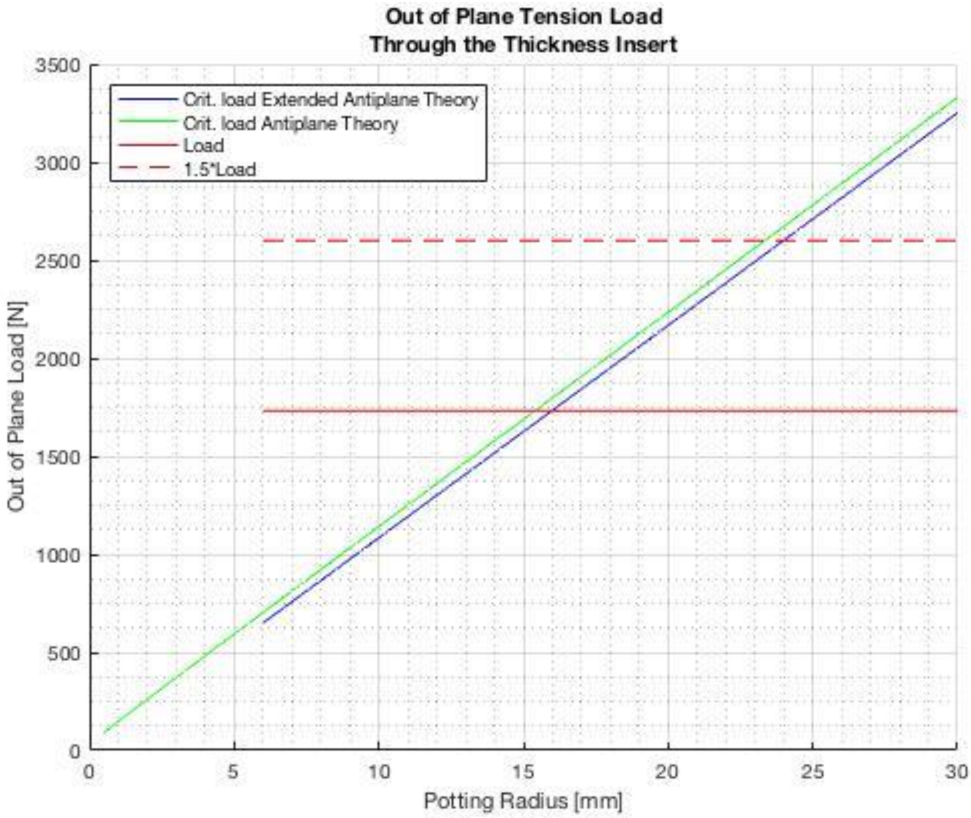

Figure 6.13 Out of plane tension loaded TTT insert versus potting radius r_p.

In figure 6.14 the out of plane compression load is compared to the sufficient potting radius. To achieve a sufficient strength r_p = 24 mm is needed.

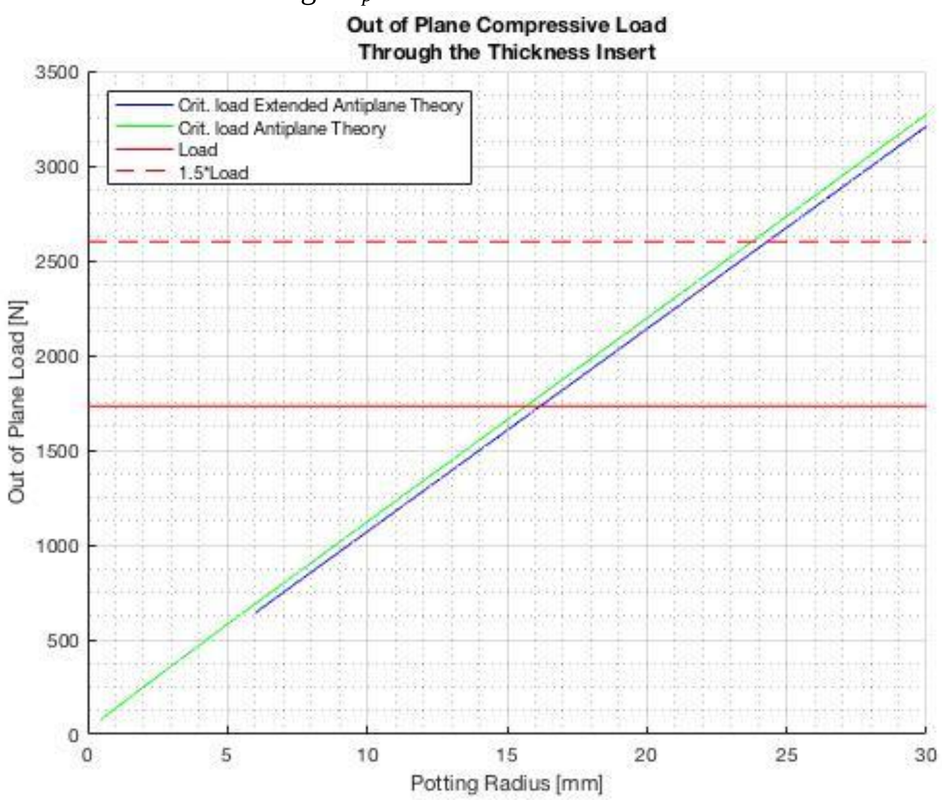

Figure 6.14- Out of plane compressive loaded TTT insert versus potting radius r_p

In figure 6.15 in-plane load is compared to the sufficient potting radius. To achieve a sufficient strength r_p = 6 mm is needed.

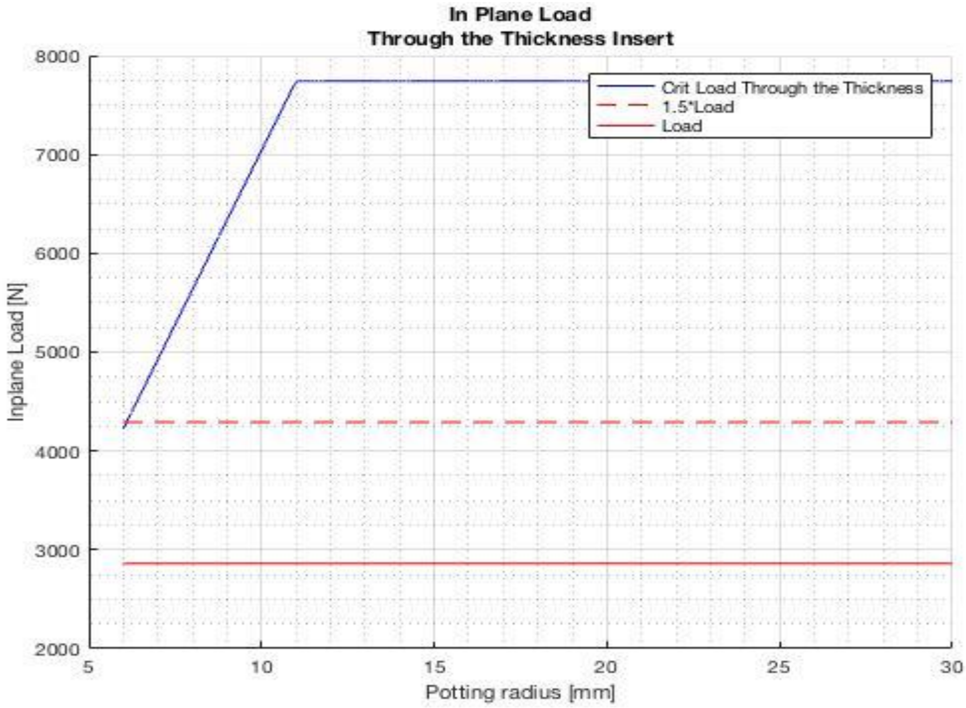

Figure 6.15 - In plane loaded TTT insert versus potting radius r_p.

Results of simplified calculations of all main components

When the same calculations as made before where done for all the main components the following result was obtained in figure 6.16.

Component	Required potting radius [mm]
Battery	24
Cooler	4
Pump sub rack	2
HJB sub rack	2
CSU sub rack	2

Figure 6.16 - Table of required potting radius for TTT-inserts for main components

Summary:

To achieve sufficient strength, the potting radius of the battery inserts needs to be 24 mm. Since the cooler and the pump sub-rack are mounted with M8 bolts it is required to choose an insert of M8 size and the minimum potting radius for a M8 insert is 17.4 mm. HJB and CSU are mounted with M10 bolts which requires M10 inserts for which the minimum potting radius equals 21.4 mm. Therefore, the potting radius for the cooler, pump, HJB and CSU will be much greater than the required potting radius with respect to strength. Suitable inserts were chosen from the Shur-Lok product catalogue. Below the final potting radiuses and chosen insert are presented in figure 6.17.

Component	Chosen potting radius r_p [mm]	Chosen Insert
Battery	24	Shur-Lok SL5169 S M12 20
Cooler	17.4	Shur-Lok SL6277 – M8 – 20 M
Pump sub rack	17.4	Shur-Lok SL6277 – M8 – 20 M
HJB sub rack	21.4	Shur-Lok SL6277 – M10 – 20 M
CSU sub rack	21.4	Shur-Lok SL6277 – M10 – 20 M

Figure 6.17 – Table of chosen potting radius and chosen inserts.

6.4.4 TTT-inserts vs. moulded in profile

To compare TTT-inserts vs. moulded in profile a simple comparison was made.
Consider replacing the 4 TTT-inserts highlighted in figure 6.18 for a moulded in profile. The profile is estimated dimensioned to give the same strength as the 4 inserts. The 4 TTT insert weights 0.216 kg and the moulded in profile weights 1.683 kg, 8 times the weight of the 4 TTT inserts.

In this case, the advantage with the ability of variation that the moulded in profile gives is small compared to the extra weight. In general, TTT-inserts is the preferred choice over moulded in profiles when using a lightweight SWP.

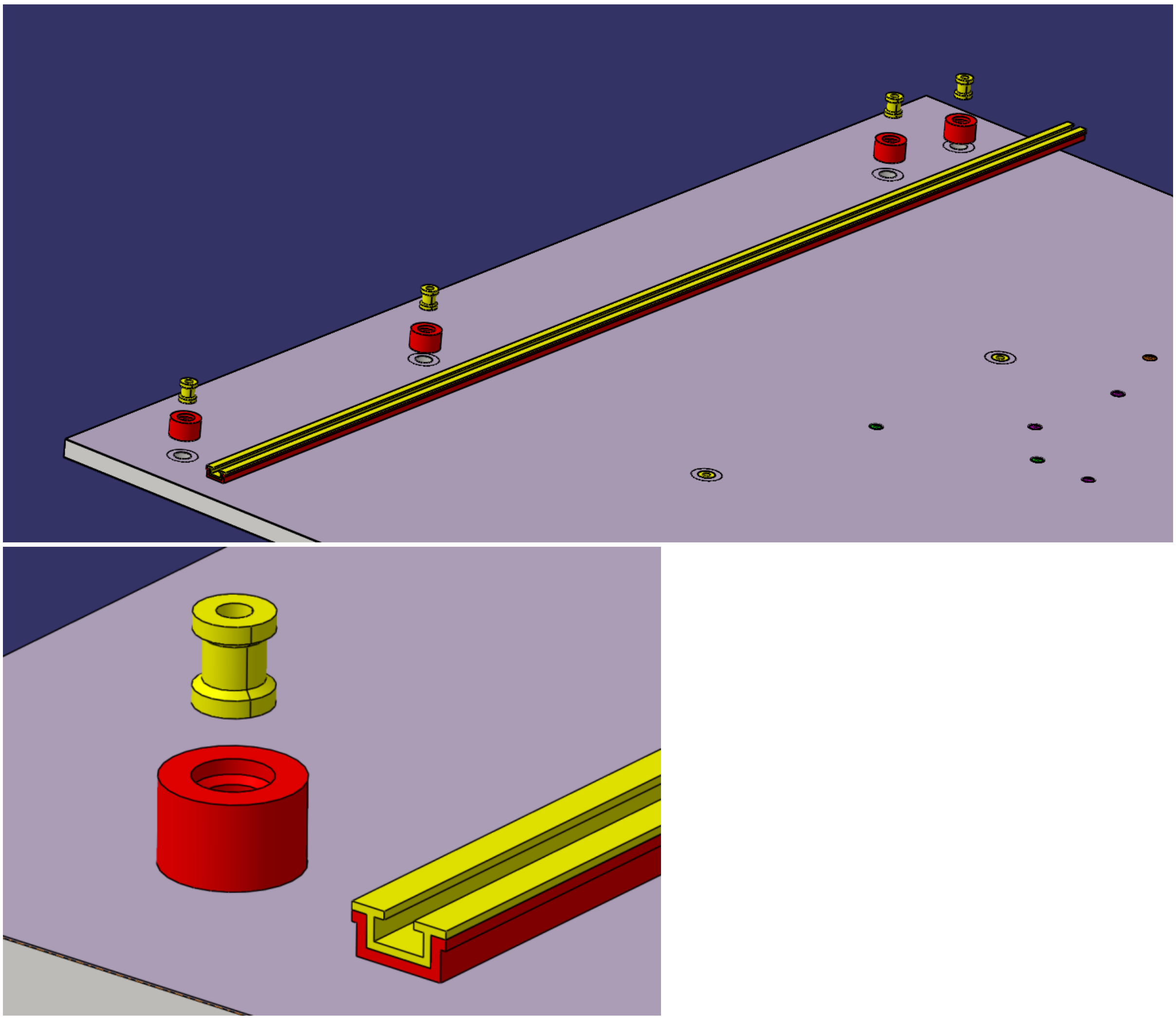

Figure 6.19 - Potted insert vs moulded-in profile

6.4.5 Validation of simplified calculations

Since there are no resources in this project to be able to validate results from the analytical analyse with a physical test of the insert capability the validation will depend on the results from two articles found in reference [7] and reference [15]. In these articles physical pull out and shear out tests were compared to the analytical results from equations found in reference [8], that is the same equations used in this project. The results from these comparisons showed that the analytical results where conservative compared to results from the physical tests. In reference [7], when performing the pull out test, the critical force was found to be approximately 23% higher than the force obtained with equations from reference [8]. The critical force in the shear out test was found to be approximately 10% higher than the calculated value. In reference [15], it was found that there is a "*very good correlation*" between the experimental and analytical results.

To further validate the results of the analytical analysis in this project a FE-analysis is made.

6.4.6 FE-analysis of insert capacity

To further analyse the new design a FE-analysis was made and the results can be found in its entirety in appendix C. A strength analysis engineer at Volvo Buses performed the FE-analysis. The model was modelled in such a way that few anomalies in stresses occurred. The few anomalies that occurred due to concentration of stress and boundary conditions could be ignored. The conclusions are described below.

In general stress levels are below the permissible limit in all load cases. In figure 6.20 the most critical stress is displayed and it appears in the core around one of the battery TTT-inserts and amounts to 0.26 MPa where the yield strength is 0.5 MPa. In a future design loop a smaller potting radius could be evaluated.

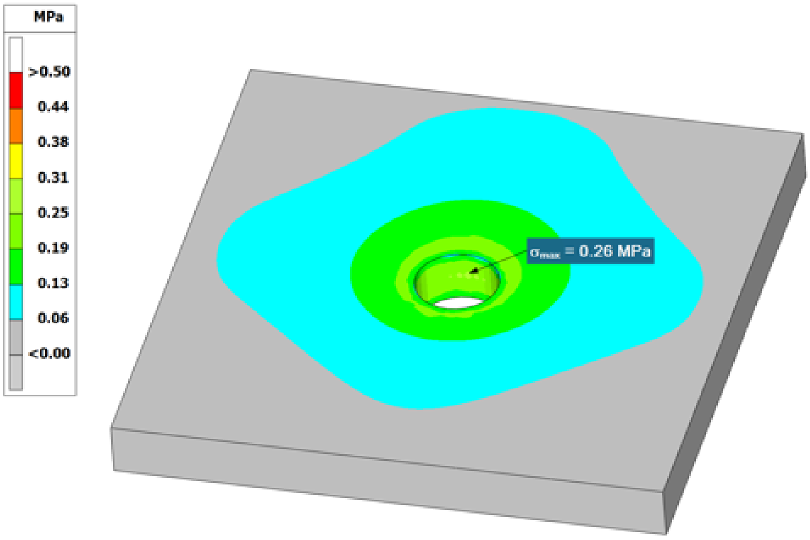

Figure 6.20 - Stress levels in core where the most critical stress is found

In the first simplified calculations of potting radius a simplified load case was made to approximate the in plane and out of plane loads. As a result of this FE-analysis a complete set of loads was calculated and can be seen in appendix C, page C12. When redoing the simplified calculations with the complete set of loads a better approximation of potting radius was achieved and amounted to 20 instead of 24 mm. The weight reduction gained would then be only 160 g for all 16 inserts. That is, very little is gained when furthermore optimising the potting radius.

6.4.7 Validation of FE-analysis

The FE-analysis has not been validated through physical testing since there are no resources in this project to perform a physical test. It has been assumed that this FE-analysis has resulted in stress levels that are accurate enough to confirm that the SWP and inserts will not fail under loading.

Nonetheless, to validate the FE-analysis stress levels in the FE-model a comparison with the corresponding values of the simplified model was done. However, when making this comparison, stress levels are found to vary greatly between the two models. The cause of these variations could be explained by the fact that when stress levels are computed in the simplified model, the component of stress is dependent only on the force P1 in figure 6.21 acting in the same direction as the component of stress. While in the FE-analysis, the component of stress is dependent on multiple forces, P1, P2 and P3 in figure 6.21 and moments M1, M2 and M3 also in figure 6.21, acting in different directions. To compare the two analyses a new FE-model where the insert is subjected to a single force in only one direction, as shown in figure 6.22, has to be made and thereby a component of stress would be dependent on this force only. Due to limited resources, such a FE-model could not be made in this project.

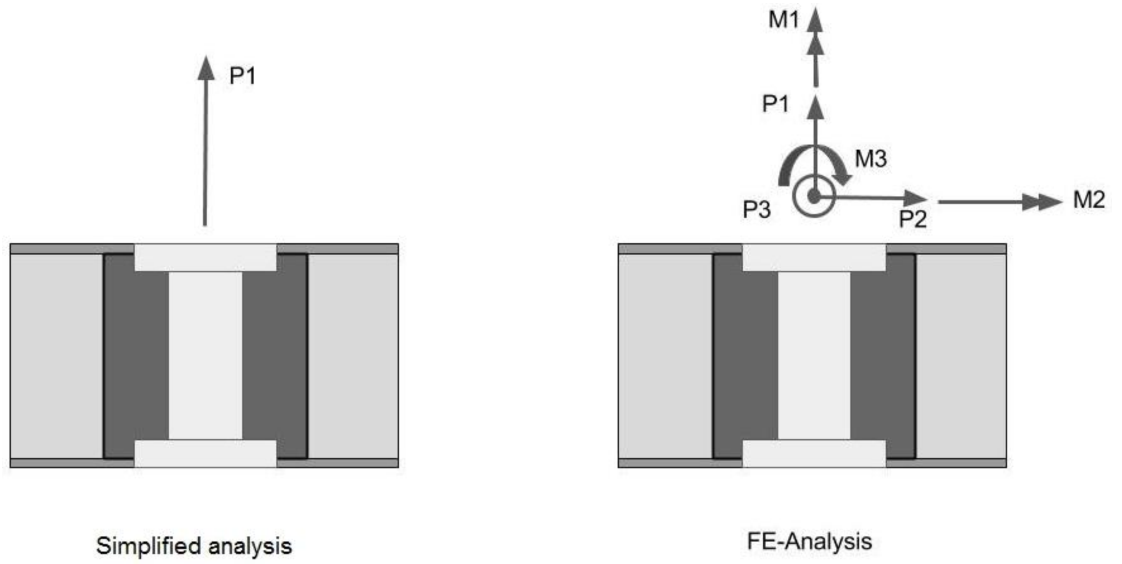

Figure 6.21 Comparison between forces and moments in simplified analysis and FE-analysis.

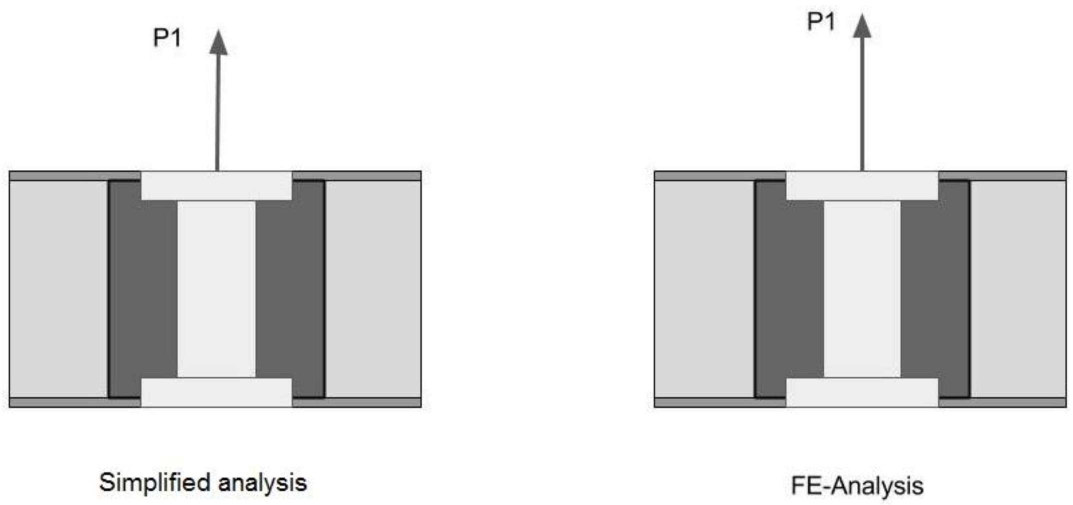

Figure 6.22- Desired relation between simplified analysis and FE-analysis.

6.5 Fastening method for media holders

In general, the fastening points for media holders are many in numbers and subjected to small loads compared to the main components. The space reserved for media holders on the ESS is limited. All of these above mentioned aspects has to be taken in to account when designing a new fastening method for media holders.

The media holders are divided into three groups. Each group of media holders will be analysed separately when the fastening methods for the media holders are designed. Below the groups of media holders are defined and displayed by different colours in figure 6.23.

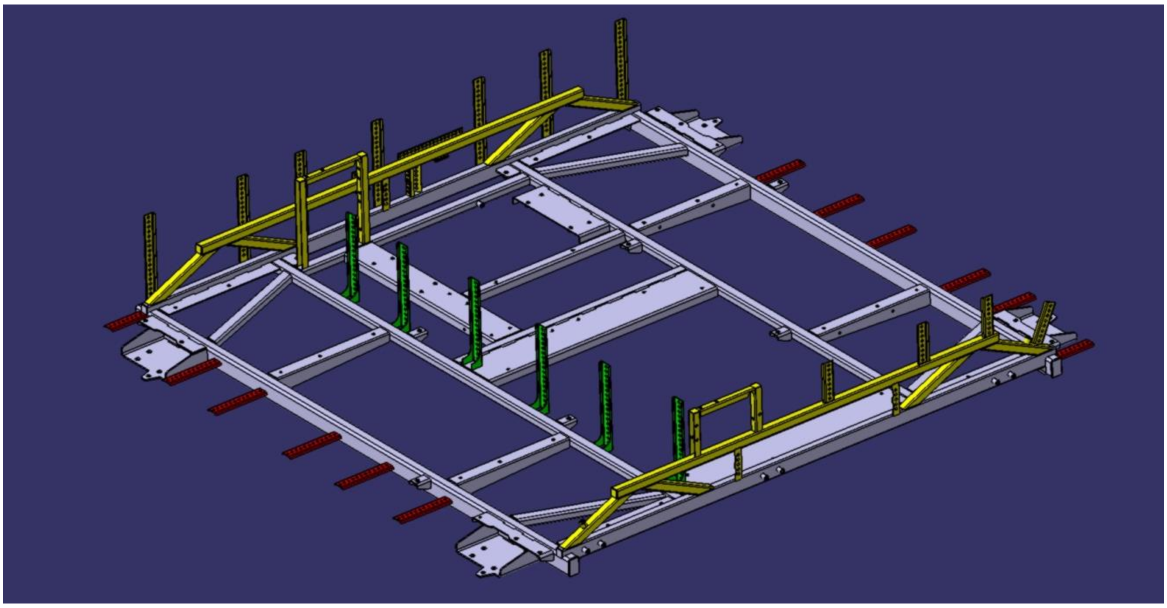

Figure 6.23 - Media holders on the current steel rack

Horizontal media holders
Horizontal media holders are displayed in red in figure 6.23. Horizontal media holders are placed on a single row on both sides of the ESS. When the media holders are loaded, the associated fastening points will be exposed to shear and out of plane loads.

Vertical media holders
Vertical media holders are displayed in green in figure 6.23. There are six vertical media holders in the ESS and they are placed on a single row on the steel rack. When a media holder is loaded it causes a bending moment about the fastening point.

Combined media holders
The combined media holders are displayed in yellow in figure 6.23. When the steel rack was designed, a framework was added to achieve sufficient stiffness to the steel rack. When designing the new media holders the need of extra stiffness is not necessary and the combined media holders therefore can be designed just like the vertical media holders.

When designing fastening methods for the media holders four concepts was made and are shown in figure 6.24.

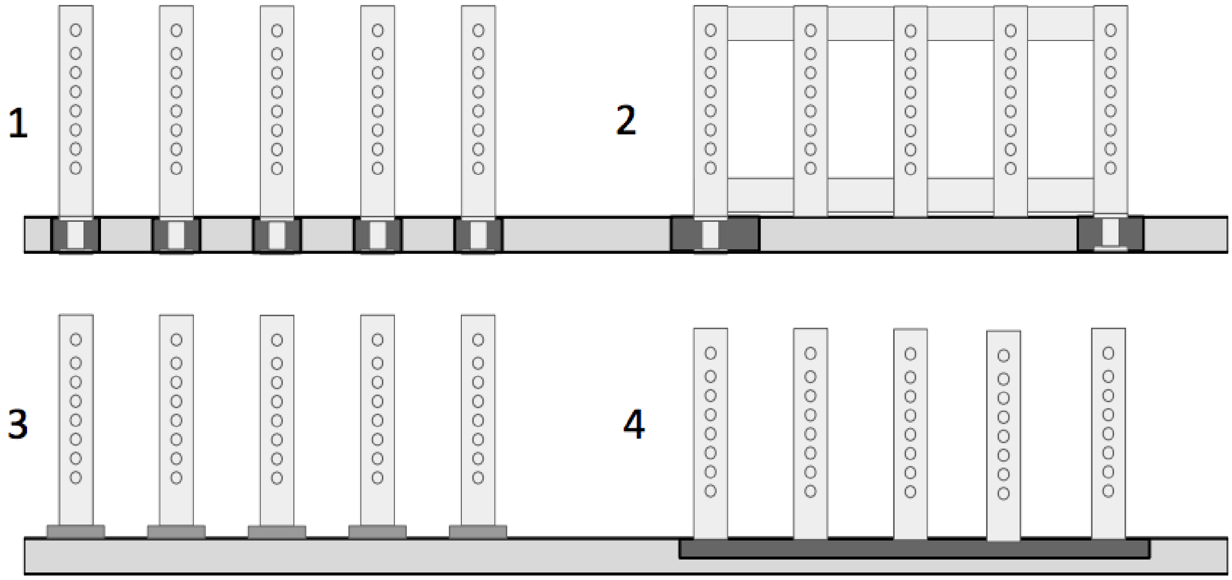

Figure 6.24 - Fastening methods for media holders

Below the concepts with its advantages and disadvantages are listed.

1. **Single media holder has a potted insert**

This concept is not complicated but results in numerous potting. Numerous potting with equal numbers of interventions of the SWP leads to higher production cost and higher total mass of the potting.

2. **Connected media holders has two potted inserts**

This concept leads to fewer but bigger potting's. The total mass of the potting will decrease and the connected media holders will be heavier compared to the media holders in concept 1. Less potting's will decrease the cost of production.

3. **Single media holders on-surface-glued insert**

This concept is lightweight, requires fewer interventions of the SWP but is not able to withstand heavy loads as concept 1 and 2. This concept needs a sufficient area under the media holder to distribute the loads. The on-surface-glued insert may be mounted in the Volvo bus production as it does not involve cutting processing. this leads to lower production cost and ability to make variations of SWP's.

4. **Multiple media holders are merged with a moulded-in profile**

This concept is robust but heavy. The moulded in profile is suitable when having heavy loads but is not be suitable in this case.

6.5.2 Concepts for media holders

To make concepts for new designed media holders the old steel rack was analysed. The parts that just exist for mounting media on, and not to add stiffness to the rack are highlighted in blue in figure 6.25.

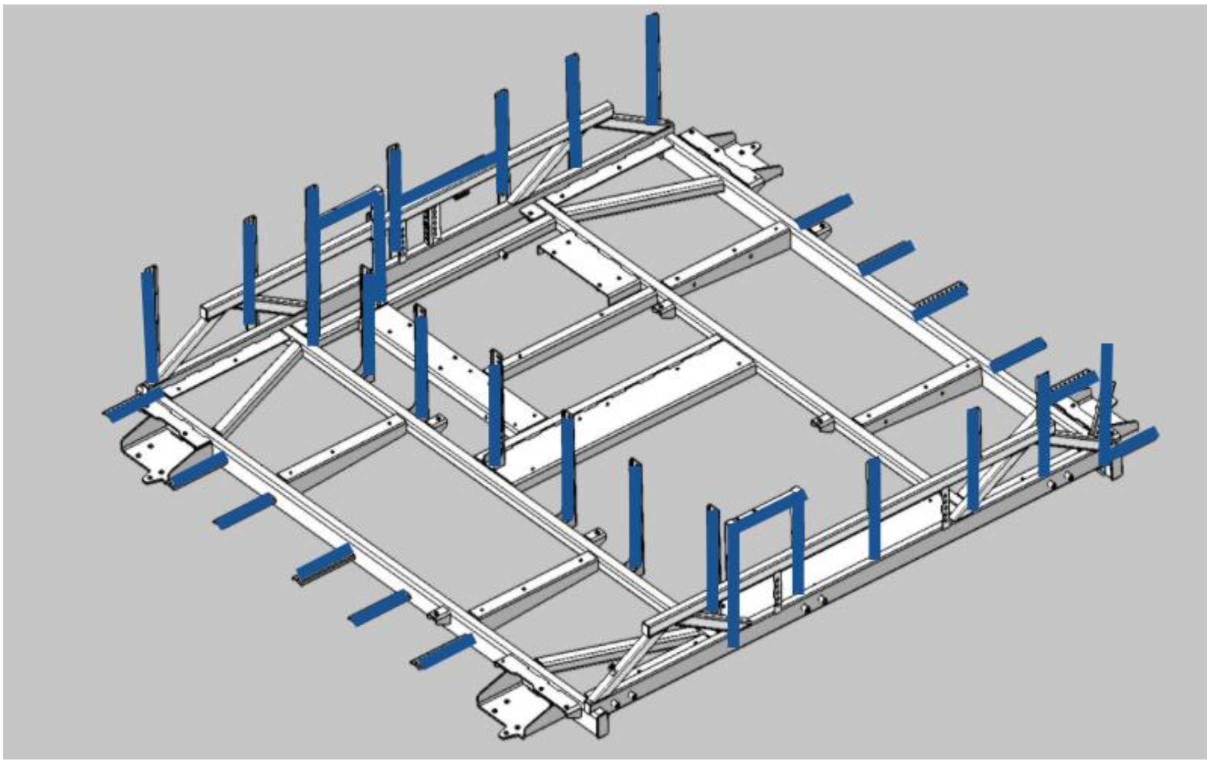

Figure 6.25 – Current steel rack with media holders highlighted

Two concepts were designed to manage the fastening of media to the SWP. In common for the two concepts is the horizontal media holders that advantageously is glued to the surface of the SWP.

Concept 1: Connected media holders
This concept, shown in figure 6.26 utilises a framework to support the vertical and combined media holders. The framework is fastened to the SWP with seven TTT-inserts. Horizontal media holders have been glued on to the SWP.

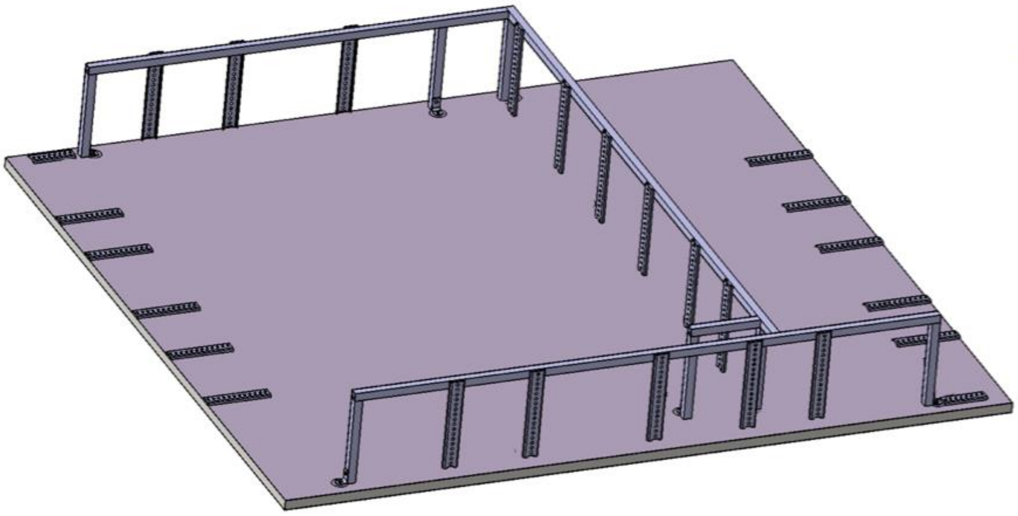

Figure – 6.26 Concept 1: Connected media holders on the SWP

During the development of this concept, the current design was analysed. In the current design vertical and combined media holders were marked in red in figure 6.27 to form a framework. This framework is connected to the SWP with seven TTT- inserts. The framework has media holders, marked with blue which is carried by the framework. The media holders marked in green is glued to the surface of the SWP.

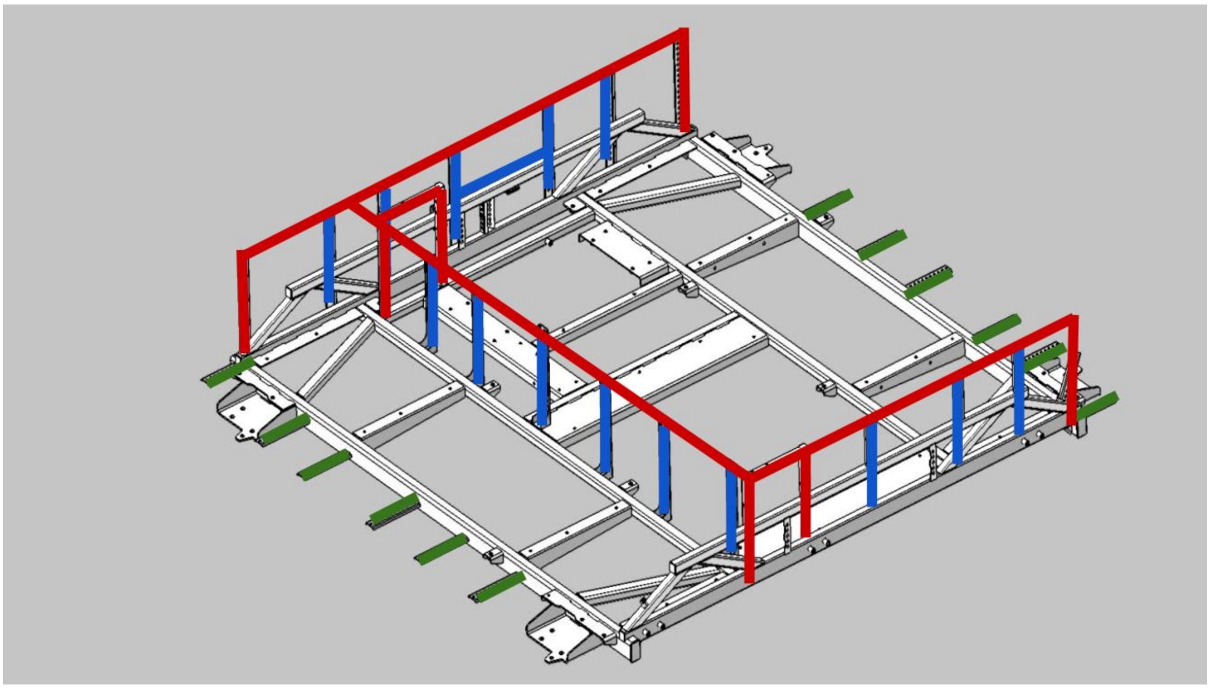

Figure 6.27 - Connected media holders placed on top of the current design

To dimension the 6 TTT-inserts the result for the battery inserts can be used.
The loads on the media holder will be small compared to the 1.7X g applied on the battery. Therefore, a potting radius as for the battery inserts, 24 mm is undoubtedly sufficient without adding considerable weight or cost. To achieve sufficient strength in the framework a 25x25

mm aluminium profile with a wall thickness of 2 mm was chosen. The media holders from the current design were re-used with the exception that they are now made of aluminium.

This concept was modelled in Catia V5 and the complete ESS can be seen in figure 6.28 and in figure 6.26 the SWP with the framework.

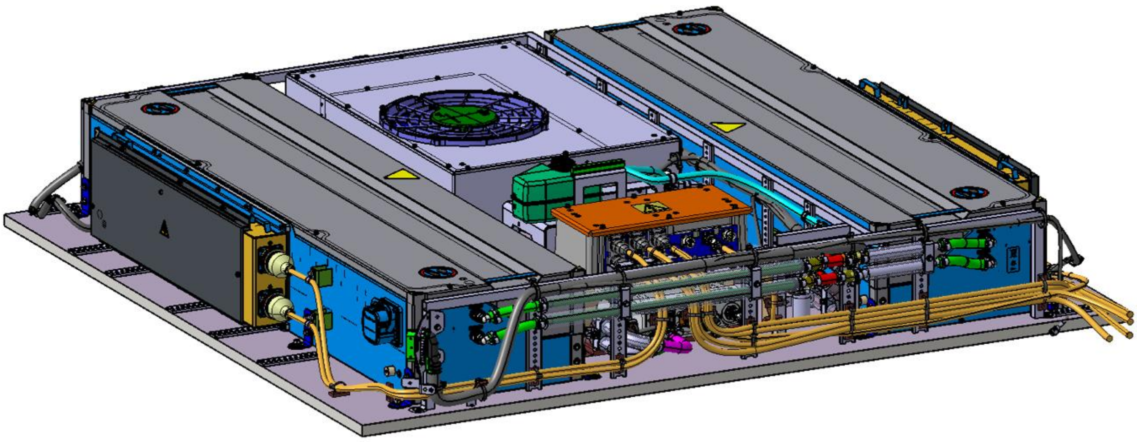

Figure 6.28 - Complete ESS with connected media holders

The weight of this concept is summarised in figure 6.30 and the total weight is 6.2 kg.

Components	**Weight [kg]**
Inserts + potting's	0.8
Framework + media holders	5.4
Total	**6.2**

Figure 6.30 – Weight for the concept: Connected media holders

The concept is working well apart from a few minor clashes, one shown in figure 6.31. The first type of clash is cable clashes. The solution for the clash shown in figure 6.31 is to place the cable 20 mm higher and that will not be a problem. The other clash is a potential clash between the upper surface of the SWP and the electric box hanging on the wall of the battery (the black surface in the upper right in figure 6.31). There's only 3 mm between them and there may be a problem if the construction deforms more than 3 mm. This potential clash is the result of placing the batteries on a flat surface instead of a framework. If using a SWP with batteries standing on the upper face sheets the potential problem has to be solved by a new design of batteries.

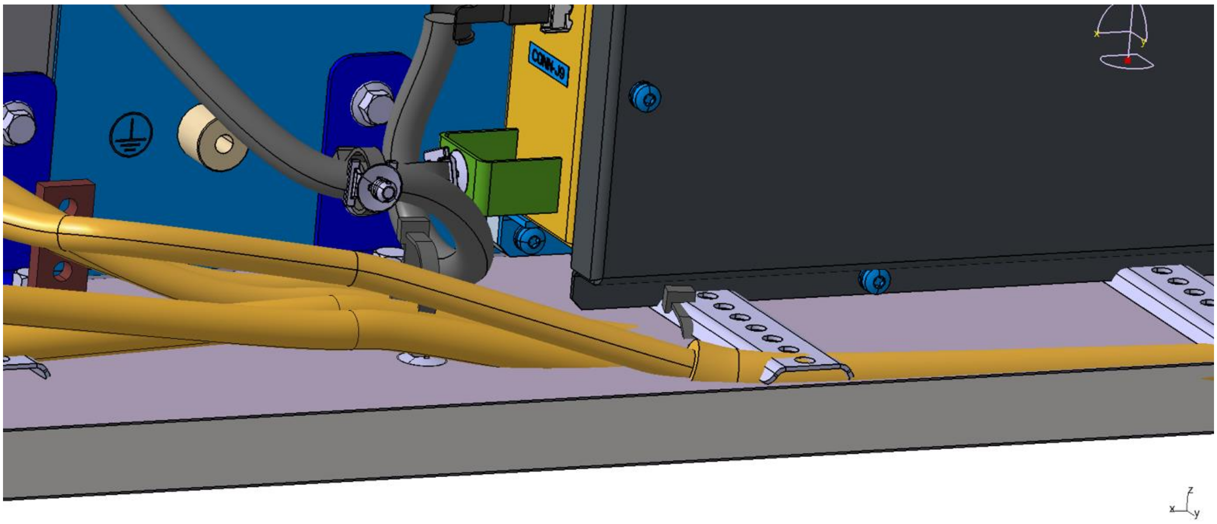

Figure 6.31 – Clashes between cables and SWP and potential clash between battery and SWP

When this concept already was designed some ideas of improvement was found. To make more room for mounting from above the combined media holder could be redesigned. The idea is to leave the media holders marked with (1) in figure 6.32 in the same position but move the profile (2) to the red mark (3) and by that make more room for mounting from above.

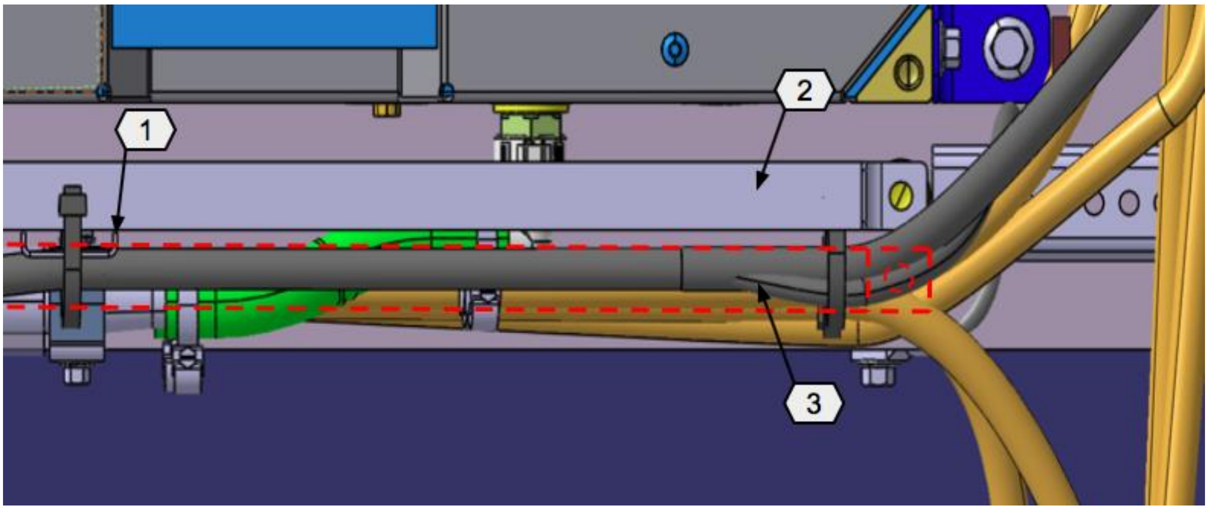

Figure 6.32 – View from above which shows a possibility to improvement on media holders

But his late in the design progress, this improvement was not possible to apply to the whole concept. As an example, a problem could occur if the insert and potting belonging to the profile marked with (2) in figure 6.32 would be placed too near the edge of the SWP.

Concept 2: Single on-surface glued media holders

In this concept shown in fig. 6.33 vertical, combined and horizontal media holders have all been glued to the surface of the SWP. Supports for the covering plate are fastened with two TTT-inserts each. The covering plate protects the ESS from environmental impact.

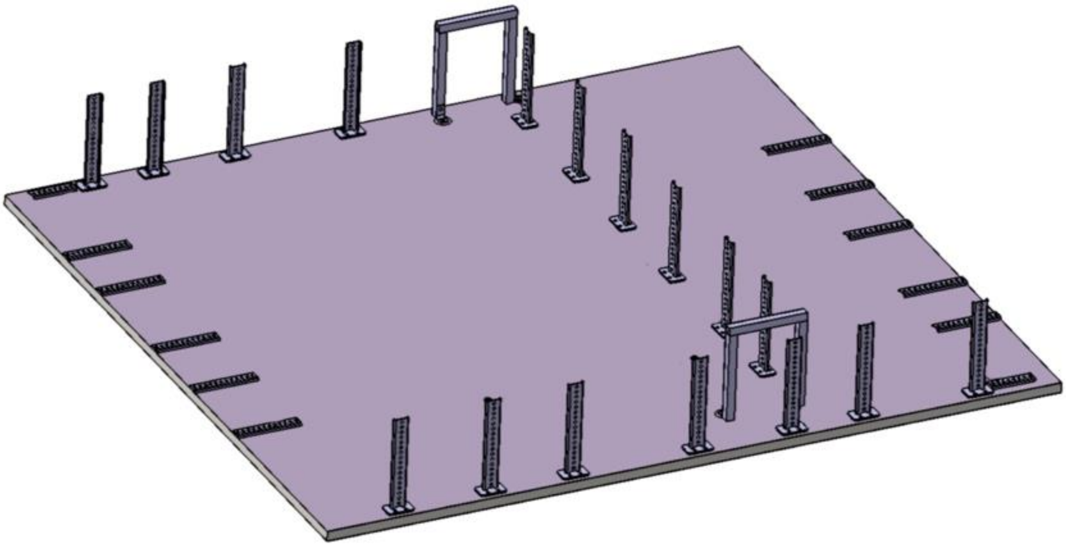

Figure – 6.33 Concept 2: Single on-surface glued media holders on the SWP

During the development of this concept, vertical, combined and horizontal media holders were identified in the current design and marked in green, see figure 6.34. Supports for the covering plate was also identified and marked with red in figure 6.34. The four TTT-inserts for the covering plate supports was approximately dimensioned as the inserts for the cooler, i.e. potting radius 8.7 mm.

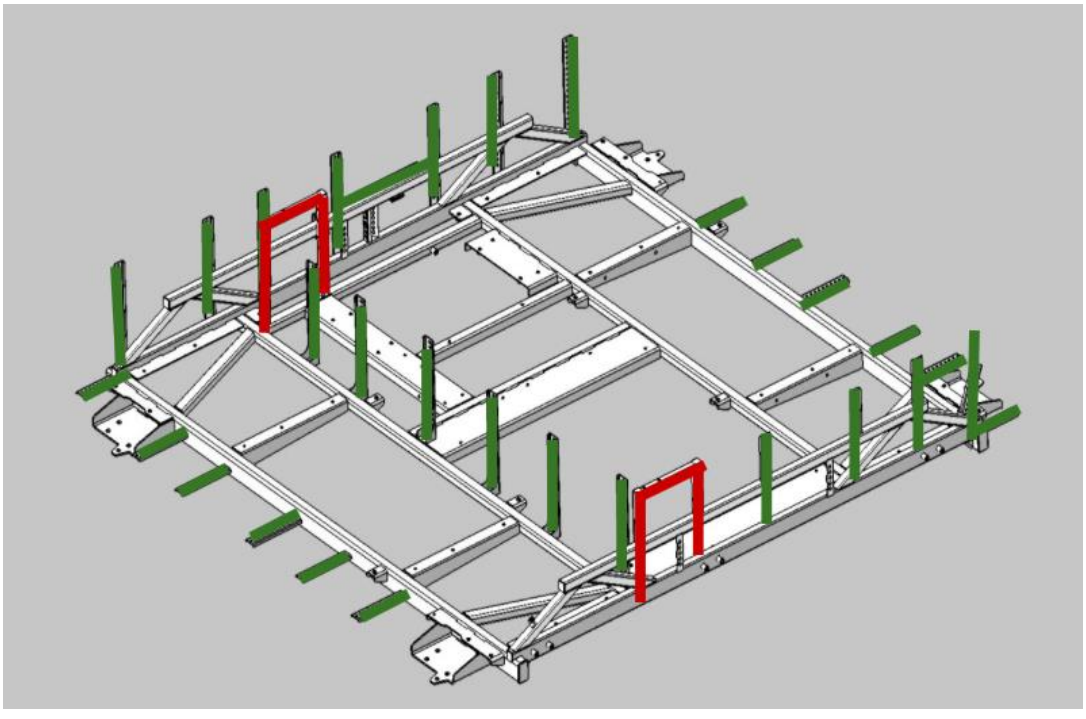

Figure 6.34 - Single on-surface glued media holders placed on top of the current design

To dimension the on-surface-glued media holders a simplified load case was adopted. Though there is a media holder every 300 mm, an approximation gives that one media holder carries 300 mm of cable. That amount of cable corresponds to a weight of 5 kg, which is a conservative approximation, causing a force of 150 N that attacks horizontally at the centre of gravity, that is 150 mm above the surface illustrated in figure 6.35.

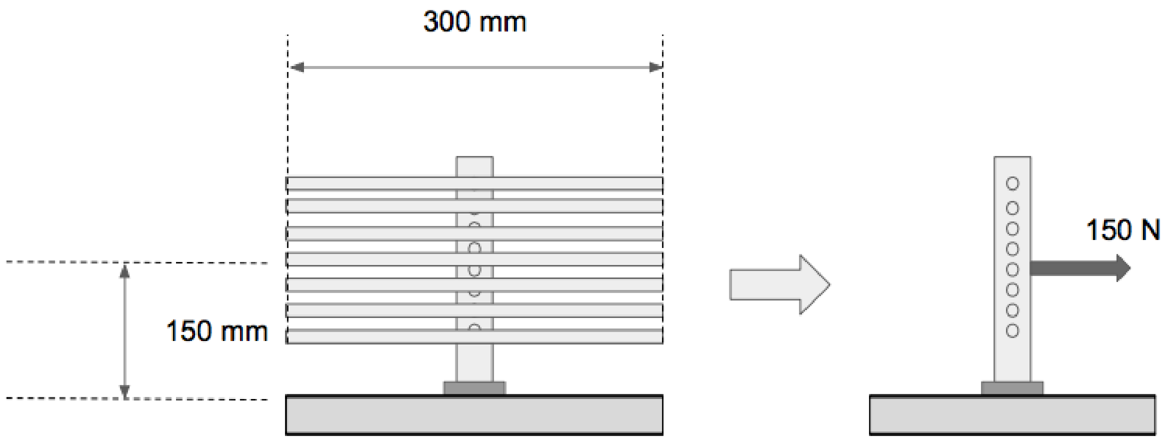

Figure 6.35 - Simplified load case at a single on-surface glued media holder

An on-surface-glued media holder distributes the load only to upper sheet.
Considering a load as small as 150 N it won't be a problem to transfer the load only to the upper face sheet. The required area of the foot glued to the SWP is unknown but a hypothetical sufficient area will fit in between other components in this concept without adding considerable weight.

This concept was modelled in Catia V5 and the complete ESS can be seen in figure 6.36 and the SWP with the on surface glued media holders in figure 6.33.

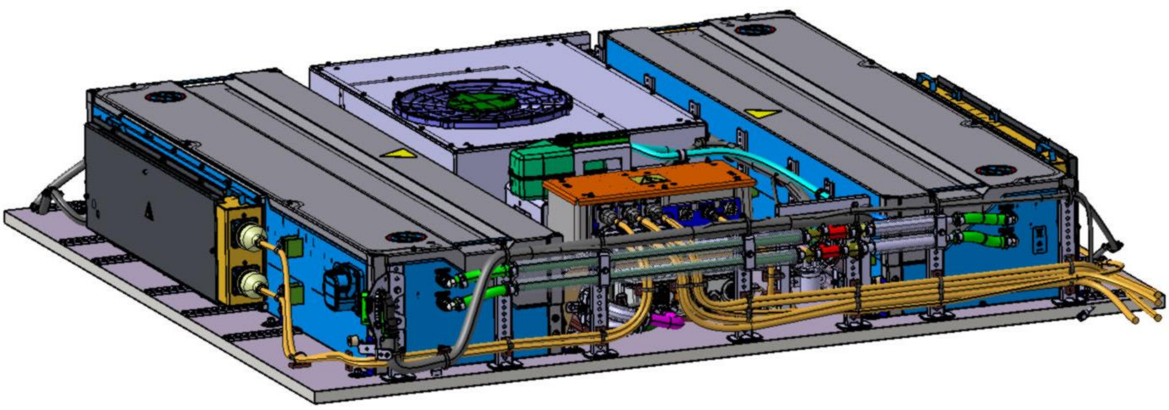

Figure 6.36 - Complete ESS with single on surface glued media holders

The media holder from the current design was re-used and a foot was added and can be seen in figure 6.38. The foot has 4 holes to enable better spreading of the adhesive.

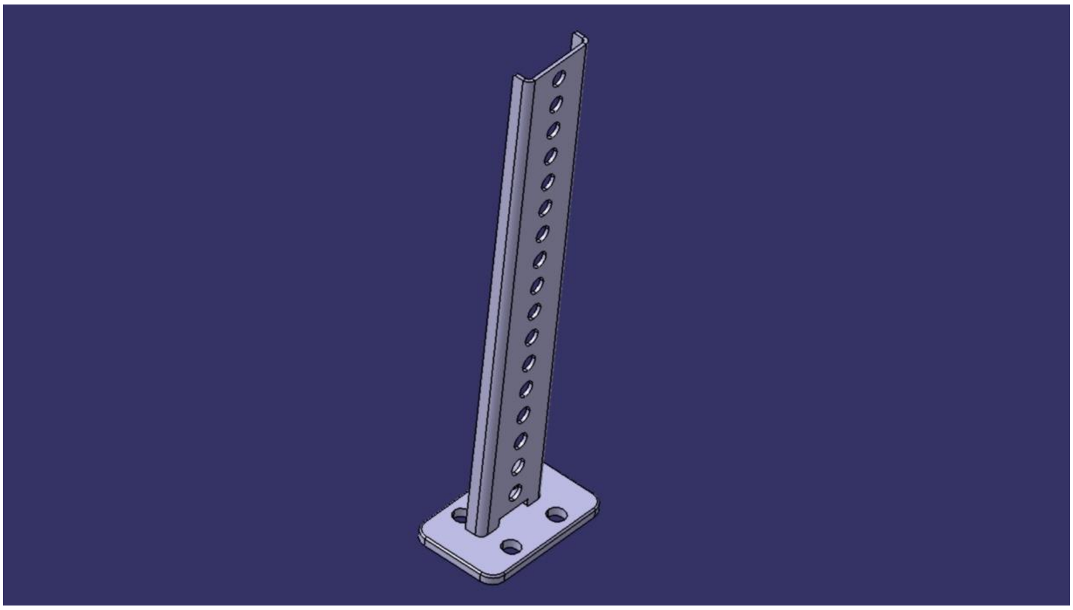

Figure 6.38 - Glued on media holder

The weight of the components in this concept is summarized in figure. 6.39. The total weight of the concept is 4.0 kg.

Components	**Weight [kg]**
Inserts + potting's	0.41
media holders	3.59
Total	**4.0**

Figure 6.39 – Weight for the concept: Single on-surface glued media holders

Even this concept is working well apart from a few minor clashes. This is the same clashes as in the first concept. For details, see section 6.5.2

6.5.3 Evaluation of the two concepts

To compare and evaluate the two concepts a decision-matrix was used. The result is summed up in figure 6.40.

	Connected media holders	On-surface glued media holders
Weight	**Sum = 3**	**Sum = 4**
Risks	+ More robust construction – Risk to break inserts and damage SWP **Sum = 4**	+ If damage on individual media holders would occur, media holder + insert can be replaced. – More sensible for bending moment **Sum = 3**
Complexity	+ Simple mounting **Sum = 4**	– More articles **Sum = 2**
	Total = 11	**Total = 9**

Figure 6.40 – Decision matrix

With its robust construction, fewer articles, its simple mounting which together leads to the best and most cost effective concept connected media holder was chosen.

6.6 Final concept

The final concept consists of, beside the SWP, of the potting’s for the main components calculated in section 6.4 and the fastening methods designed in section 6.5. The result can be seen in figure 6.41 and 6.42. The total weight of the concept is 35 kg corresponding to a weight loss of 62%.

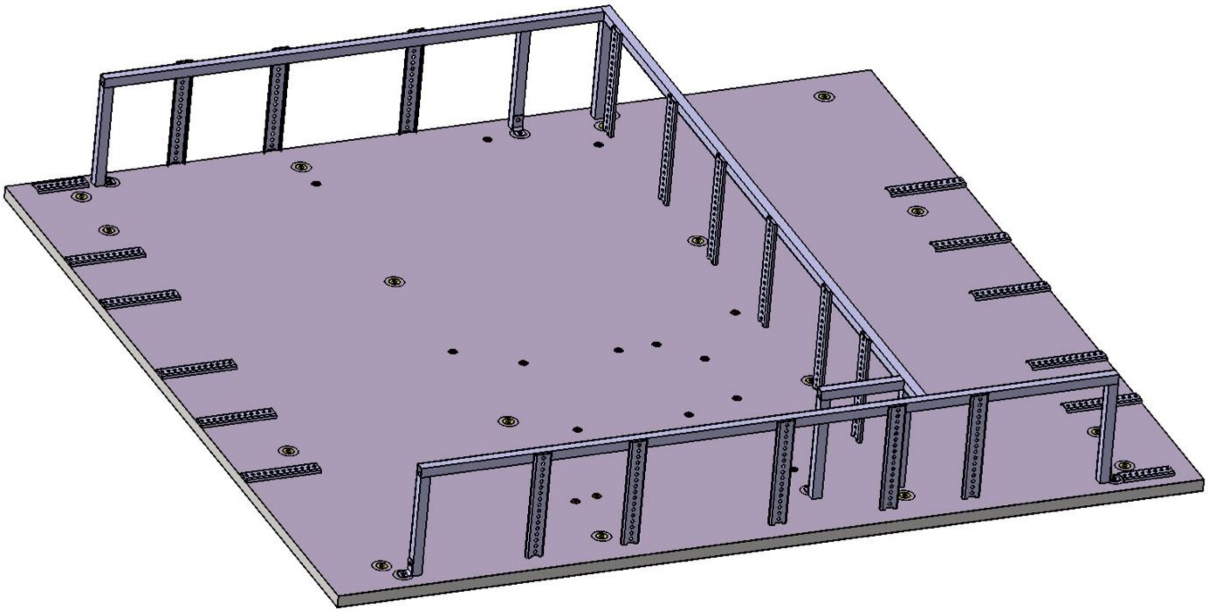

Figure 6.41 - Final concept for SWP and media holders

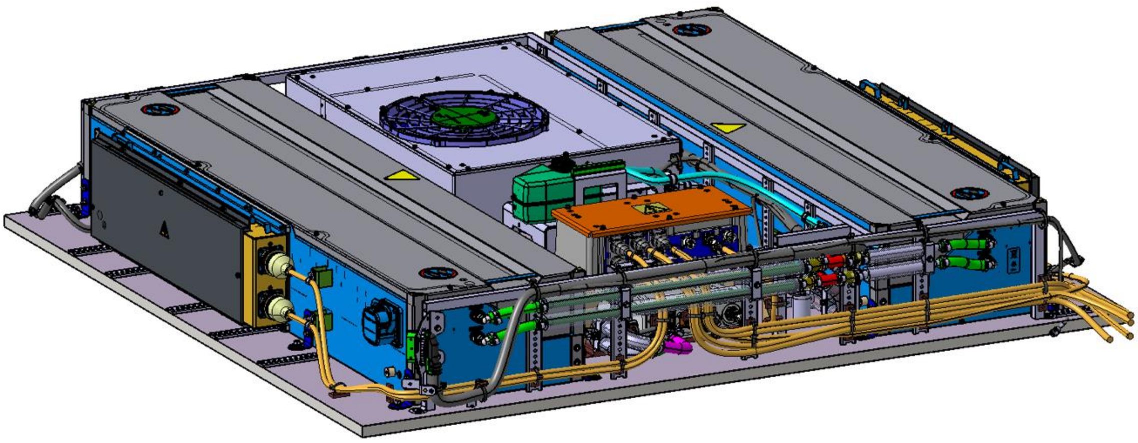

Figure 6.42 – Final concept for SWP and media holders with complete ESS

7. Conclusions

In this chapter conclusions from previous chapters are made.

By its nature sandwich panels has low capacity of carrying concentrated loads. The best way to distribute great loads to sandwich panels without inhibiting the sandwich panels lightweight nature is by using a potted trough-the-thickness (TTT) insert which distributes the loads to both core and the two face sheets

It is possible to analyse the static strength of inserts, both analytically on simplified models and in FE-analysis. The fatigue life of the new design has not been analysed mainly due to insufficient material data. Furthermore, to perform a complete fatigue analysis, the method of fastening the ESS to the bus has to be known.

The demands on backwards compatibility have been met and the functions of the steel rack have been transferred to the SWP, through the use of TTT-inserts and redesign of media holders. The new design of media holders features media holders connected through a framework that is fastened to the SWP with seven TTT-inserts. The redesign of media holders resulted in slight modifications of the original arrangement of media holders. Clashes of minor significance occur in the new design, mainly between media and the SWP and eventually between media holders and the battery. With the new design, a weight reduction of 62% has been achieved. The potting radius given by the simplified calculations resulted in an oversized potting. However, to further optimize the potting radius would result in a very small weight reduction.

8. Reliability analysis

For increased reliability in the results the following improvements could have been done.

A validation of the simplified and FE-analysis could have been made by physical testing of insert in a SWP. It has not been possible to perform such a test due to insufficient resources. A FE-model that could be compared to the simplified model (section 6.4.8) should have been made to confirm that stress levels produced by the simplified analysis and FE-analysis in the SWP are reliable.

A more thorough analysis of the load case in section 6.4.1 could have been made to give a better approximation of forces and possibly moments that inserts are subjected to and thereby a better approximation of the potting radius.

Rough approximation in the design of media holders has affected its weight. The total weight reduction of 62% could possibly be slightly higher or lower.

9. Discussion and suggestions for further work

For continued work there is a need to evaluate, analyse and design things that were outside the perimeter of this project.

To further optimize the potting radius would result in a very small weight reduction. Optimise the thickness of the face sheets could save a lot of weight. That requires an analysis of the detail constructed SWP with its fastening method to the bus. If the required thickness of the face sheets is 0.7 mm instead of the 0.8 mm used in the calculations the weight reduction would be 2 500 g compared to the weight reduction of 160 g due to the possible reduction of potting radius of the 16 potting's of the battery mentioned in section 6.4.6.

It has been concluded that on-surface-glued inserts are suitable when having small loads. To further investigate the possibility to use this lightweight fastening method for upcoming projects would be highly beneficial.

To reduce weight, larger and fewer potted inserts is desirable. For the potting used for the battery, the steel insert weights 3 times the weight of the potting. To reduce the number of inserts and increase the potting radius could reduce the total weight. How this affect the possibility to bear load is described by a linear relationship (see section 6.4). To perform a FE-analysis using a larger potting radius would help determine the accuracy of the linear relationship.

To further analyse potted inserts, the aspects of fatigue needs to be analysed.

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Appendix A – Equations for insert theory

In this appendix theories and equations used to approximate the design of the inserts are presented.

A.1 Out of plane static load capacity

Out of plane capacity of the insert is defined as the static capability of an insert with the load normal to the SWP. Out of plane capacity was analysed with two theories presented in reference [8]. These theories are:

- Antiplane theory
- Extended antiplane theory

In both theories stress acting normal to the plane are taken into account, the plane in this case is the SWP. The stress acting in the direction of the plane are set to nil. In both theories the critical failure mode is shear rupture of the core.

These theories are thereby very similar to the real case when an insert is loaded by a normal load where, also here, the critical failure mode is shear rupture of the core.

The theories are valid for fully potted (FP), partially potted (PP) and through the thickness (TTT) inserts, see figure A1. To find the critical out of plane load for a TTT-insert the same equations used to find the load for FP-insert are applied. The geometry of a general insert and SWP is shown in figure A2.

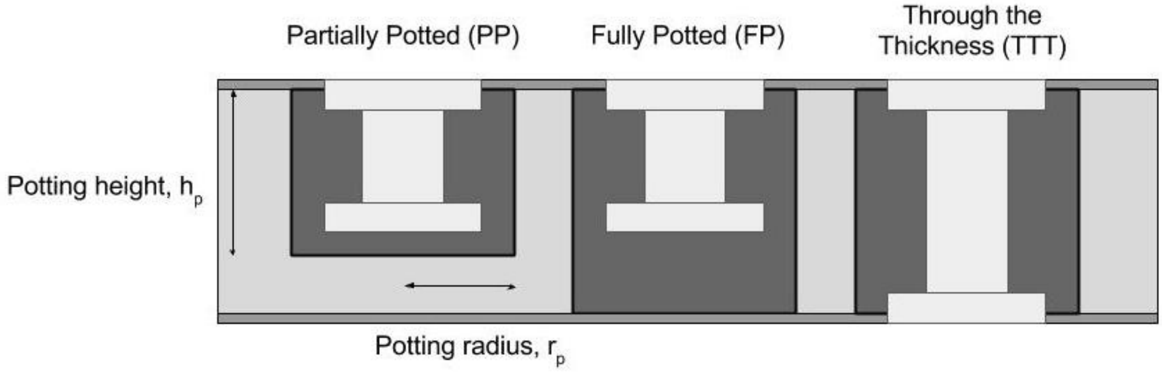

Figure A1- The three different kinds of inserts.

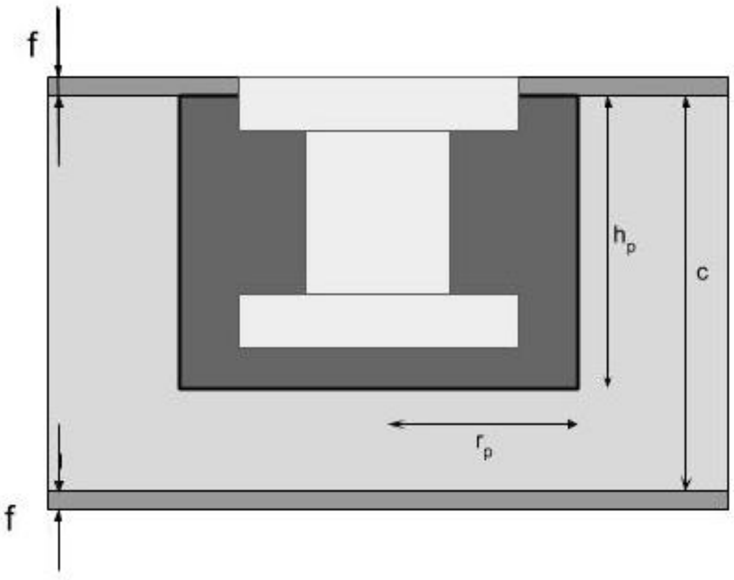

Figure A2- Geometry of an insert and SWP.

A.1.1 Antiplane theory

Insert capacity was analysed in tension loading as well as in compressive loading for both the fully and partially potted insert.

A.1.1.1 Tension loading of a FP-insert

Critical tension load for a fully potted insert is given by equation 1 below.

$$P_{tension,crit,FP} = \frac{2\pi r_p c \tau_{c,crit}}{C^* K_{max}} \qquad \text{[eq. 1]}$$

Where:

r_p = potting radius
c = core height
$\tau_{c,\,crit}$ = core shear strength

C^* is given by equation 2.

$$C^* = \frac{\frac{c}{f}}{\left(\frac{c}{f}\right) + 1} \qquad \text{[eq. 2]}$$

Where:

f = face sheet thickness

K_{max} is given by equation 3

$$K_{max} = \frac{r_p}{r_{\tau,max}}\left[1 - \sqrt{\frac{r_{\tau,max}}{r_p}}\, e^{\alpha(r_p - r_{\tau,max})}\right] \qquad \text{[eq. 3]}$$

In equation 3 $r_{\tau,max}$ is the radius at which the maximum shear stress occurs. $r_{\tau,max}$ is measured from the centre of the insert and is given by equation 4 below.

$$r_{\tau,max} = \frac{r_p}{[1 - e^{c_2(\alpha r_p)^n}]} \qquad \text{[eq. 4]}$$

Where:

c_2 = -0.931714 (constant)
n = 0.262866 (constant)

The variable α that occurs in both eq. 3 and eq. 4 is given by eq. 5 below.

$$\alpha = \frac{1}{f}\sqrt{\frac{G}{E}12(1 - \upsilon^2)(1 + \frac{c/f}{2})} \qquad \text{[eq. 5]}$$

Where:

G = shear modulus of the face sheet
E = Young's modulus of the face sheet
υ = Poissonn's ratio of the face sheet

A.1.1.2 Compressive loading of a FP-insert

Critical compressive load for a fully potted insert is given by eq. 6 below.

$$P_{comp,crit,FP} = \frac{P_{tension,crit,FP}}{2} + \pi r_{\tau,max} c \tau_{c,crit} \qquad \text{[eq. 6]}$$

Where $P_{tension,\ crit,\ FP}$ is given by eq. 1 and $r_{\tau,max}$ is given by eq. 4.

A.1.1.3 Tension loading of a PP-insert

Critical load for a partially potted insert loaded in tension is given by eq. 7.

$$P_{tension,crit,PP} = P_{tension,crit,FP} \cdot K_{tPP} \qquad \text{[eq 7]}$$

Where $P_{tension,\ crit,\ FP}$ is given by eq. 1 and the stress concentration factor K_{tPP} is given by eq. 8 below:

$$K_{tPP} = \left(\frac{h_p}{c}\right)^{0.62} \qquad \text{[eq. 8]}$$

h_p = potting height

A.1.1.4 Compressive loading of a PP-insert

Critical load for a partially potted insert loaded in compression is given by eq. 9.

$$P_{comp,crit,PP} = \frac{P_{tension,crit,FP}}{2} + \pi r_{\tau,max} c \tau_{c,crit} \cdot K_{tPP} \qquad \text{[eq. 9]}$$

See eq. 1 for $P_{tension,crit,FP}$ and eq.8 for K_{tPP}.

A.1.2 Extended antiplane theory

Insert capacity was analysed with the extended antiplane theory as a complement to the analysis made with the antiplane theory. The analyse was made for tension and compressive loading for both the fully and partially potted insert.

A.1.2.1 Tension loading of a FP-insert

Critical tension load for a fully potted insert is given by eq. 10.

$$P_{tension,crit,FP} = 2\pi r_p d \tau_{c,crit} \qquad \text{[eq. 10]}$$

Where:

r_p = potting radius

$\tau_{C,\ crit}$ = core shear strength

d is the distance between the face sheet middle surfaces and is given by eq. 11.

$$d = c + f \qquad \text{[eq. 11]}$$

c = core height
f = face sheet thickness

A.1.2.2 Compressive loading of a FP-insert

Critical compressive load for a fully potted insert is given by eq. 12 below.

$$P_{comp,crit,FP} = \frac{P_{tension,crit,FP}}{2} + \pi r_p c \tau_{c,crit} \qquad \text{[eq. 12]}$$

Where $P_{tension,\ crit,\ FP}$ is given by eq. 10.

A.1.2.3 Tension loading of a PP-insert

When a partially potted insert loaded in tension the critical load is given by eq. 13.

$$P_{tension,crit,PP} = \left(2\pi r_p\left(d + h_p - c\right)\tau_{c,crit}\ \right) \cdot K_{tPP} \qquad \text{[eq. 13]}$$

h_p = potting height

The stress concentration factor K_{tPP} is given by equation 8.

A.1.2.4 Compressive loading of a PP-insert

Critical load for a partially potted insert loaded in compression is given by eq. 14 below.

$$P_{comp,crit,PP} = P_{comp,crit,FP} \cdot K_{tPP} \qquad \text{[eq. 14]}$$

Where the K_{tPP} is given by eq. 8 and $P_{comp,crit,FP}$ is given by eq. 12.

A.2 In plane static load capacity

Insert in plane load capacity was analysed using equations found in reference [8]. When in plane capacity is analysed the critical failure mode is considered to be buckling of the face sheet.

It is assumed that the entire load is carried through both face sheets in the case of through the thickness (TTT) and fully potted (FP) inserts. When it comes to partially potted (PP) inserts the load is considered to be carried mainly by one of the face sheets and secondarily by the core.

A.2.1 In plane critical load FP and TTT inserts

The in plane capacity for FP and TTT inserts are given by eq. 15 below.

$$Q_{crit,FP} = (2 f r_p \sigma_y) \quad \text{for } r_p \leq 11 \text{ mm} \qquad \text{[eq. 15]}$$

Where

f = face sheet thickness
r_p = potting radius
σ_y = yield strength of the face sheets

A.2.2 In plane critical load for PP inserts

Critical in plane load for partially potted inserts are given by eq. 16.

$$Q_{crit,PP} = 8 r_p^2 \tau_{c,crit} + 2 f r_p \sigma_y \quad \text{for } r_p \leq 11 \text{ mm} \qquad \text{[eq. 16]}$$

$\tau_{c,crit}$ = core shear strength

A.3 Combined Loads

When multiple loads are applied to insert simultaneously according to figure A3 equation 17 can be applied to determine the capacity of the insert.

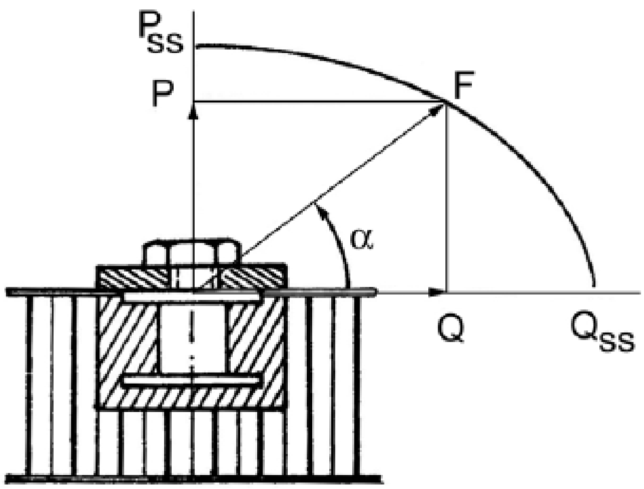

Figure A1- Combined loads acting on insert [8]

$$\left(\frac{P}{P_{SS}}\right)^2 + \left(\frac{Q}{Q_{SS}}\right)^2 \leq 1 \qquad \text{[eq. 17]}$$

Where:

P = the out of plane load

P_{SS} = the critical out of plane load

Q = the in plane load

Q_{SS} = the critical in plane load

Appendix B – Specification of demands

In this appendix the specifications of demand is found.

Criterion	Interested Party	Demand/Requests (1-5)	Control Method	Target Value
General				
Carry loads in a sufficient way	Volvo	D	FE-analysis	See Loads
Minimize weight	Volvo	R 1*	CAD-model	Yes
Dimensions SWP	Volvo	D	CAD-model	Do not exceed 2244x2063x35 [mm]
Life span	Volvo	D	Life span analysis	One million kilometers
Production cost	Volvo	R 1	Production cost analysis	Minimize
Ensure media is not damaged during operation	Volvo	D		Yes
Backwards compatibility				
Use of same arrangement of components as current	Volvo	D	CAD-model	Yes
Use of same media fasteners as current	Volvo	D	Production process analysis/CAD-model	Yes
Modification of main components	Volvo	D	CAD-model	No
Use of existing tools when mounting	Service/Aftermarket	D	Production process analysis/CAD-model	Yes
Need of Abutment when mounting components	Service/Aftermarket	D	Production process analysis/CAD-model	No
Mounting components from above	Service/Aftermarket	D	Production process analysis/CAD-model	Yes
Complete mount of ESS when not mounted on bus	Service/Aftermarket	D	Production process analysis/CAD-model	Yes
Precision of manufacturing	Volvo	D	Production process analysis/CAD-model	High
Operating Environment				
Resist corrosion	Volvo	D	Material/CAD analysis	Yes
Operating temperature	Volvo	D	Material/CAD analysis	From -40 to 80 °C
Resist oil	Volvo	D	Material/CAD analysis	Yes
Resist road salt	Volvo	D	Material/CAD analysis	Yes
Resist formation of ice	Volvo	D	Material/CAD analysis	Yes
Resist Water	Volvo	D	Material/CAD analysis	Yes
Resist impact from sunlight	Volvo	D	Material/CAD analysis	Yes

Environmental Impact (EI)				
Recyclable materials	Volvo	R4	LCA	Yes
The EI due to the production process	Volvo	R4	LCA	Low
Aftermarket				
Possibility to replace individual components	Service/Af termarket	D	CAD-model	Yes
Serviceability	Service/Af termarket	D	CAD-model	Good

* Requests are ranked from R1 to R5 where R1 is the highest priority request and R5 is the lowest priority request.

APPENDIX C – FEM ANALYSIS

THESIS ESS SANDWICH PANEL STRUCTURAL ANALYSIS

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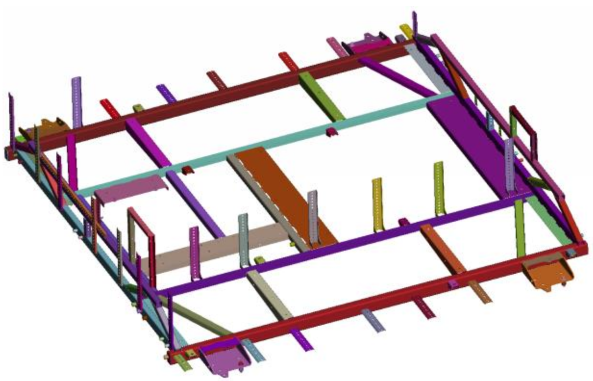
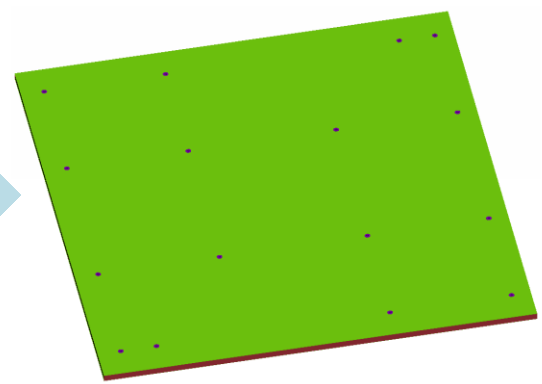
2016 – 05 – 02

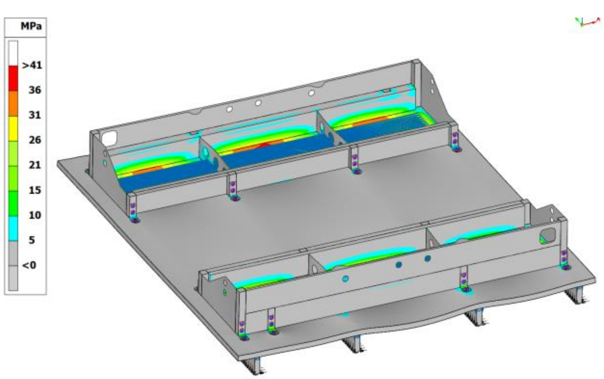
Summary

Thesis ESS SAFT sandwich panel Structural Analysis

- **Background:** Replace Plug-in hybrid ESS framework with sandwich panel.
- **Conclusion:** Stress levels are below permissible limit in all load cases.
- **Recommendation:** Reduce size of potting in next design loop. Perform fatigue analysis.







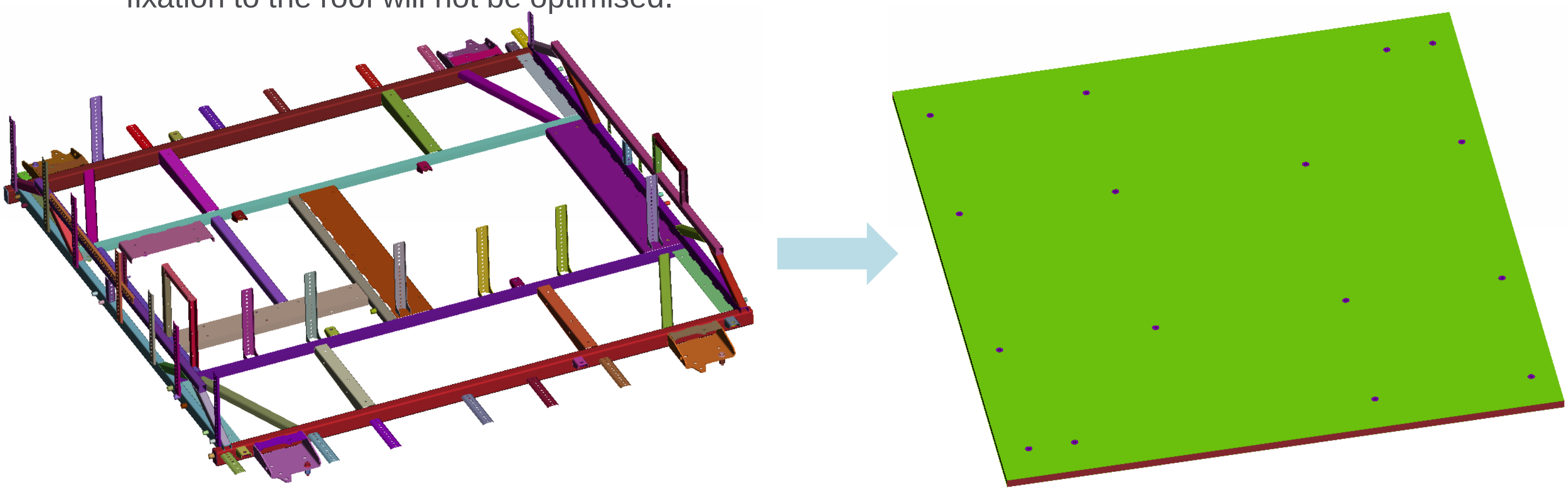
Thesis ESS SAFT sandwich panel Structural Analysis

- Project: Thesis
- Designer: Eric Eriksson, Filip Jönsson, CD74170, Chalmers/ARAK3
- References: -
- Load cases:*
  - Max load durability:
    - Vertical acceleration X g
    - Lateral acceleration 0.5X g
    - Longitudinal acceleration 0.5X g
  - Shock load:
    - Lateral acceleration 1.3X g
    - Longitudinal acceleration 1.7X g
- Requirements: Stresses below permissible limits.
- Tools:
  - ANSA v16.0.0
  - META v16.0.0
  - Nastran 2013.1

* Loads have been censored due to secrecy

Problem Description

- The purpose with the thesis work is to partly design a supporting sandwich structure for the ESS SAFT as a replacement for the traditional steel frame.
- The goal is to reduce the weight with 70 % from the original weight of about 100 kg.
- The scope of the thesis is to dimension the fixations of the batteries. The sandwich panel and the fixation to the roof will not be optimised.



Load Cases

Max load*

- Durability:
  - Vertical acceleration: –X g
  - Lateral acceleration: 0.5X g
  - Longitudinal acceleration: 0.5X g
- Shock:
  - Lateral acceleration: 1.3X g
  - Longitudinal acceleration: 1.7X g

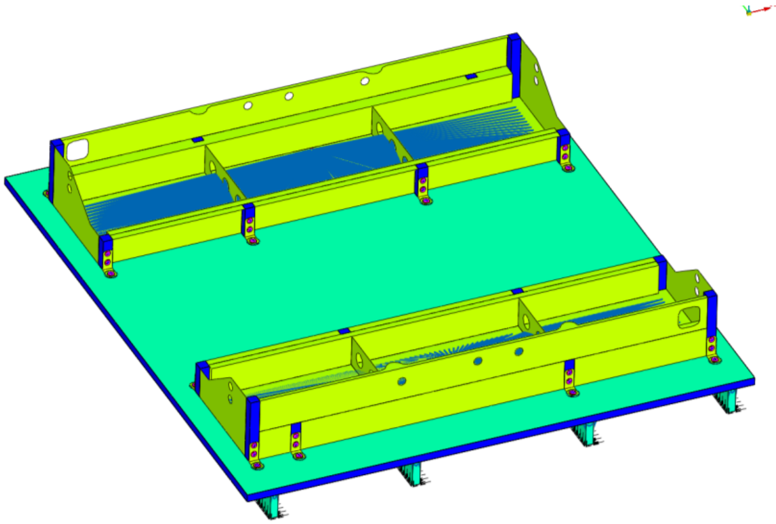
Fatigue load

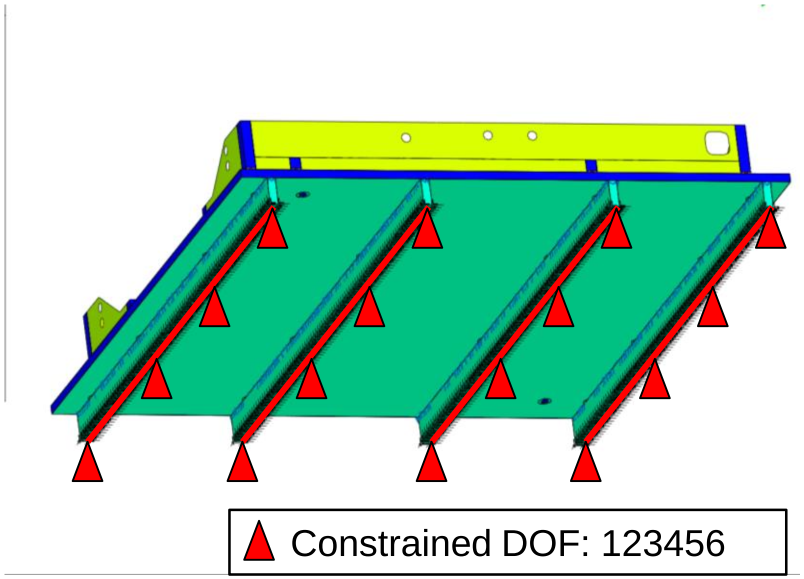
- Not considered due to insufficient material data

* Loads have been censored du to secrecy

Model / Assumptions / BCs

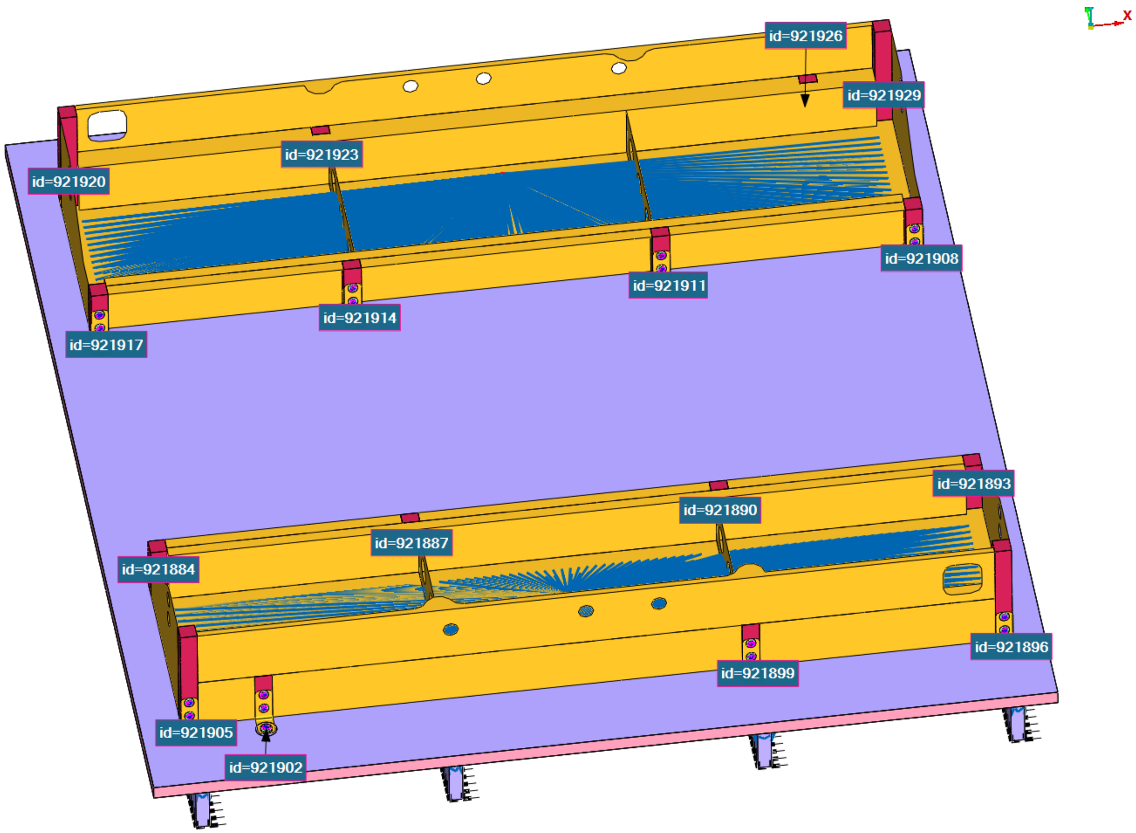
- 2x350 kg SAFT batteries
- 2244x2063x31.6 mm sandwich panel





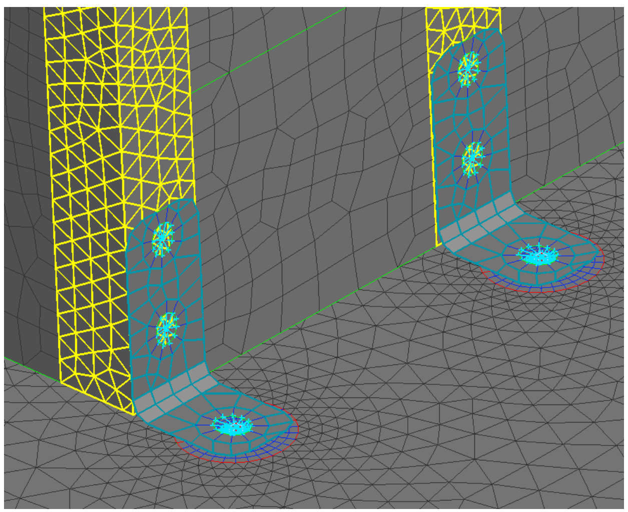
Model

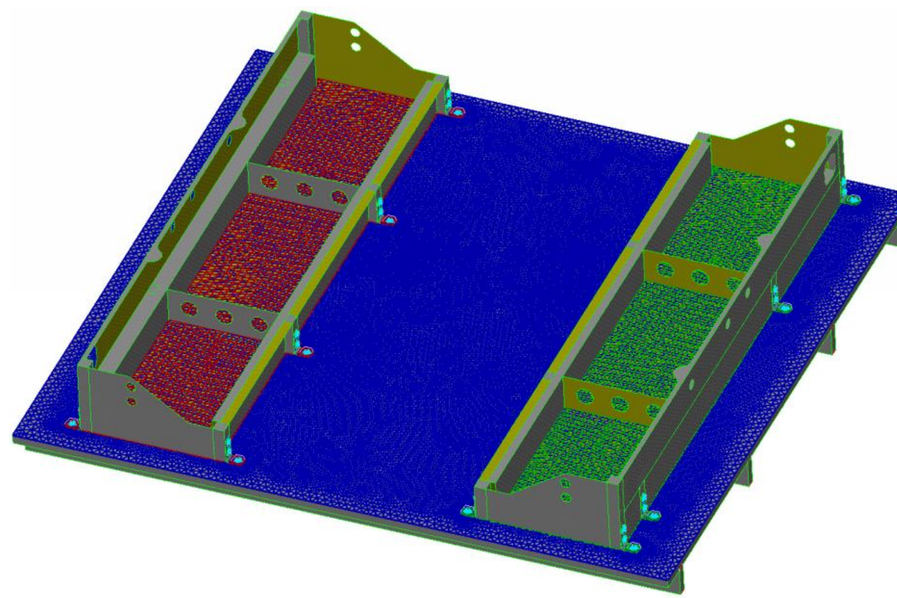
Bolt id’s



Contacts

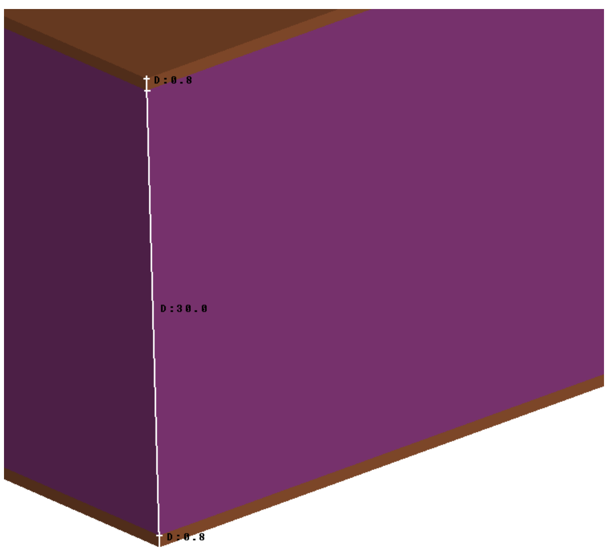
- Battery brackets – battery
- Sandwich panel – battery

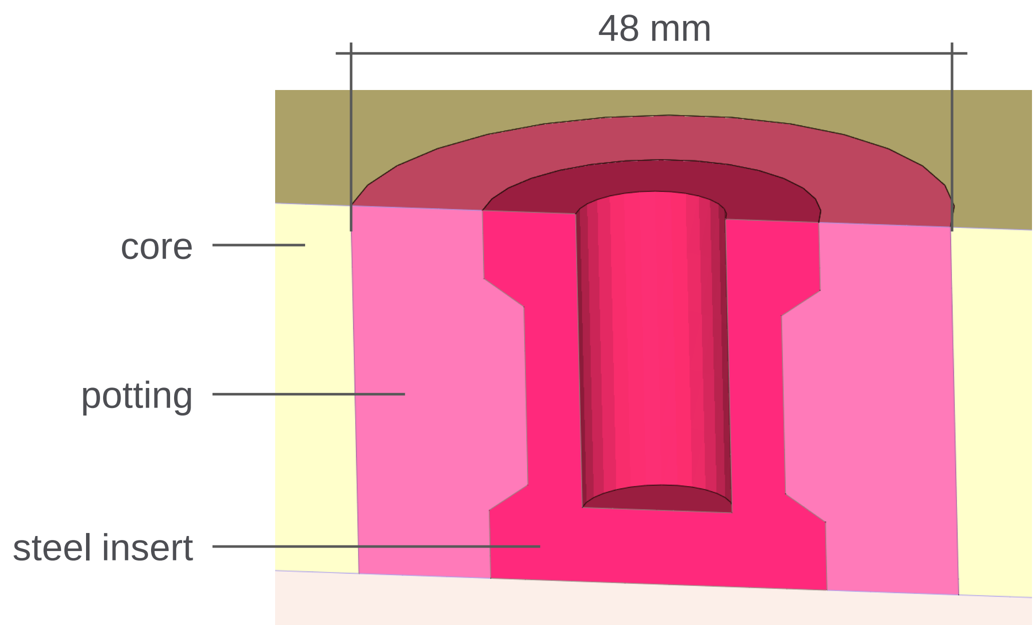




Sandwich panel

- 0.8 mm aluminium skin + 30 mm Divinycell H45 + 0.8 mm aluminium skin
- Steel insert with surrounding potting at every battery fixation point





Materials

	E [GPa]	ρ [kg/m³]	ν [-]	$R_{p0.2}$ [MPa]	Shear strength [MPa]
steel, VSHR350	210	7850	0.3	350	202
aluminium, VAW5754+H16	70	2700	0.3	220	127
potting, Lekutherm X227	2.3	640	0.49	14	10
core, Divinycell H45	0.045	48	0.49	0.50	0.46

Materials

potting:

Supplier:	Cure temp.	Density	Tensile strength	Compressive strength	Shear strength	Tensile modulus	Temp. use	Source[ ]
Product code	°C	γ_R kg/m³	$\sigma_{R\,crit}$ N/mm²	σ_R N/mm²	$\tau_{R\,crit}$ N/mm²	E_R N/mm²	°C	
Altropol: Neukadur EP 270 + 3M Scotchlite H20/1000 micro-ballons	RT/24h + 60/2h	0.64	14	36	10	2300	<100	CASA [1]; Patria [4] [7]; Astrium UK [7] with T3 hardener

7.1.2.1 Lekutherm X227

The potting material, applied in the manufacturing procedure [See: 23.3] is a liquid two-component epoxy resin of reduced weight and simultaneously improved viscosity. This is achieved by the addition of glass microballoons.

A characteristic property of this resin is that it can only be applied b injection with an air-pressurised gun. Provided that the correct viscosity is maintained, it does not flow after injection.

[See Table 7-1]: for basic RT properties of Lekutherm X227; 25.3 for mixing and cure conditions]

NOTE Neukadur EP 270, which is widely used for insert potting, is a more recent variant of the Lekutherm X227 epoxy system. Some variation within properties can therefore be expected between the two resin systems.

core:

Mechanical properties Divinycell® H

Property	Test Procedure	Unit		H35	H45
Compressive Strength[1]	ASTM D 1621	MPa	Nominal	0.5	0.6
			Minimum	0.3	0.5
Compressive Modulus[1]	ASTM D1621-B-73	MPa	Nominal	40	50
			Minimum	29	45
Tensile Strength[1]	ASTM D 1623	MPa	Nominal	1.0	1.4
			Minimum	0.8	1.1
Tensile Modulus[1]	ASTM D 1623	MPa	Nominal	49	55
			Minimum	37	45
Shear Strength	ASTM C 273	MPa	Nominal	0.4	0.56
			Minimum	0.3	0.46
Shear Modulus	ASTM C 273	MPa	Nominal	12	15
			Minimum	9	12
Shear Strain	ASTM C 273	%	Nominal	9	12
Density	ISO 845	kg/m³	Nominal	38	48

The glue between the joining parts is not evaluated in this analysis.

Results

Bolt load

Loads archived in: DL-160429-Bolt_loads.xlsx

DL-160429-Bolt_loads.xlsx

id	Bolt	M [Nm]	Faxial [N]	Fshear [N]	Fshear1 [N]	Fshear2 [N]	Mbend1 [Nm]	Mbend2 [Nm]
921884	M12	-3,0	-10,9	148,6	-115,3	93,7	0,2	-0,8
921887	M12	-0,8	-123,2	269,0	-268,2	19,9	-2,3	-0,2
921890	M12	1,1	-133,7	357,5	-354,7	-44,6	-2,6	-0,1
921893	M12	3,0	-8,6	189,2	-161,9	-97,9	0,3	0,9
921896	M12	-4,7	-23,5	197,2	-989,4	222,6	-14,2	0,5
921899	M12	-2,1	-136,3	515,4	512,4	-55,8	4,8	-0,9
921902	M12	3,6	245,0	127,4	-11,5	126,9	-6,2	-1,1
921905	M12	3,0	-88,0	290,9	270,7	106,5	3,2	-1,2
921908	M12	-2,9	-7,3	186,5	163,2	-90,3	-0,5	0,8
921911	M12	-0,7	-55,7	273,8	273,6	-11,5	1,4	0,1
921914	M12	0,8	-76,0	365,1	363,3	36,0	1,8	-0,1
921917	M12	3,2	-0,3	212,1	187,6	99,0	-0,6	-0,6
921920	M12	-5,0	-37,9	197,8	-125,9	152,5	-2,1	0,3
921923	M12	-1,0	-171,9	548,4	-548,0	20,9	-5,6	1,0
921926	M12	2,8	83,7	153,4	-106,9	-109,9	2,3	0,5
921929	M12	2,8	-100,9	229,2	-207,6	-97,1	-3,4	1,1

-X g vertical

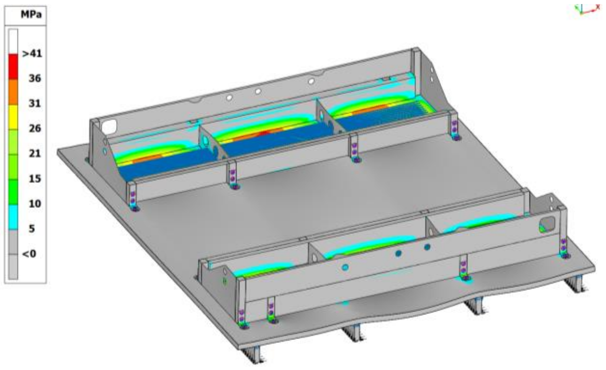
id	Bolt	M [Nm]	Faxial [N]	Fshear [N]	Fshear1 [N]	Fshear2 [N]	Mbend1 [Nm]	Mbend2 [Nm]
921884	M12	-7,0	-161,4	2527,1	-2504,7	336,1	5,3	0,6
921887	M12	-4,1	-832,1	4422,6	-4422,0	75,2	-13,2	-0,1
921890	M12	1,8	-745,0	3991,2	-3984,4	-233,0	-11,5	-0,5
921893	M12	4,8	-213,4	2348,9	-2338,0	-225,4	3,4	-0,2
921896	M12	7,1	700,4	1014,1	-989,4	222,6	-14,2	0,5
921899	M12	6,0	1449,7	1689,8	-1679,5	186,2	-31,3	0,6
921902	M12	-5,2	221,5	666,1	-645,5	-164,4	-1,7	-0,6
921905	M12	-6,3	1130,3	1322,6	-1307,7	-198,0	-24,4	0,5
921908	M12	8,1	518,9	1043,8	-1008,7	268,7	-8,1	0,6
921911	M12	5,1	1377,2	1899,3	-1891,8	168,3	-25,4	0,5
921914	M12	-5,2	1193,9	1639,5	-1630,0	-175,9	-22,2	0,4
921917	M12	-5,5	507,2	941,9	-923,7	-184,3	-8,2	-0,2
921920	M12	-8,5	-244,2	2646,2	-2618,3	383,5	3,2	0,5
921923	M12	-6,9	-856,8	4589,0	-4585,5	177,9	-16,2	1,6
921926	M12	5,9	85,9	2343,0	-2327,4	-270,1	9,9	0,3
921929	M12	8,6	-469,4	2909,0	-2885,6	-368,6	-8,3	0,9

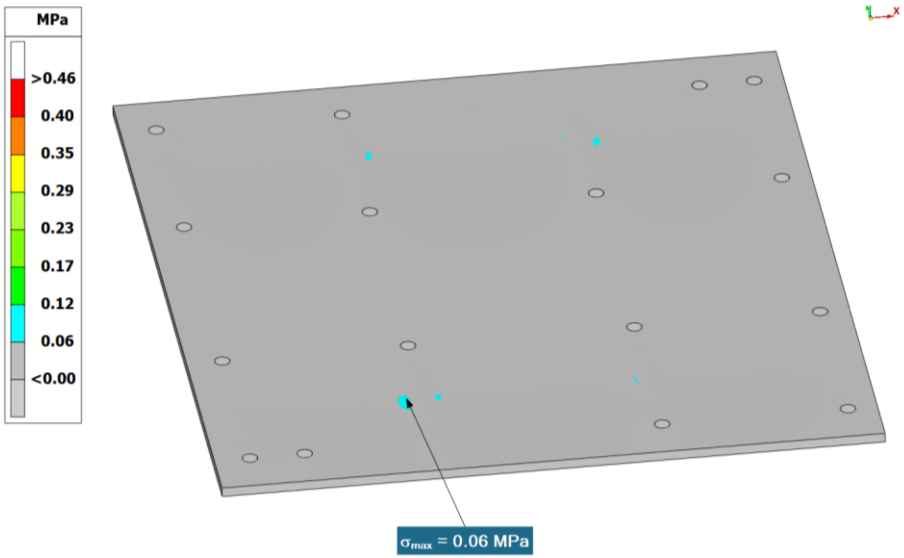
1.3X g lateral

id	Bolt	M [Nm]	Faxial [N]	Fshear [N]	Fshear1 [N]	Fshear2 [N]	Mbend1 [Nm]	Mbend2 [Nm]
921884	M12	78,7	435,7	2666,6	220,0	-2657,5	9,3	3,0
921887	M12	89,2	269,9	3063,6	-90,3	-3062,3	6,0	4,4
921890	M12	87,1	8,9	3200,8	-667,9	-3130,4	2,1	3,7
921893	M12	75,6	-123,8	2947,6	-908,1	-2804,2	-1,7	-2,9
921896	M12	-90,7	-42,5	3036,3	400,5	-3009,8	2,1	-4,0
921899	M12	-102,1	136,2	3460,0	533,0	-3418,7	-4,3	3,4
921902	M12	-85,9	204,3	2924,5	406,1	-2896,1	-5,5	-4,0
921905	M12	-77,1	533,9	2611,3	107,3	-2609,1	-13,6	-4,2
921908	M12	-75,5	-76,6	2913,4	887,9	-2774,8	1,1	-2,7
921911	M12	-85,9	4,9	3155,3	705,0	-3075,5	-2,3	3,5
921914	M12	-90,1	239,4	3090,3	158,0	-3086,3	-5,7	4,2
921917	M12	-79,0	447,4	2649,7	-251,2	-2637,8	-9,7	3,1
921920	M12	87,7	513,2	3006,9	-269,7	-2994,8	13,3	-4,2
921923	M12	102,4	267,6	3495,6	-486,3	-3461,6	7,6	3,3
921926	M12	86,5	99,4	2968,9	-480,2	-2929,8	2,2	-3,4
921929	M12	78,1	50,2	2641,1	-264,1	-2627,9	-0,3	-3,2

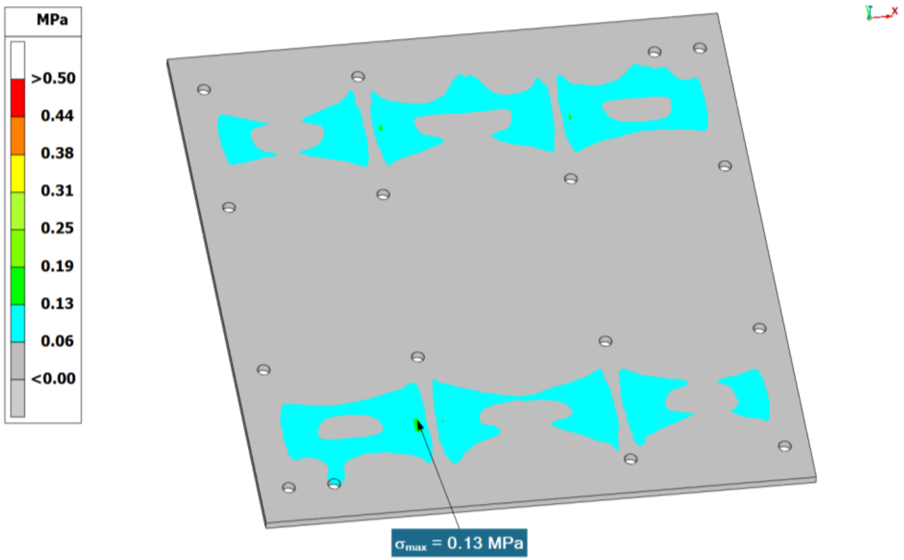
1.7X g longitudinal

Results, core
-X g vertical





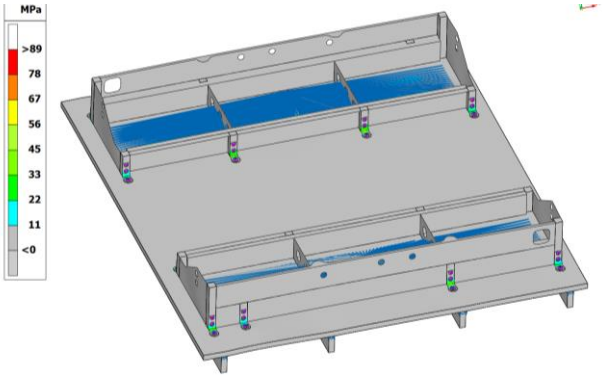
Max shear stress

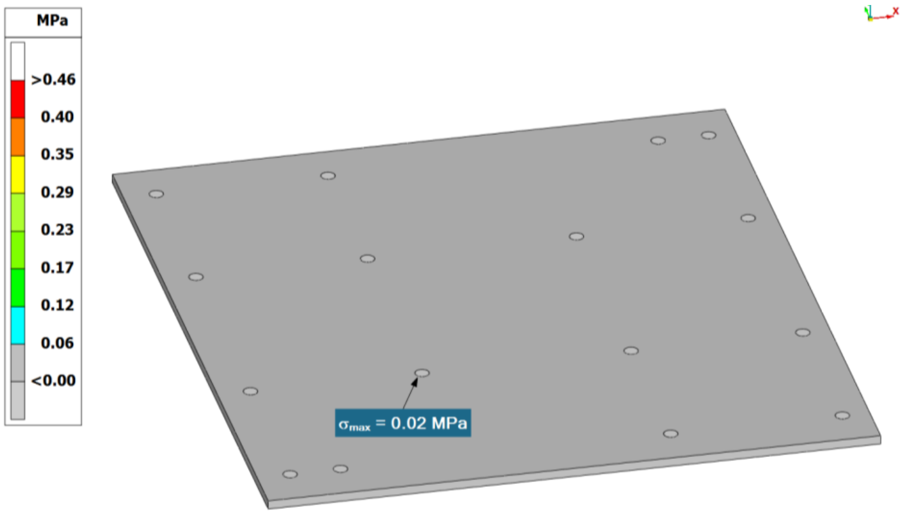


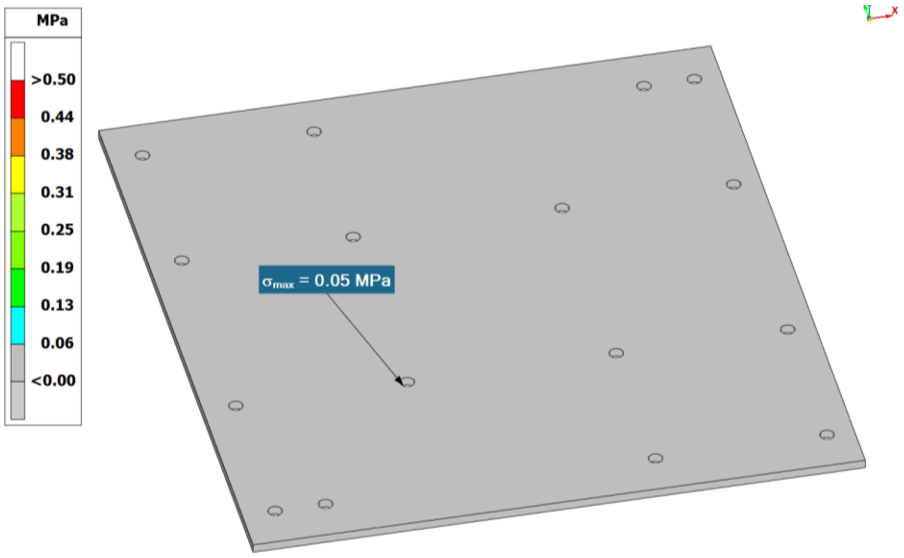
Max von Mises stress

Results, core

0.5X g lateral





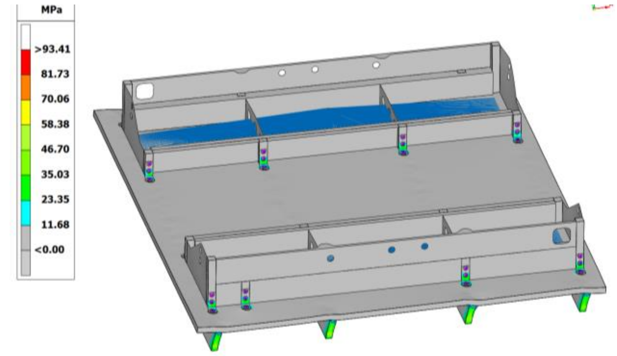


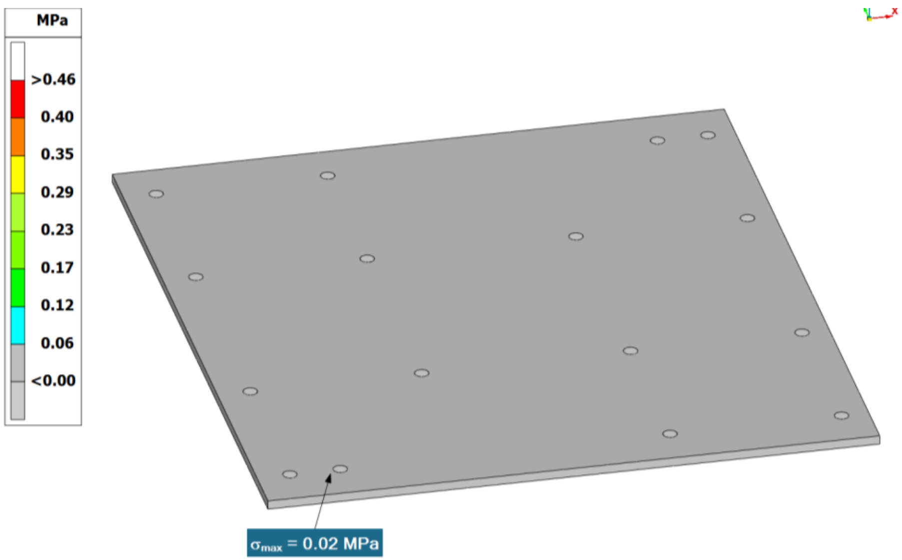
Max shear stress

Max von Mises stress

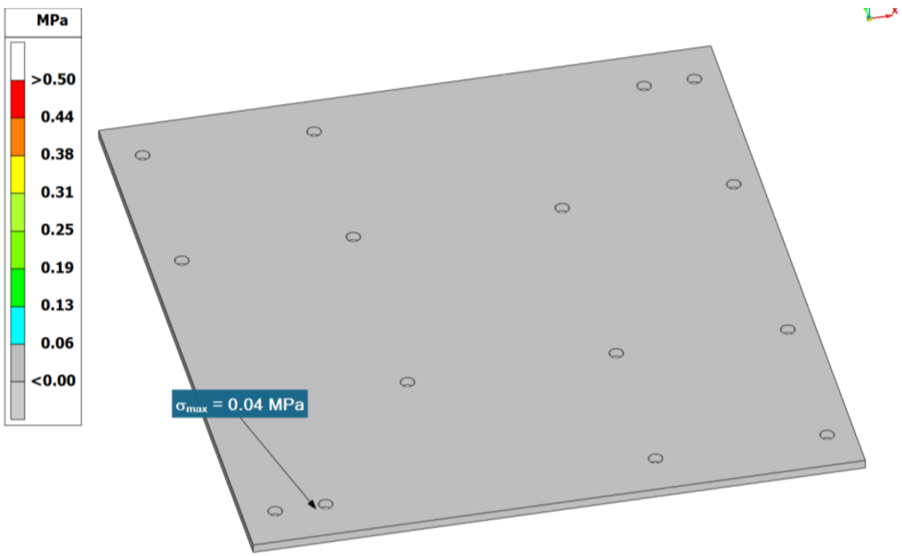
Results, core

0.5X g longitudinal





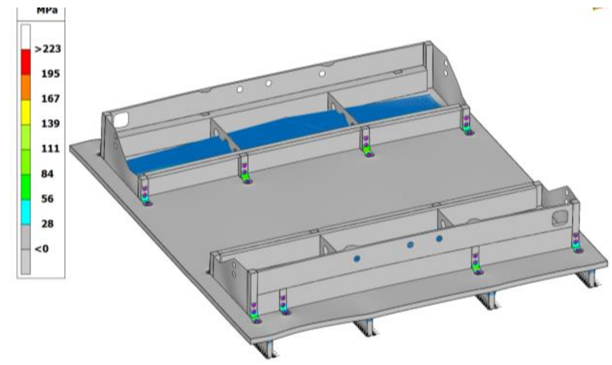
Max shear stress

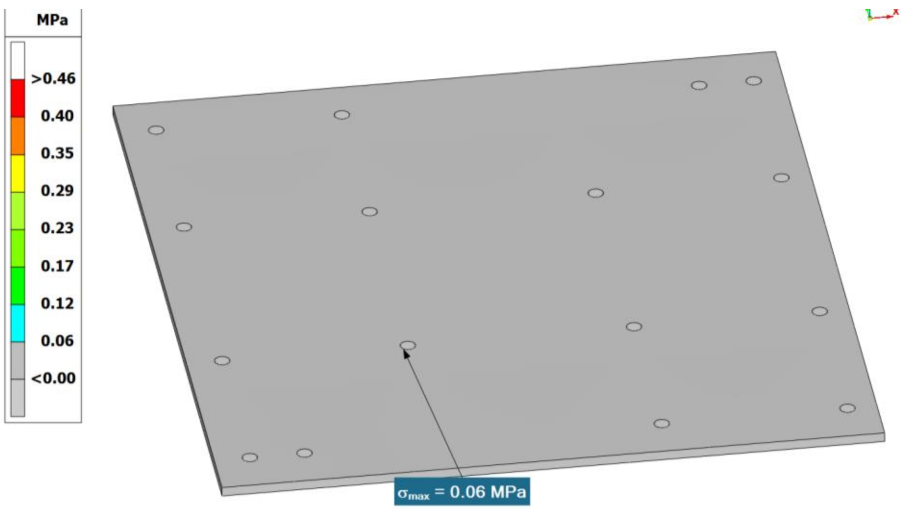


Max von Mises stress

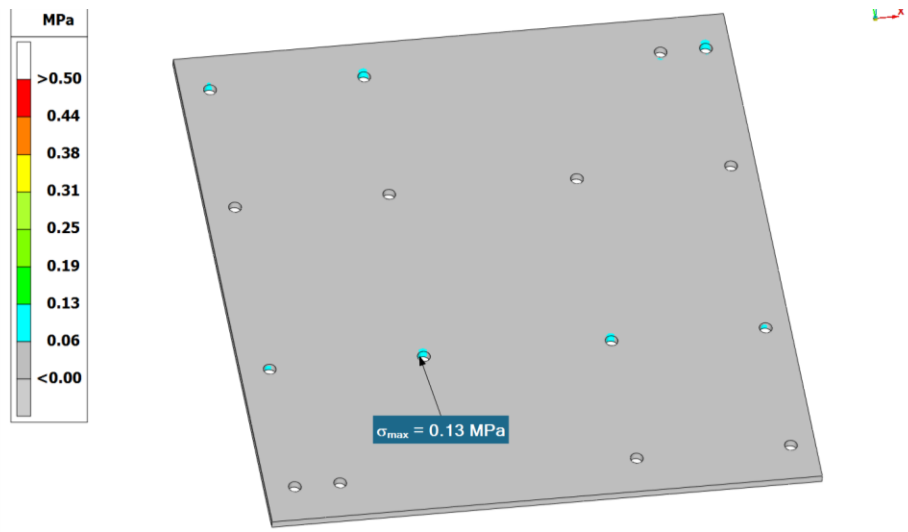
Results, core

1.3X g lateral



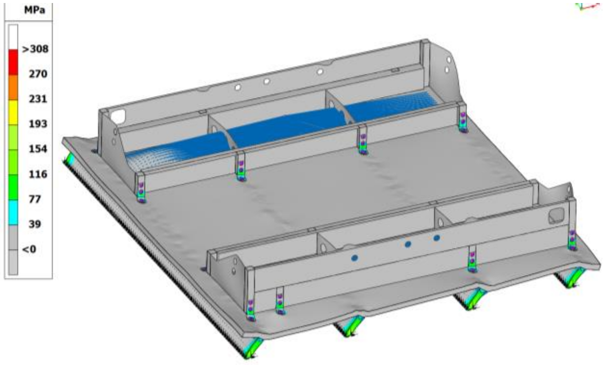


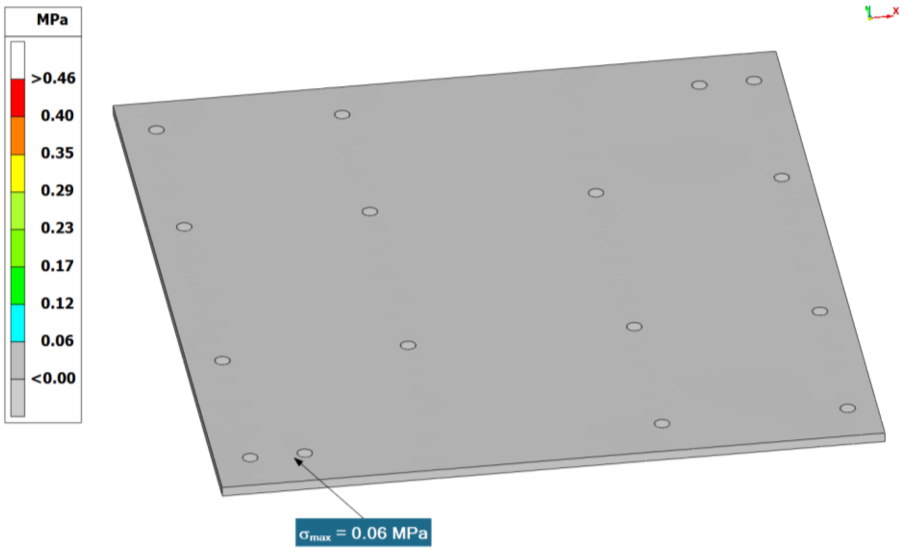
Max shear stress



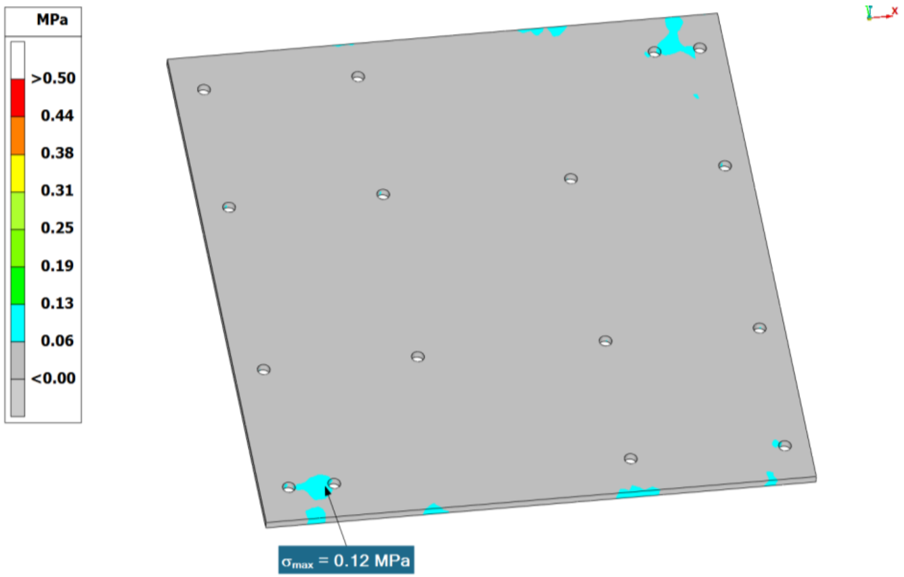
Max von Mises stress

Results, core
1.7X g longitudinal



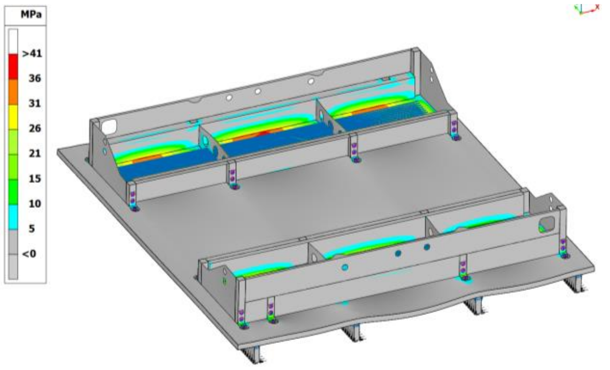


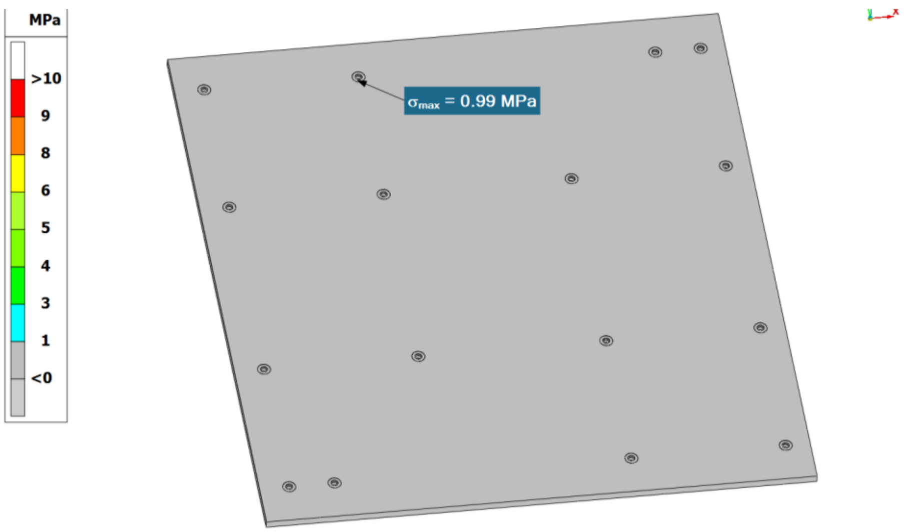
Max shear stress



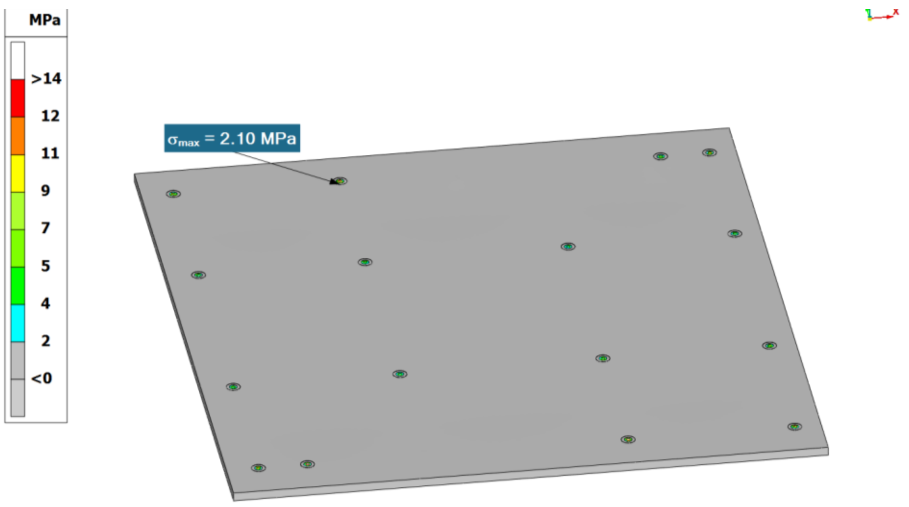
Max von Mises stress

Results, potting
-X g vertical





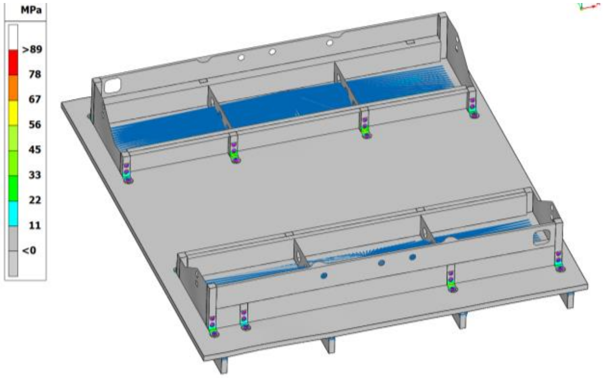
Max shear stress

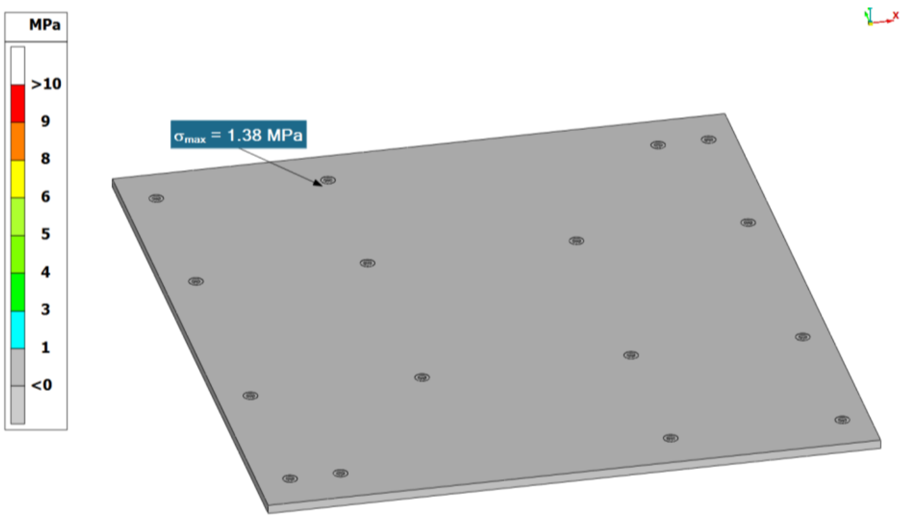


Max von Mises stress

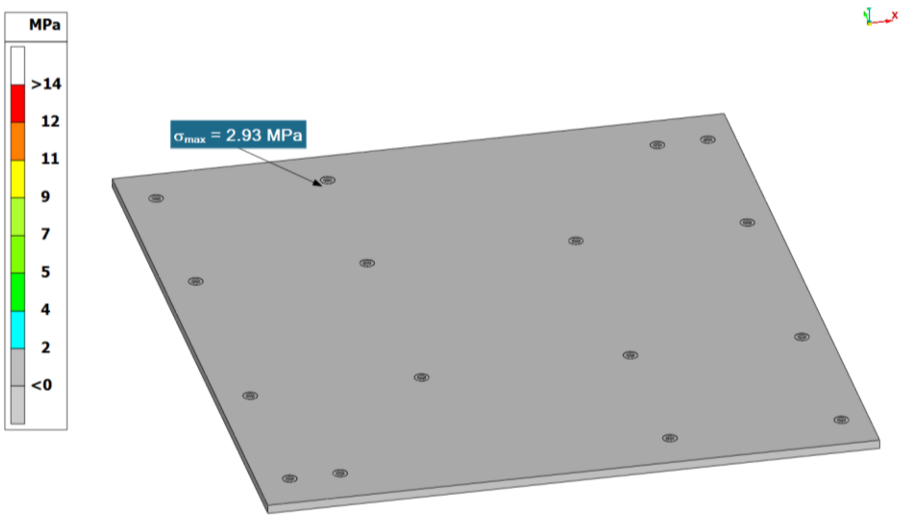
Results, potting

0.5X g lateral





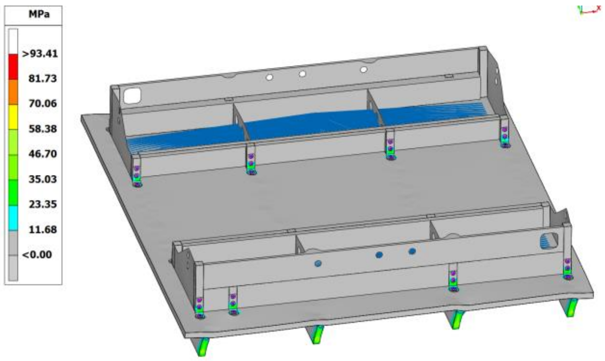
Max shear stress

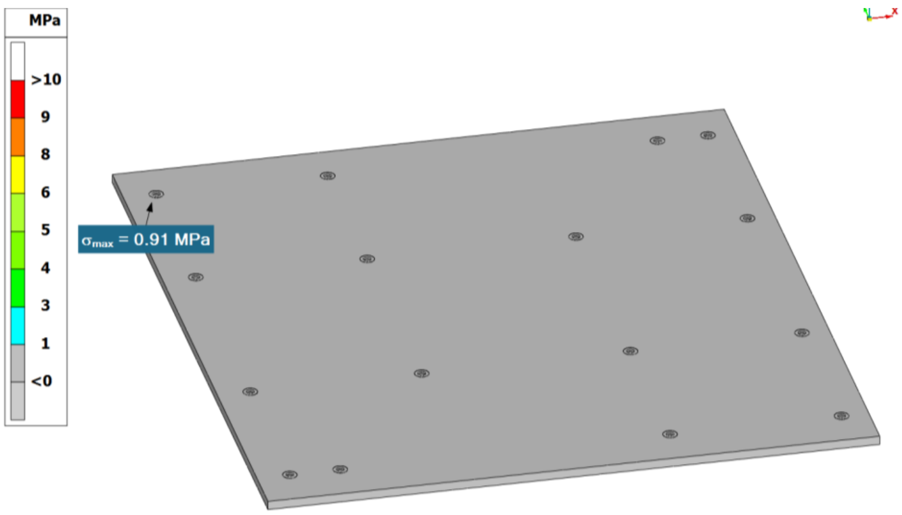


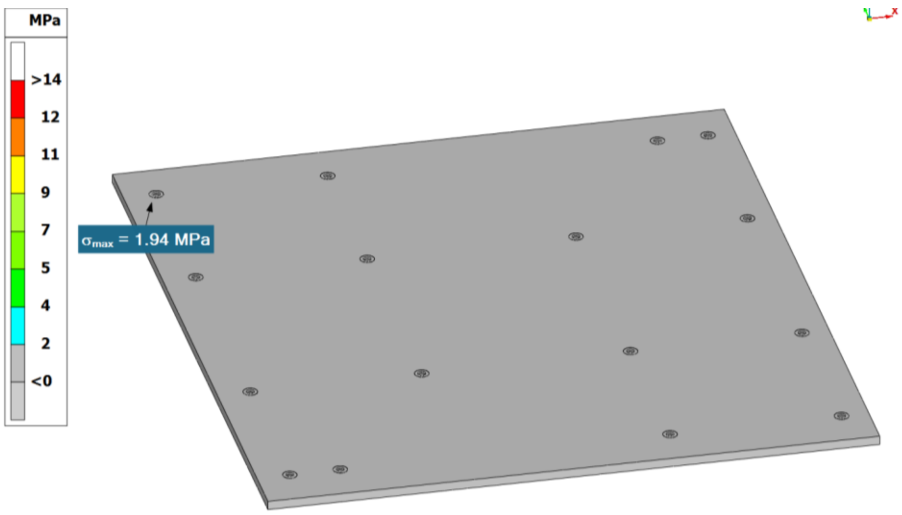
Max von Mises stress

Results, potting

0.5X g longitudinal



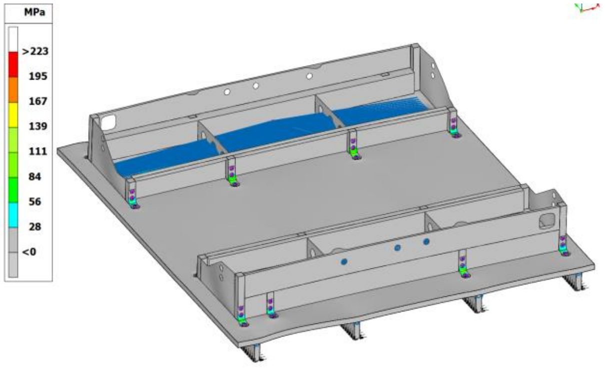


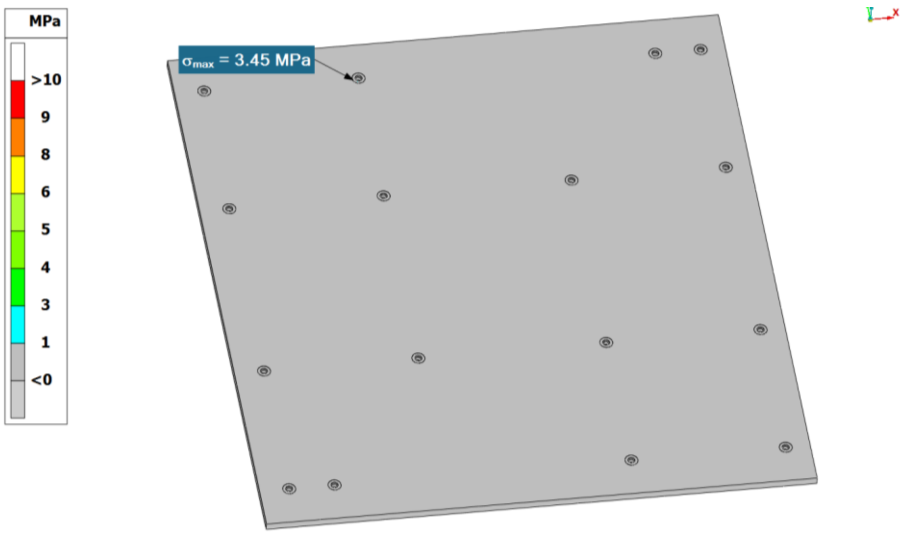


Max shear stress

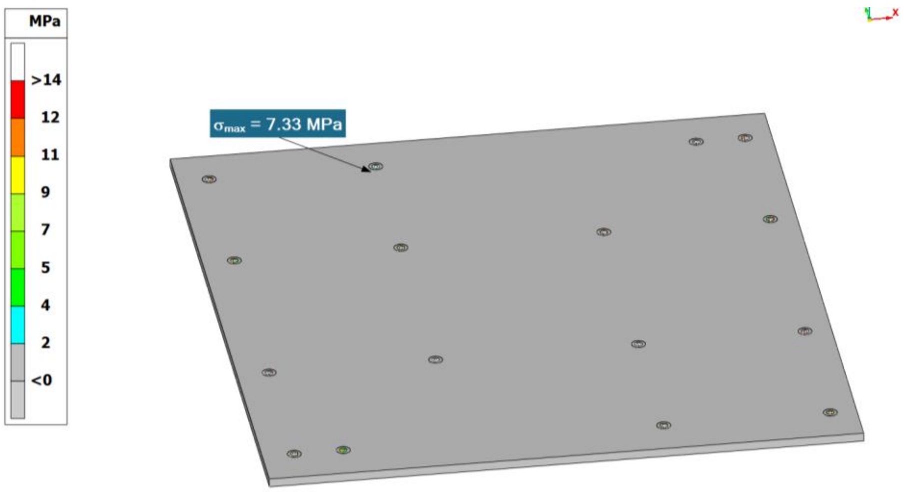
Max von Mises stress

Results, potting
1.3X g lateral





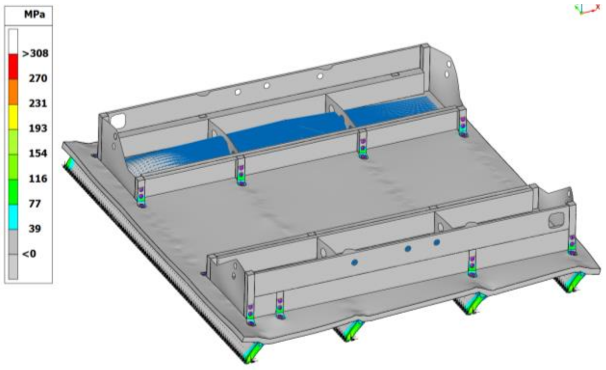
Max shear stress

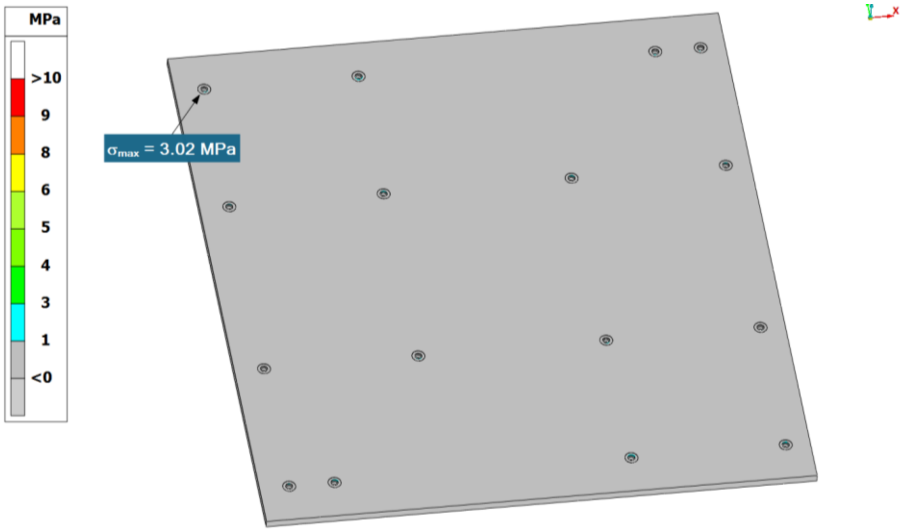


Max von Mises stress

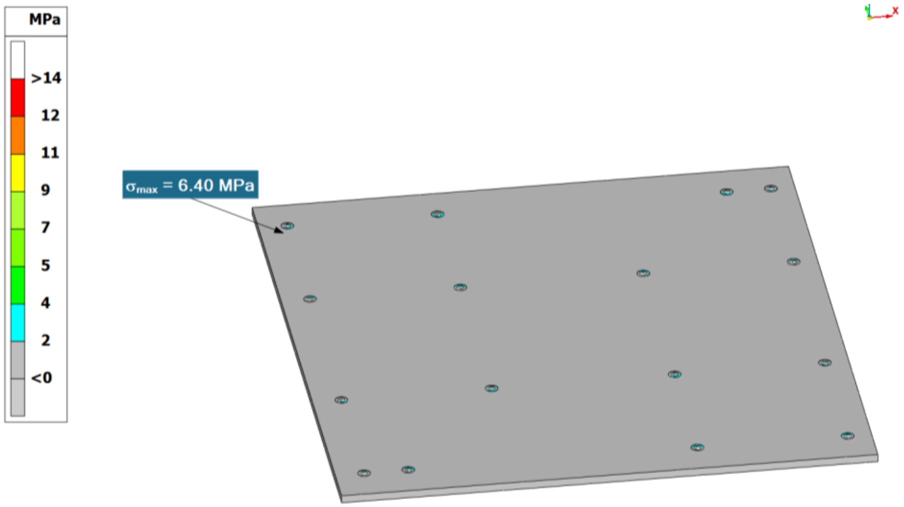
Results, potting

1.7X g longitudinal





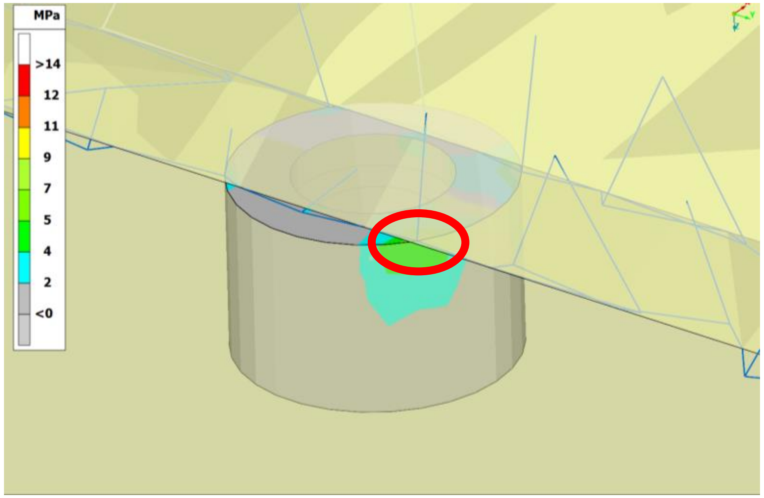
Max shear stress



Max von Mises stress

Conclusions

- Conclusions:
  - Stress levels are in general low in all load cases.
  - In some load cases the maximum stress occurs at the boundary nodes between the supporting panels and the potting in the large sandwich panel. Therefore a sub-model of a potting is created, see next slides.

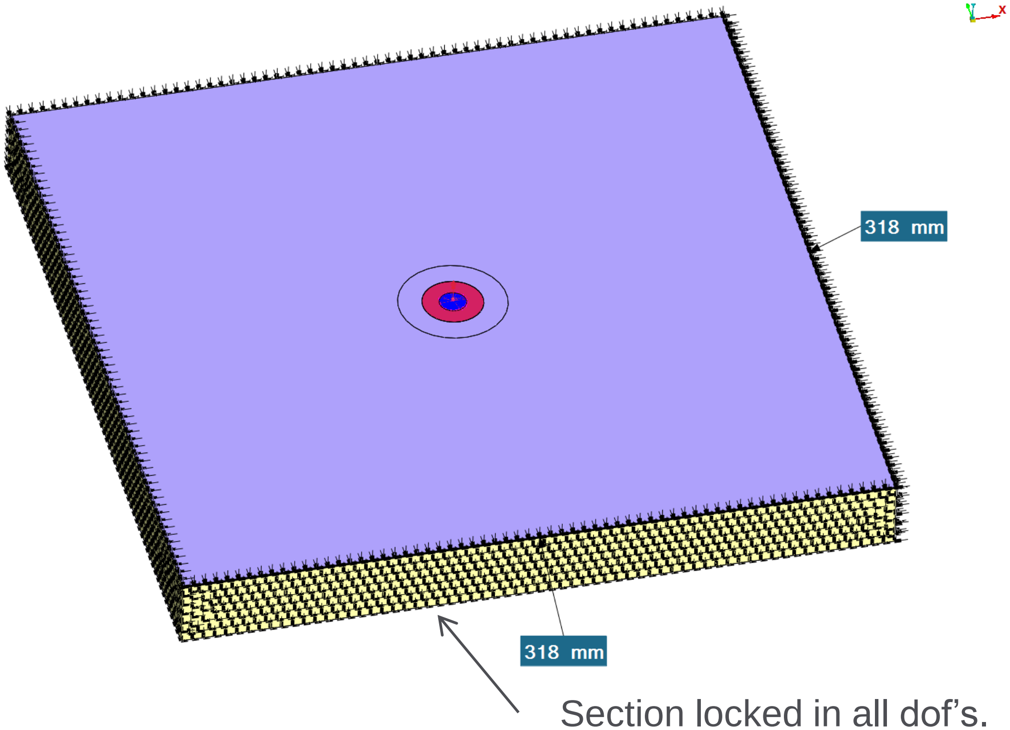


FE-model

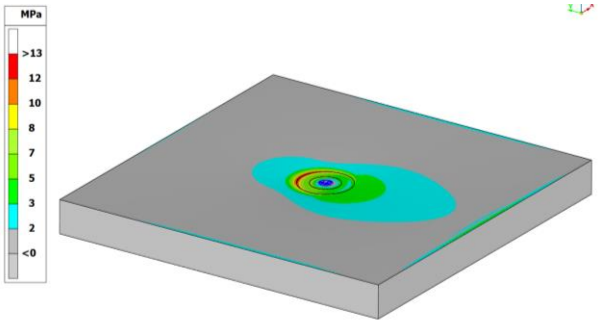
Local model of insert

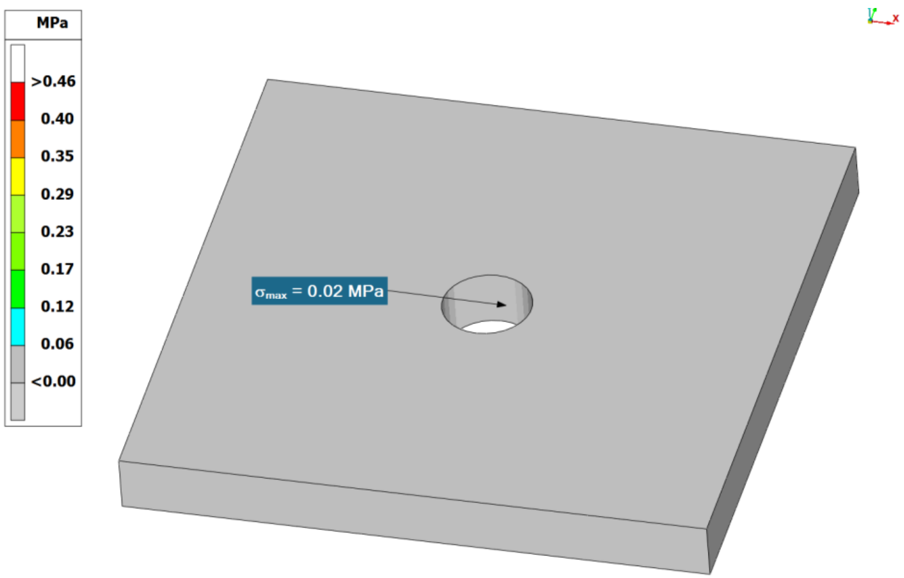
- Loads taken from the most loaded cbar in the global FE-model (EID921923).
- Loads applied to cbar in local FE-model.

N1	N2	N3	SID	F	TYPE
0.	0.	1.	1	-171.9	FORCE
0.	1.	0.	1	548.	FORCE
1.	0.	0.	1	-20.9	FORCE
0.	0.	1.	1	-1000.	MOMENT
1.	0.	0.	1	5600.	MOMENT
0.	1.	0.	1	1000.	MOMENT
0.	0.	1.	2	-856.8	FORCE
0.	1.	0.	2	4585.5	FORCE
1.	0.	0.	2	-177.9	FORCE
0.	0.	1.	2	-6900.	MOMENT
1.	0.	0.	2	16200.	MOMENT
0.	1.	0.	2	1600.	MOMENT
0.	0.	1.	3	267.6	FORCE
0.	1.	0.	3	486.3	FORCE
1.	0.	0.	3	3461.6	FORCE
0.	0.	1.	3	102400.	MOMENT
1.	0.	0.	3	-7600.	MOMENT
0.	1.	0.	3	3300.	MOMENT

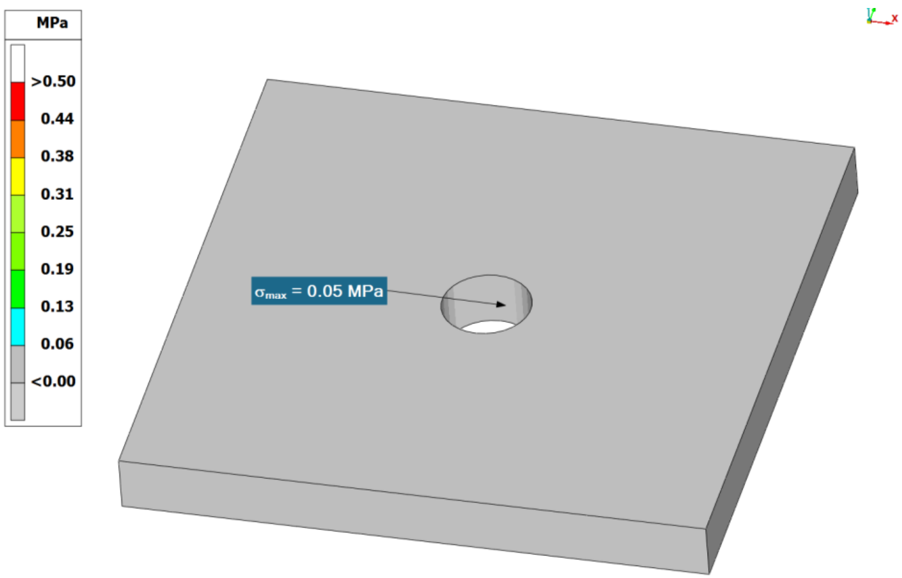


Results, core
-X g vertical





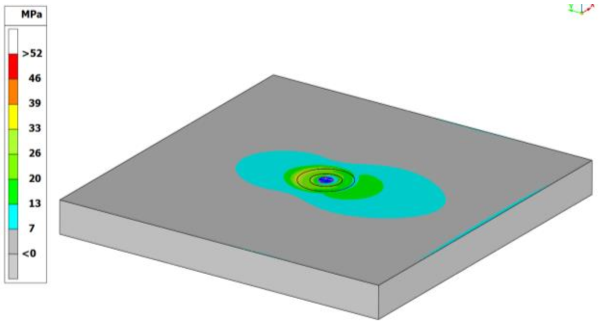
Max shear stress

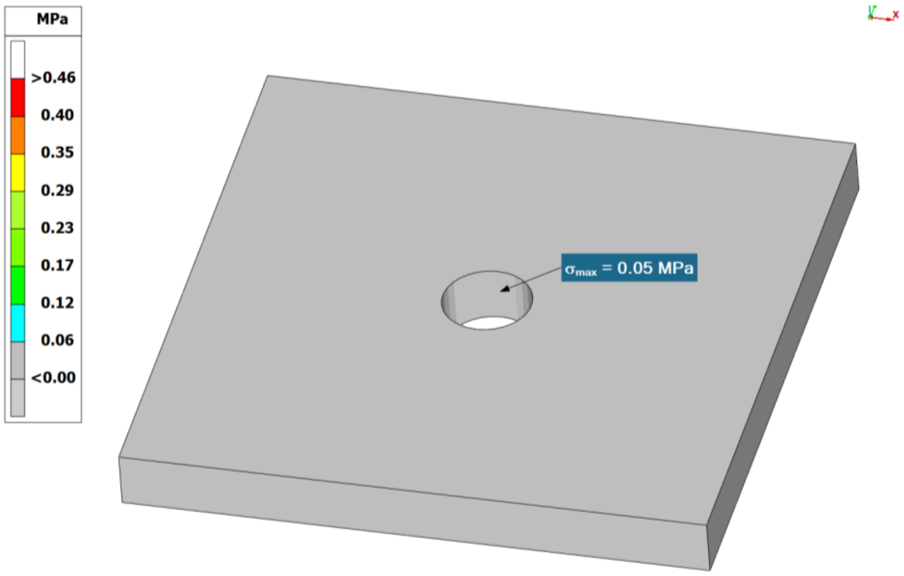


Max von Mises stress

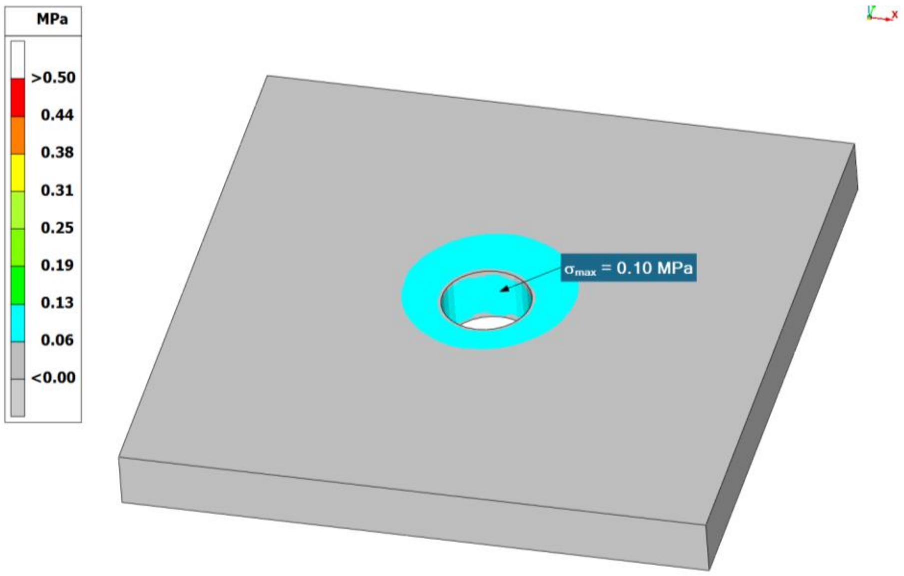
Results, core

0.5X g lateral





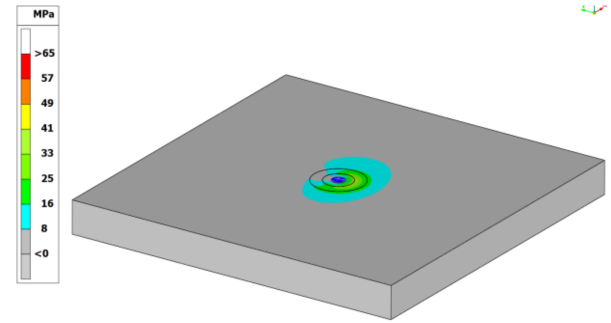
Max shear stress

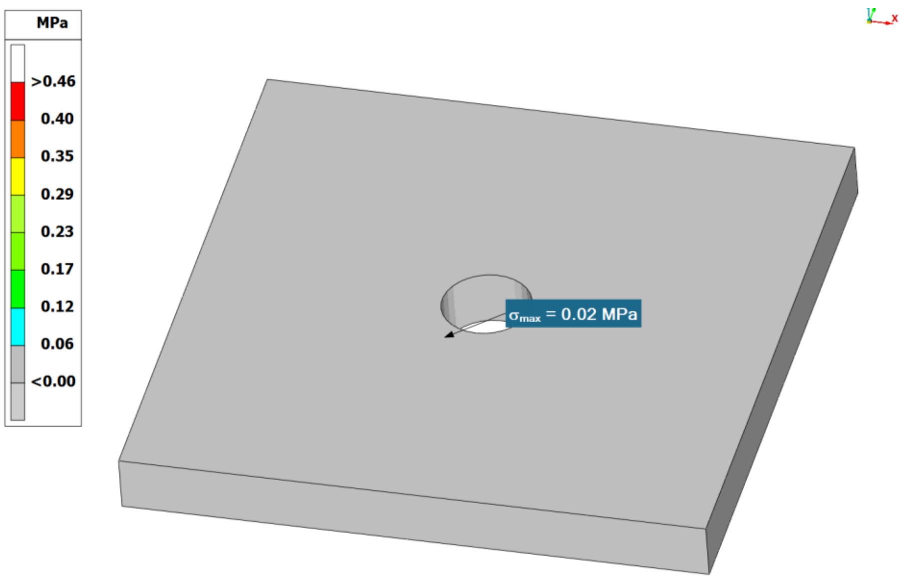


Max von Mises stress

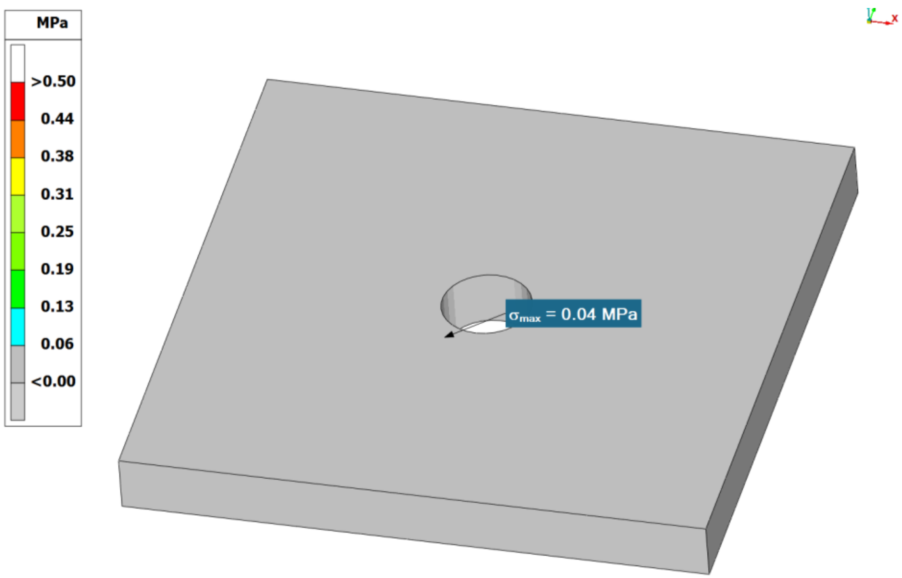
Results, core

0.5X g longitudinal





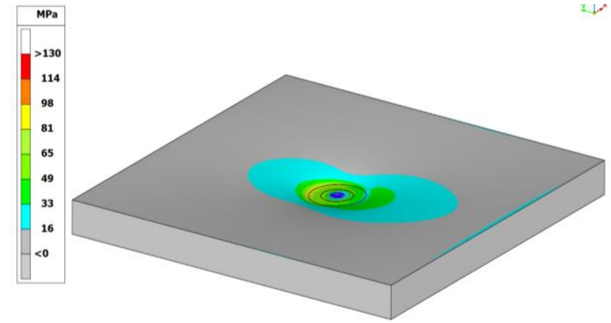
Max shear stress

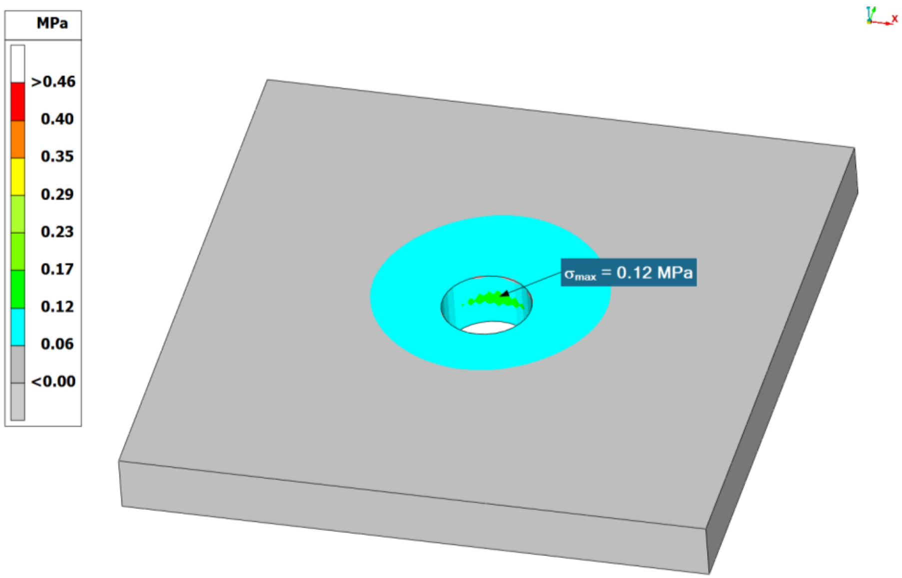


Max von Mises stress

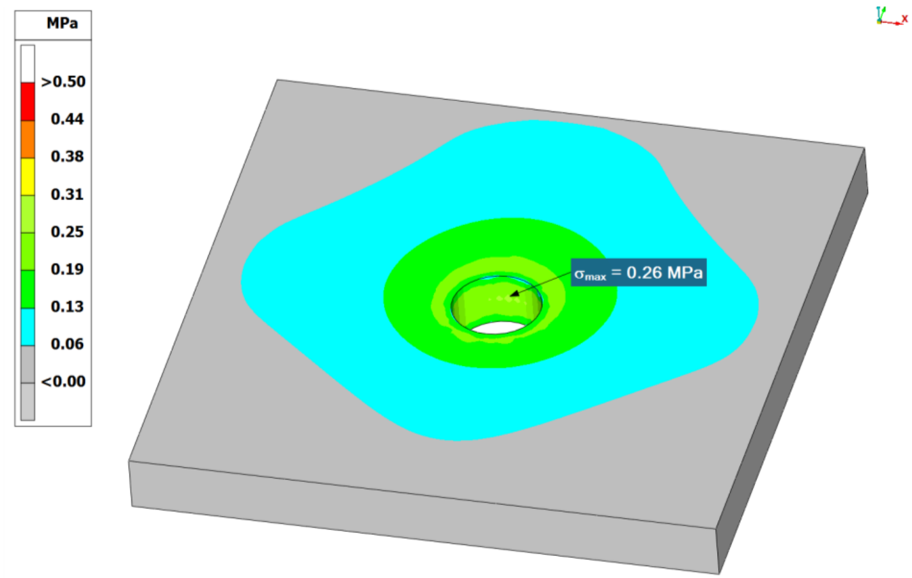
Results, core

1.3X g lateral





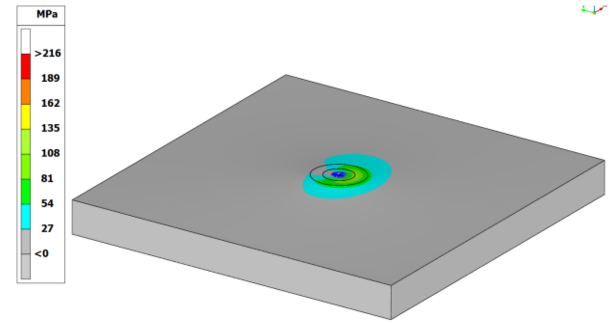
Max shear stress

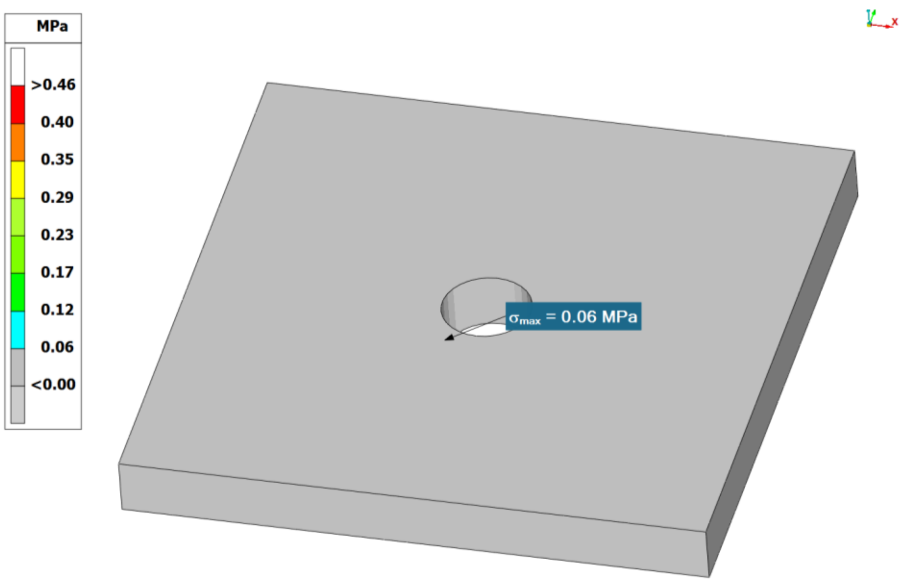


Max von Mises stress

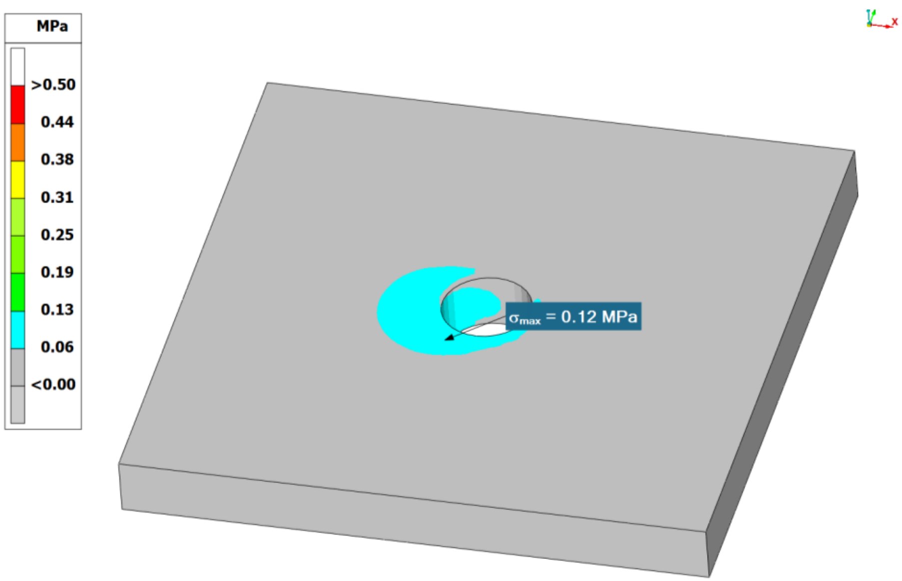
Results, core

1.7X g longitudinal



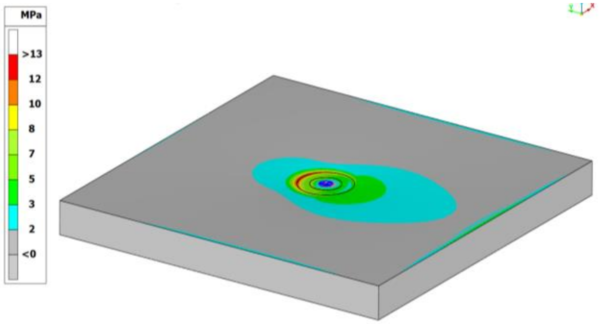


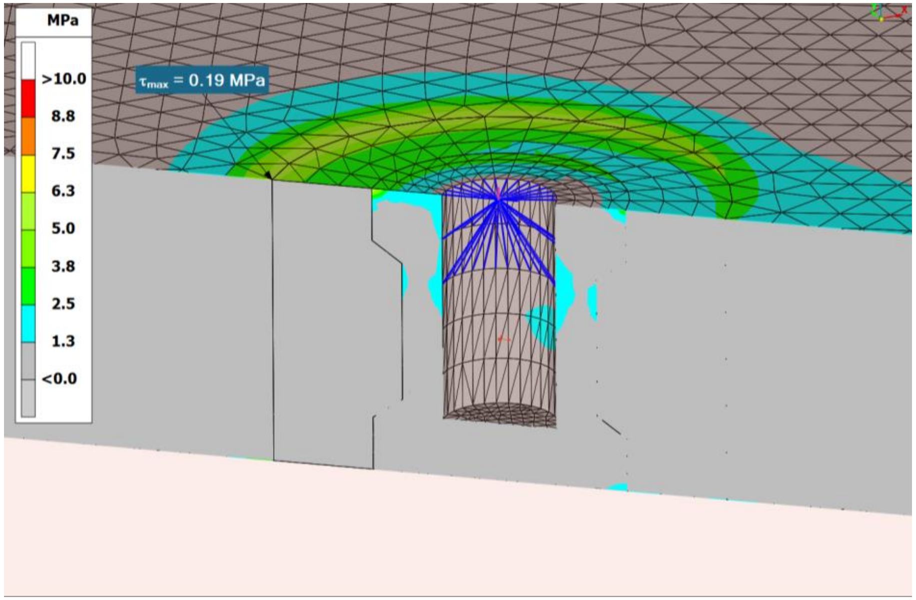
Max shear stress



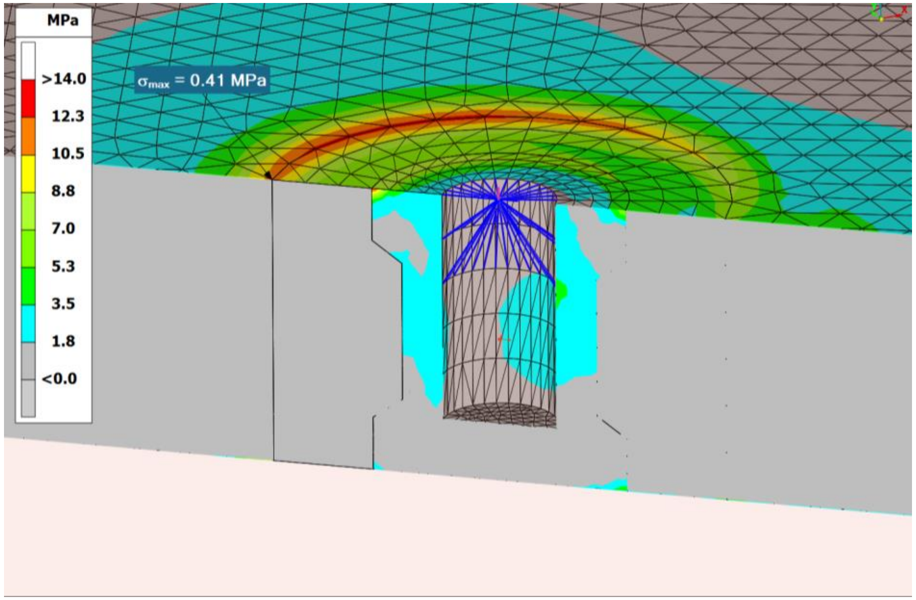
Max von Mises stress

Results, potting
-X g vertical



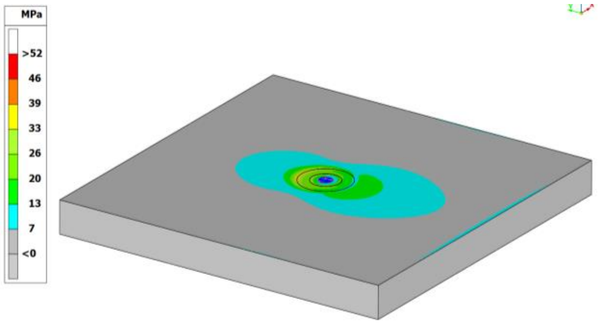


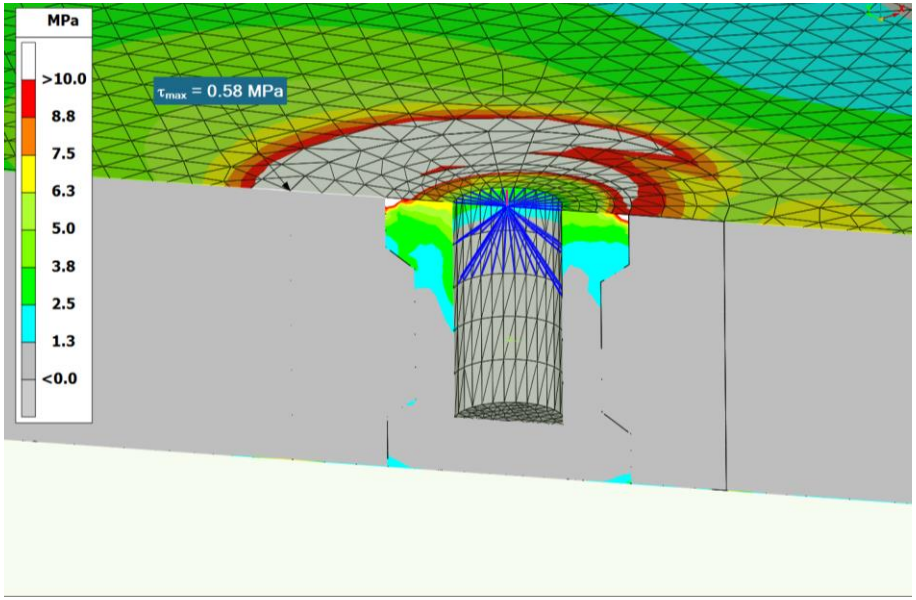
Max shear stress



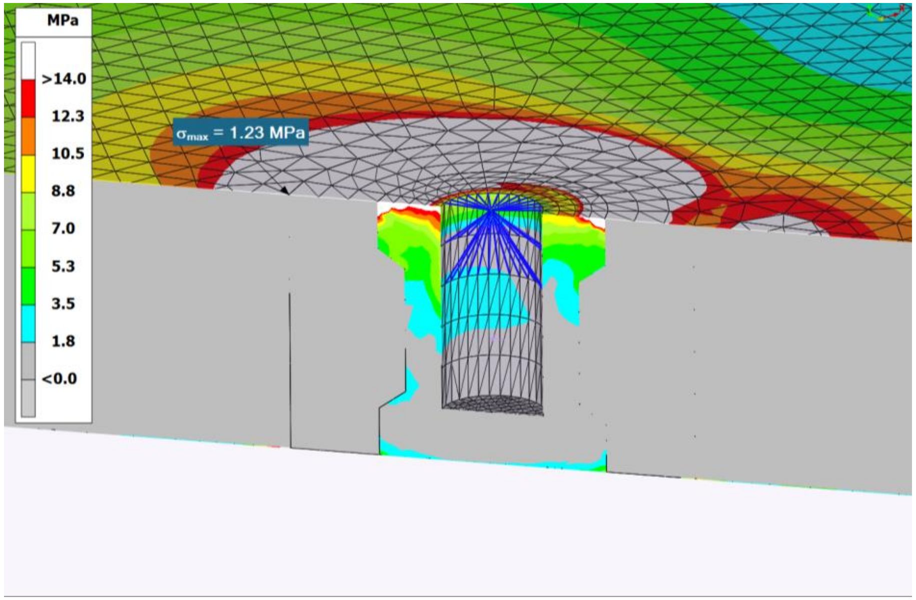
Max von Mises stress

Results, potting
0.5X g lateral





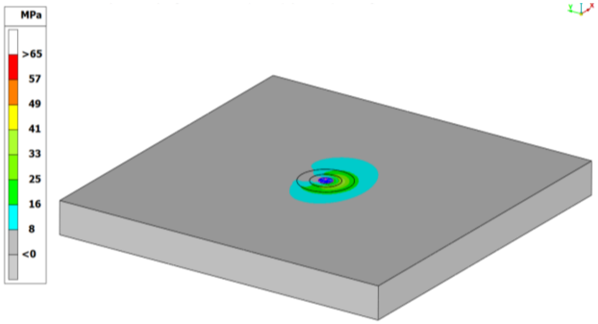
Max shear stress

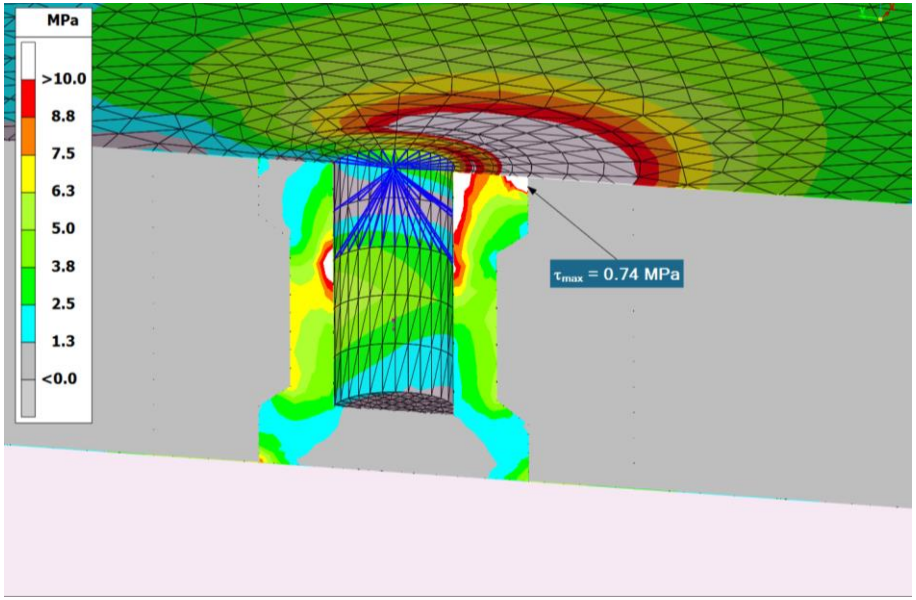


Max von Mises stress

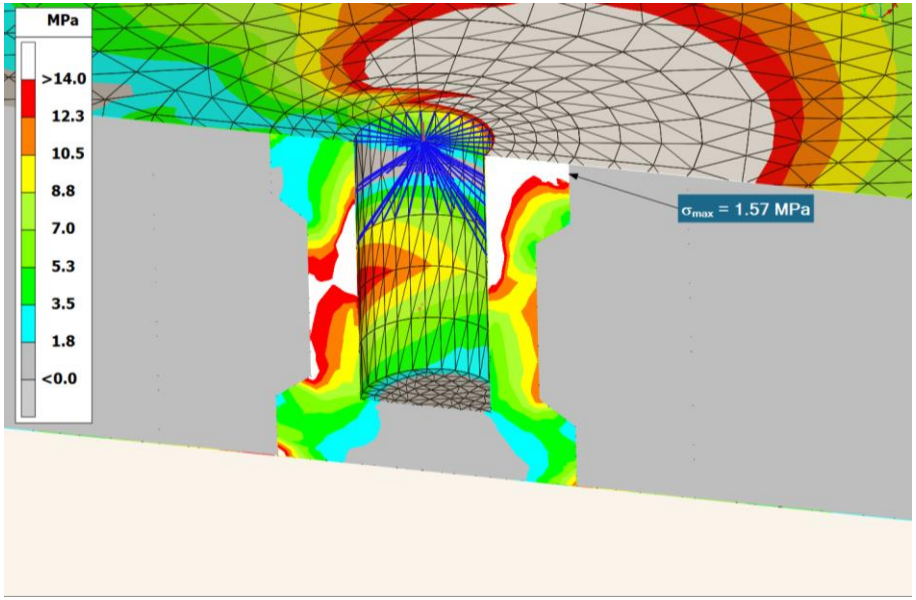
Results, potting

0.5X g longitudinal





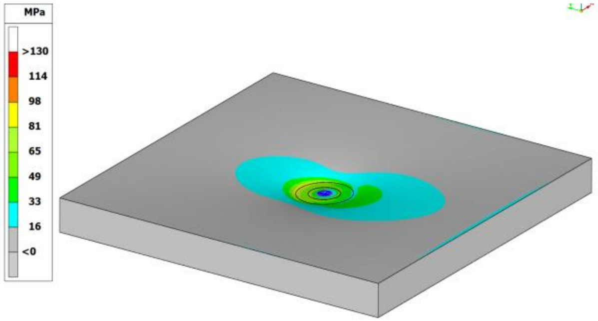
Max shear stress

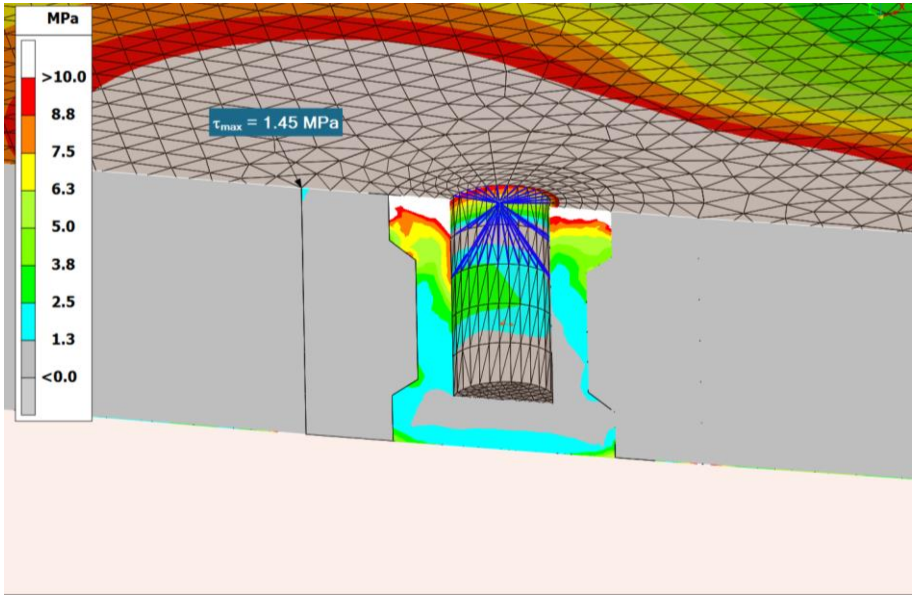


Max von Mises stress

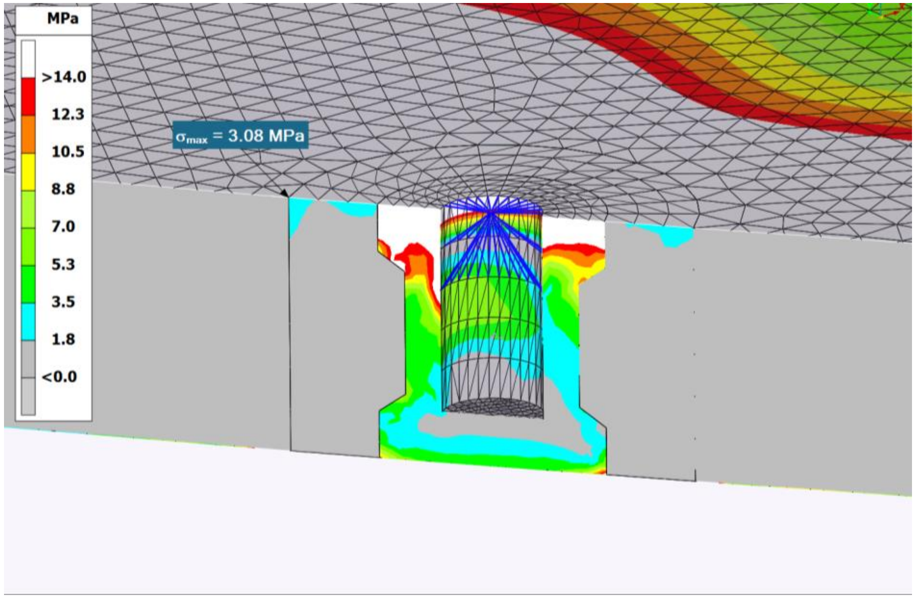
Results, potting

1.3X g lateral





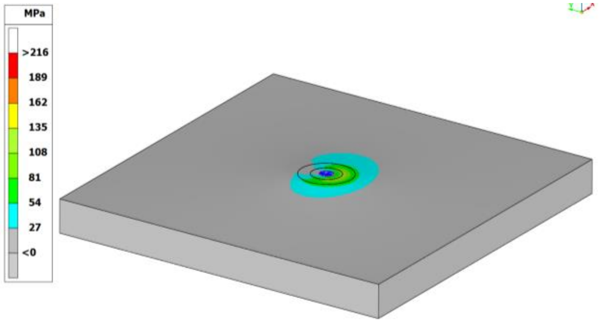
Max shear stress

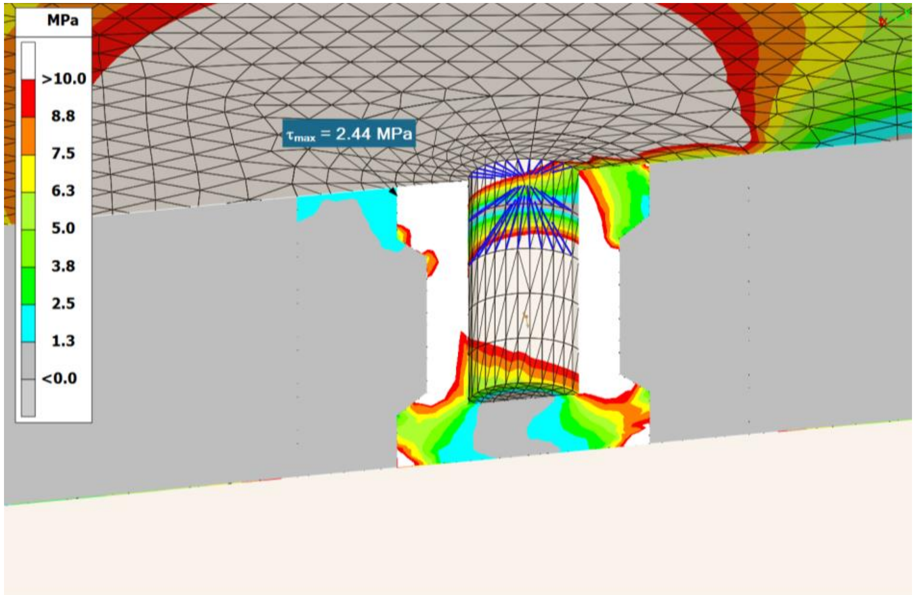


Max von Mises stress

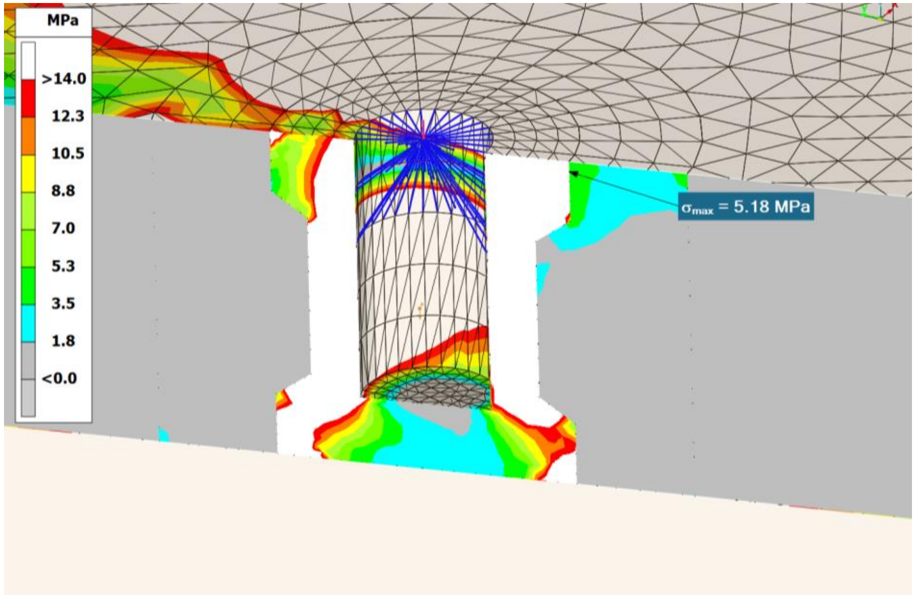
Results, potting

1.7X g longitudinal





Max shear stress



Max von Mises stress

Conclusions

- Conclusions:
  - Stress levels are below permissible limit in all load cases.
  - Fatigue evaluation has not been performed due to insufficient material data.
  - Evaluate smaller potting in future design loops to reduce weight of insert further.

Appendix D – Technical Readiness Level

TRL stands for technical readiness level. In this project the scale developed by NASA is used [12]. Below is a quote taken directly from NASA's website and it describes the definition of TRL.

"Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest."

This project aims to develop a concept that reaches TRL4. Below is again a quote from NASA's website that describes all the levels in the TRL system.

"When a technology is at TRL 1, scientific research is beginning and those results are being translated into future research and development. TRL 2 occurs once the basic principles have been studied and practical applications can be applied to those initial findings. TRL 2 technology is very speculative, as there is little to no experimental proof of concept for the technology.

When active research and design begin, a technology is elevated to TRL 3. Generally both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept model is constructed.

Once the proof-of-concept technology is ready, the technology advances to TRL 4. During TRL 4, multiple component pieces are tested with one another. TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model.

TRL 7 technology requires that the working model or prototype be demonstrated in a space environment. TRL 8 technology has been tested and "flight qualified" and it's ready for implementation into an already existing technology or technology system. Once a technology has been "flight proven" during a successful mission, it can be called TRL 9."