High-pressure frame design for gasketed plate heat exchangers

Enhanced engineering design for manufacturability, distribution, and maintenance

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DIVISION OF INNOVATION | DEPARTMENT OF DESIGN SCIENCES
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Abstract

Alfa Laval is the market leader within gasketed plate heat exchanger (GPHE) technology. To remain the leader of the GPHE sector, Alfa Laval regularly performs design studies to investigate new solutions and find inspiration for possible functions. Alfa Laval always work to improve their products, regarding many aspects, such as manufacturability, distribution, and maintenance as well as sustainability.

The objective of this thesis was to perform a design study of large high-pressure GPHE frame designs to enhance manufacturability, distribution, and maintenance. The output of the project was intended to give new design perspectives for Alfa Laval's development projects. The project process included interviewing stakeholders in Alfa Laval's organization, problem decomposition, concept generation, concept selection and calculation analysis. The method applied in the project was mainly based on the methods outlined by Ulrich and Eppinger in the book *Product Design and Development*.

The project resulted in four main concepts. The concepts incorporated wire ropes, beams, modular designs, and external supports. The most promising concept incorporated wire ropes substituting large tightening bolts to simplify maintenance processes. The project concluded that the current frame, in many ways, already is optimized, especially regarding a cost-efficient manufacturing process. While the proposed new concepts offer advantages in some areas, they also introduce new challenges. Therefore, future work should first analyze whether any of the concepts contribute to an overall improvement of the product and then refine the most promising concepts on a component level.

Keywords: heat exchanger, gasketed plate heat exchanger, high-pressure, large heat exchangers, design study

Sammanfattning

Alfa Laval är marknadsledande på teknologin packningsförsedda plattvärmeväxlare (GPHE). För att behålla sin position som marknadsledare inom GPHE-sektorn så utför Alfa Laval regelbundet designstudier. Designstudierna utförs för att undersöka nya lösningar och få inspiration till nya möjliga funktioner. Alfa Laval strävar alltid efter att förbättra sina produkter med avseende på många faktorer, exempelvis tillverkningsbarhet, distribution, och underhåll liksom hållbarhet.

Målet med detta examensarbete var att utföra en konceptstudie av stora högtrycks-GPHE stativdesigner för att förbättra tillverkning, distribution och underhåll. Projektets resultat var tänkt att ge nya designperspektiv för Alfa Lavals utvecklingsprojekt. Projektprocessen inkluderade att intervjua intressenter inom Alfa Lavals organisation, problemnedbrytning, konceptgenerering, konceptval och beräkningsanalys. Metoden som tillämpades i projektet baseras på metoderna som beskrivs av Ulrich och Eppinger i boken *Product Design and Development.*

Projeketet resulterade i fyra huvudkoncept. Koncepten inkluderar vajrar, balkar, modulära designer, och externa stöd. I stället för stora dragbultar så använde det mest lovande konceptet vajrar för att förenkla serviceprocesserna. Slutsatsen att den befintliga stativdesignen i många avseenden redan är optimerad, särskilt vad gäller kostnadseffektivitet under tillverkningsprocessen, kunde dras från detta projekt. Medan de resulterande fyra huvudkoncepten erbjuder många fördelar så introducerar de också nya utmaningar. Detta innebär att framtida utvecklingsarbete först bör analysera huruvida något av koncepten kan bidra till en övergripande förbättring av produkten och sedan förfina de mest lovande koncepten på komponentnivå.

Nyckelord: värmeväxlare, packningsförsedd plattvärmeväxlare, högtryck, stora värmeväxlare, designstudie

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Abbreviations

ALS	Alfa Laval standard
ASME	American society of mechanical engineers
BPVC	boiler and pressure vessel code
CFRP	carbon fiber reinforced plastic
CB	carrying bar
CAD	computer-aided design
FEA	finite element analysis
FLC	fully locked coil ropes
FP	frame plate
GB	guiding bar
GPHE	gasketed plate heat exchanger
HVAC	heating, ventilation, and air conditioning
NPD	new product development
OSS	spiral strand ropes
PED	Pressure equipment directive
PHE	plate heat exchanger
PP	pressure plate
SWR	Steel wire rope

1. Introduction

This chapter briefly describes Alfa Laval as a company and the function of a gasketed plate heat exchanger. The background context and main objective of this master thesis is presented. Lastly, the outline of the thesis is stated.

1.1 The company Alfa Laval

Alfa Laval AB is the parent company of Alfa Laval Technologies AB and is an international company with headquarters in Lund. (Alfa Laval, 2022, p.108) The company was founded in 1883 by Gustav de Laval and was at this time selling centrifugal separators for cream. Since 1883, the company has diversified into several new business areas and industries. In the year of 1938, Alfa Laval introduced their first heat exchanger, with the development and production located in Lund. (Alfa Laval, 2023c) Alfa Laval is today world leading in the areas of heat transfer, separation and fluid handling and has three different business divisions: “Energy”, “Food & Water” and “Marine”. Even though their customers mainly come from the energy, food and marine industries, Alfa Laval’s products can be found in many other different businesses around the world, too. (Alfa Laval, 2022, p.3)

1.2 Alfa Laval heat exchangers

The concept of a heat exchanger is to transfer heat between one fluid or gas to another one. Alfa Laval has developed plate heat exchanger (PHE) technology for over 90 years. To offer the most efficient and reliable heat transfer, the technology needs to be adapted to the customers’ specific conditions. (Alfa Laval, 2023a) The heat exchangers produced by Alfa Laval are designed to meet the highest expectations within energy efficiency, compactness, and reliable performance. An Alfa Laval gasketed plate heat exchanger (GPHE) consists of the components: a frame as well as multiple channel plates and gaskets. The frame can be further divided into sub-components (Figure 1.1).

The channel plates are the heat-transfer surface in the GPHE, and the gaskets are the sealing solution between the channel plates that guide the process medium in the plates' channels. The frame keeps the channel plates together and acts as the interface toward the surrounding environment. The frame design is designed with the goal of lowest cost of ownership, i.e., reduced maintenance cost, reduced spare part cost, staff safety, and time savings. The frame should ensure that the heat exchangers can be easy and quick to open, to enable inspection and gasket replacement by one man with standard tools. (Alfa Laval, n.d.) The channel plates and gaskets of a GPHE make up a plate package. The plate package is mounted between a frame plate (FP) and a pressure plate (PP), and the plate package is tightened using several tightening bolts. The channel plates and the PP are suspended on a carrying bar (CB) and a guiding bar (GB) beneath the channel plates ensure that the plate package remains in its right position. The CB and GB are fixed using the FP as well as an additional support column placed on the opposite side of the FP (Figure 1.1). (Alfa Laval, 2023b)

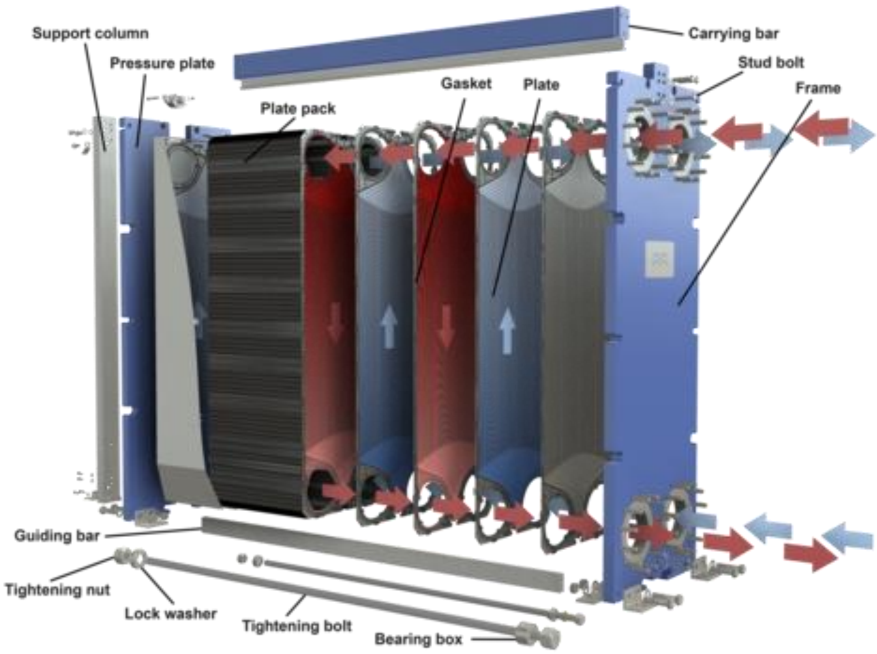

Figure 1.1 Frame components of an Alfa Laval GPHE (Alfa Laval, 2023b).

1.3 Alfa Laval large high-pressure GPHE

Large GPHEs are used in almost all kinds of industries. The large GPHE can be combined with a range of different plates and gaskets. The size of one of Alfa Laval's current large GPHEs (Figure 1.2) is 3540 mm in height, 1430 mm in width and the length depends on the plate package but is approximately 4000 mm. Today, the highest allowed design pressure and temperature for a non-customized large GPHE is ~25 bar and 250 degrees Celsius. (Alfa Laval, n.d.c) The size dimensions, described in this section, will act as reference values during this master thesis to not disclose the true size of the actual Alfa Laval GPHE that will be used for high-pressure applications. The large high-pressure GPHEs use much material and has a heavy weight. Therefore, a new large high-pressure GPHE design could possibly reduce the material usage and become better from an environmental perspective.

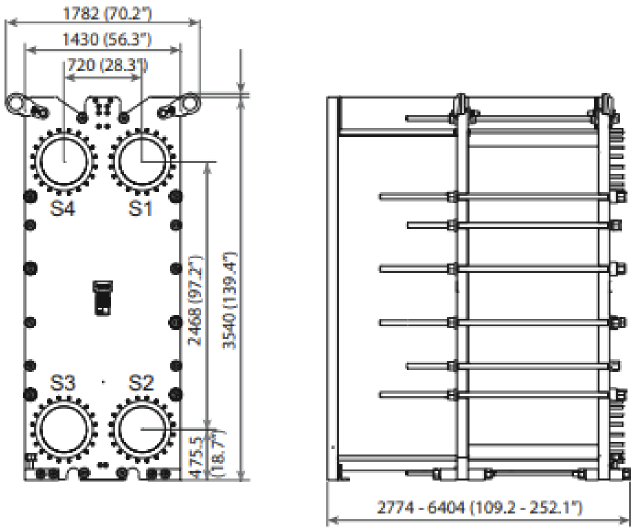

Figure 1.2 Technical drawing of a standard large GPHE (Alfa Laval, n.d.c).

1.4 Problem description

Alfa Laval uses a GPHE design that has been refined for almost 90 years. The GPHE design works very well and is optimized for today's needs. However, to be the leader within GPHE technology, new concepts and ideas must be regularly investigated to inspire new solutions and functions as well as to find new solutions to new trends within the field. Alfa Laval was interested in getting a student perspective, less biased from today's GPHE design compared to Alfa Laval's own development engineers, to give their input on their GPHE design and possible future designs. A topic of interest was to look on frame designs to enhance the activities of manufacturability, distribution and maintenance of the GPHEs and how this could contribute to make their GPHE design more sustainable.

1.5 Objective

To provide Alfa Laval new inspiration for frame design solutions, the objective of this thesis is to perform a design study of large high-pressure GPHE frames to find new solutions that have less environmental impact. The investigation takes into account manufacturability of the frame, distribution of the GPHE, and maintenance of the GPHE.

1.6 Delimitations

This master thesis will not focus on any individual component rather the whole design of the GPHE. The final design(s) of this master thesis will not be fully developed, instead the objective is to have one or a few well defined frame design concepts that can be further analyzed on a component level. For this project, the design of the plate package will remain unchanged and consist of gasketed channel plates.

1.7 Confidential information

Data have been intentionally removed from the report due to confidentiality. The removed data include information about operational parameters, component dimensions, and product details. Values and parameters marked with an "*" have been modified and do not reflect the actual values.

1.8 Brief about the selected method

The methods selected for this project is based on the Double Diamond framework and the methods outlined by Ulrich and Eppinger in the book *Product Design and*

Development. The approach of the project was to first gather the needs and requirements by having interviews with stakeholders at Alfa Laval. The concept generation started by reviewing similar solutions by searching internally and externally. The concept generation was made by a problem decomposition based on the key needs and thereafter solutions were generated for each sub-problem. The solutions of the sub-problems were combined into frame concepts. By having a design review and discussions with stakeholders, a decision was made to further refine and analyze some of the frame concepts. The dimensions of the selected concepts were analyzed by using traditional solid mechanics. Computer-Aided Design (CAD) models were made of the concepts. A new design review was held with relevant Alfa Laval stakeholders to discuss the refined designs. The design that was deemed the most interesting was further analyzed using Finite Element Analysis (FEA) simulations. Lastly, the details of the final concept were further developed, and an interview was held with the regulatory expert at Alfa Laval.

1.9 Thesis outline

The structure of this thesis is as follows: Chapter 1 introduces Alfa Laval and GPHEs and Chapter 2 presents the relevant theoretical background for the thesis. Chapter 3 describes the method and Chapters 4-6 include a stakeholder analysis, identification of needs and formulation of product specifications for the project. Then, Chapters 7-14 describe the concept generation, concept refinement, and concept selection. In Chapter 15, the concepts are evaluated by a pressure vessel expert and a final concept is presented in Chapter 16. Finally, Chapter 17 concludes the thesis with a discussion regarding the generated concepts, limitations of the study, sustainability aspects, and future avenues of development for Alfa Laval.

2. Theory

This chapter covers Alfa Laval's GPHE product architecture, strengths and weaknesses of GPHEs as well as distinguishing characteristics of the GPHE design. It also provides information on pressure vessel standards, GPHE assembly, and maintenance.

2.1 Different kinds of heat exchangers

There are many kinds of heat exchangers (Figure 2.1). Normally, there are no external heat and work interactions in heat exchangers. The most common processes are heating or cooling of a specific fluid stream and to evaporate or condensing a specific fluid stream. The most common applications are to recover or reject heat, to sterilize, and to crystallize the process-fluid. In many heat exchangers, the process fluids are separated by a separating wall which results in that the fluids do not mix. The heat transfer surface is the surface which is in direct contact with the process-fluids, and it is through these surfaces that heat is transferred by conduction. (Shah and Sekulic, 2003, p.1-2)

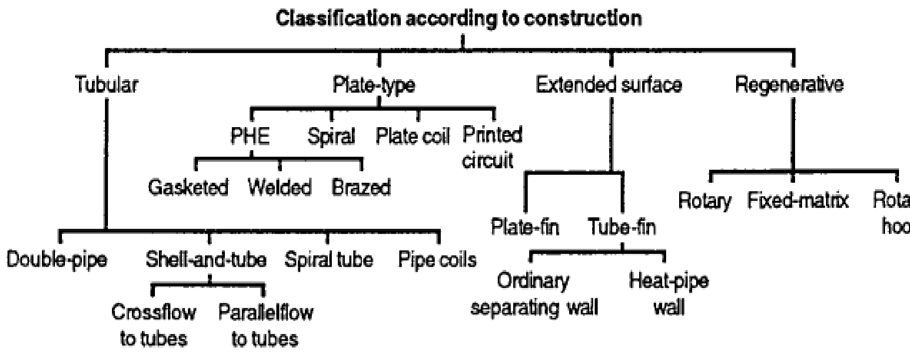

Figure 2.1 Heat exchanger classification (Shah and Sekulic, 2003, p.2).

PHEs are usually built using thin plates that work as the surface area for the process fluid. Generally, PHEs cannot be used for high pressures, temperatures, or large temperature and pressure differences. PHEs are categorized into welded, brazed. and gasketed PHEs, which describes the type of interface between the individual channel plates. The GPHE (Figure 2.2), uses elastomeric molded gaskets to seal between the channel plates (Shah and Sekulic, 2003, p.22) and in the welded PHE the plates are instead welded together. One of the limitations of GPHEs is the use of gaskets as gaskets limit the operating temperatures and pressures, as well as restrict the use of process mediums, to those that are compatible with the gasket material. Due to their absence of gaskets, welded and brazed PHEs can deal with other mediums, temperatures, and pressures. However, a limitation of the welded and brazed PHEs is their low disassembly flexibility. (Shah and Sekulic, 2003)

Figure 2.2. Alfa Laval GPHE. (Alfa Laval, n.d.j)

Shell-and-tube heat exchangers is a type of tubular heat exchanger that is usually built by mounting tubes in a cylindrical shell (Figure 2.3). Tubular heat exchangers are widely used in high-pressure applications. (Shah and Sekulic, 2003, p.14-15)

Figure 2.3 Alfa Laval shell-and-tube heat exchanger (Alfa Laval, n.d.k).

2.1.1 **Why to choose a GPHE instead of a shell-and-tube heat exchanger?**

GPHEs are up to five times more energy efficient than shell-and-tube heat exchangers, thus allowing the end customer to save energy. The GPHE also occupies 1/10 of the storage space compared to a shell-and-tube heat exchanger (Figure 2.4), which leads to lower cost of transportation and installation. The GPHEs are easier to service, which is a result of the channel plates being easy to access by removing the tightening bolts and push back the PP. The heat exchanger capacity of a GPHE can be changed to new demands by adding or removing channel plates while still using the same frame. The total weight of a GPHE is less than 1/16 of a shell-and-tube heat exchanger, which results in cost savings in shipping, handling, and installation. In addition, GPHEs can both be assembled and disassembled at customers' sites. (Alfa Laval, 2023d)

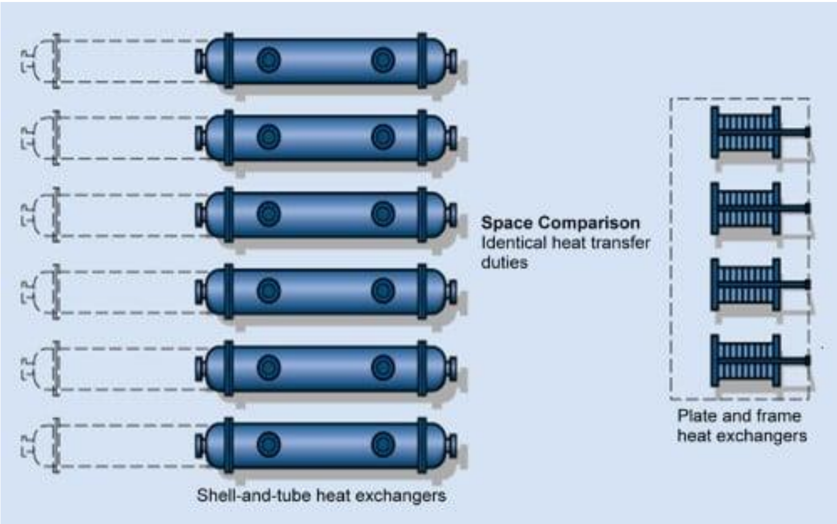

Figure 2.4 Space comparison of shell-and-tube heat exchanger and GPHEs (Alfa Laval, 2023d).

2.2 Key terminology

The following paragraphs will explain five important terms: A-measurement, closure of the GPHE, opening of the GPHE, design pressure, and test pressure.

2.2.1 **A-measurement**

The A-measurement is the dimension of the compressed plate package (Figure 2.5) and the dimension between the FP and PP during operations. (Alfa Laval, n.d.l)

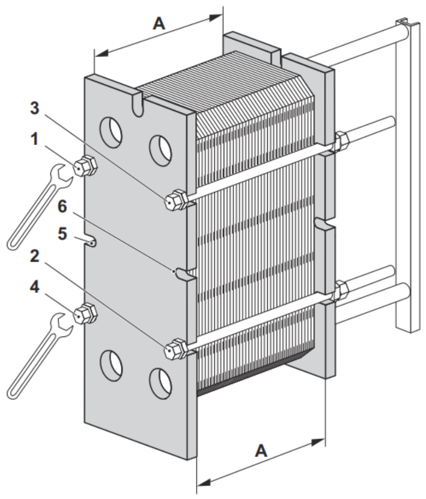

Figure 2.5 A-measurement (Alfa Laval, n.d.l).

2.2.2 **Closure of the GPHE**

The closure of the GPHE refers to when the plate package is compressed to the specified A-measurement by tightening the tightening bolts (see number 1, 2, 3, and 4 in Figure 2.5).

2.2.3 **Opening of the GPHE**

The opening of the GPHE occurs when the tightening bolts (see number 1, 2, 3, and 4 in Figure 2.5) are loosened and removed, allowing the plate package to expand, thus enabling removal of the channel plates.

2.2.4 **Design pressure**

The design pressure is the highest operational pressure during end-user use.

2.2.5 **Test pressure**

To obtain regulatory approval under pressure vessel standards, the GPHE must withstand the test pressure, which exceeds the design pressure.

2.3 Alfa Laval's existing GPHE design

Alfa Laval's GPHE range is based on a general product concept with the three main components: frame, gaskets, and channel plates. The frame incorporates a range of different sub-components that are customized to be suitable to be used for a variety of pressures, mediums, and operational environments.

2.3.1 **Plate package**

The GPHE is characterized by the plate package which consists of several channel plates with gaskets (Figure 2.6). The plate package is placed in between the FP and PP (Figure 2.7). (Alfa Laval, 2023e)

Figure 2.6 Plate package (Alfa Laval, 2023f).

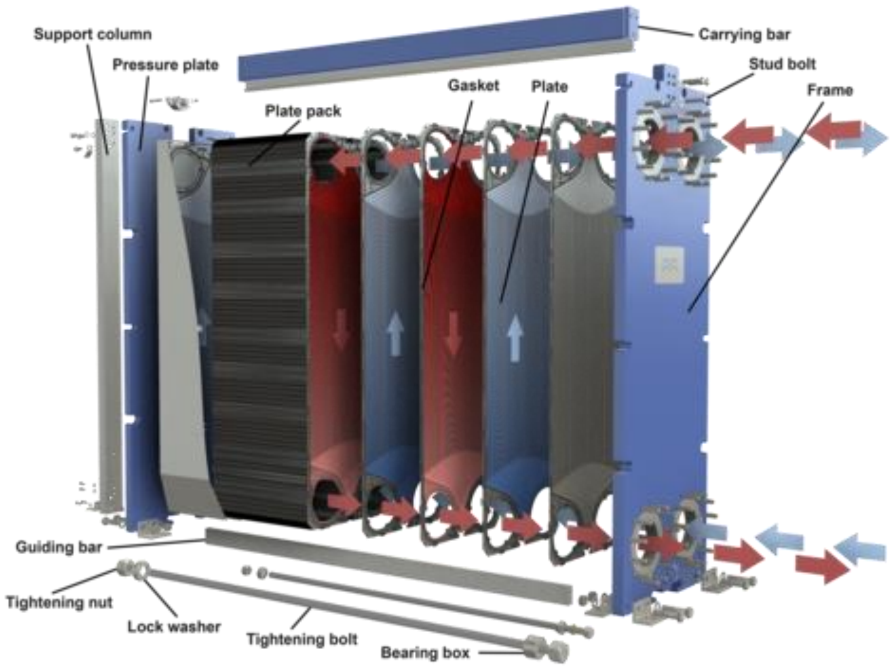

Figure 2.7 GPHE components (Alfa Laval, 2023e).

2.3.1.1 Channel plate

The channel plate is the heat transfer surface between the mediums in a GPHE. The advantage of using channel plates is the large surface area where heat transfer can occur. The pattern on the channel plates is designed to maximize the heat-transfer efficiency of the GPHE (Figure 2.8). (Alfa Laval, 2023f)

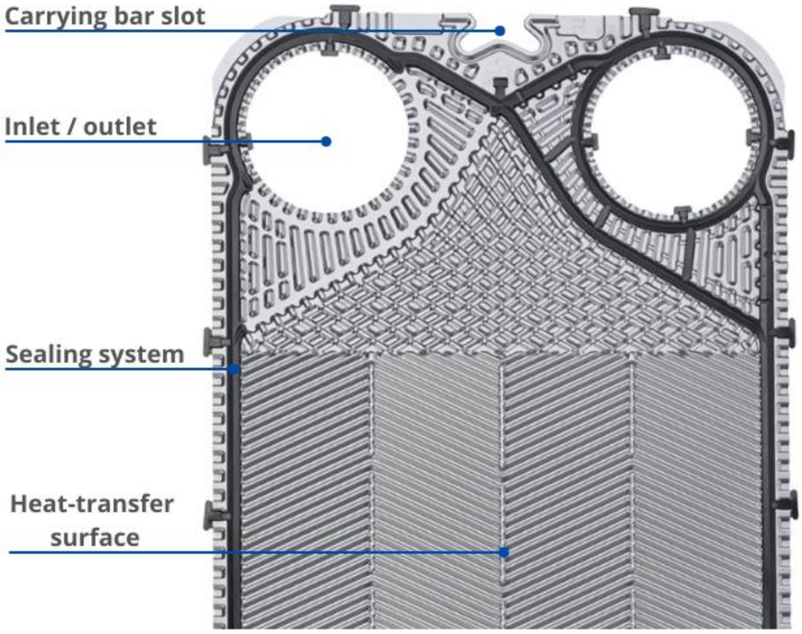

Figure 2.8 Channel plate with gasket, adapted from (Alfa Laval, n.d.m)

2.3.1.2 Gaskets

The most common type of gaskets used in GPHEs is elastomeric gaskets (Figure 2.9). By placing the gaskets on the channel plates, the gaskets act as seals between the channel plates and prevent leakage of process medium. (Rai & Bhanuprakash, 2021, p.15).

Figure 2.9 Elastomeric gasket (Alfa Laval, n.d.b).

2.3.2 Frame sub-components

This section briefly describes the main sub-components of the frame. The information in the sub-sections of section 2.3.2 is based on information from Alfa Laval's internal database.

2.3.2.1 FP and PP

The main tasks of the FP and PP are to hold the plate package together and to be the interface to which many of the other components are attached. Pipes, feet, stud bolts, tightening bolts, plate package, CB and GB are often attached to the FP. Both the FP and PP are made of painted carbon steel (Figure 2.10). The FP and PP experience large forces. The largest deflection of today's FP and PP occurs in the center of the plates where no bolts are placed. Since the FP and PP are classified as pressure vessel components, they are designed to fulfill the requirements of various pressure vessel standards. (Alfa Laval internal database)

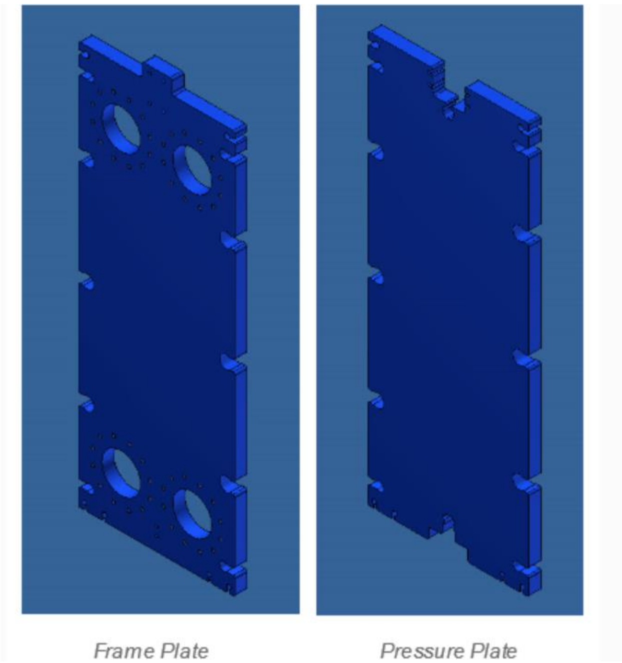

Figure 2.10 FP and PP (Alfa Laval internal database).

2.3.2.2 Tightening bolts

The tightening bolts (Figure 2.11) have two main functions. The first function is to compress the plate package to A-measurement. The second function is to withstand the design pressure of the GPHE. Normally, the plate package is compressed to

A-measurement with four tightening bolts and thereafter the remaining tightening bolts are attached. The tightening bolts are used in combination with bearing boxes, wearing washers, and nuts. The bearing boxes and wearing washers are used to reduce friction between bolthead and FP when the plate package is compressed to A-measurement. (Alfa Laval internal database)

Figure 2.11 Tightening bolt (Alfa Laval internal database).

2.3.2.3 Feet

The feet are used to give the GPHEs stability. The feet are connected to the FP (and sometimes also the PP depending on the weight and size of the GPHE) and then bolted to the foundation.

2.3.2.4 Bars

The frame includes two bars: the upper bar, CB, and the lower bar, GB (Figure 2.12). The PP and the plate package are mounted on the CB. The main function of the GB is to secure a correct placement of the channel plates in the GPHE. The channel plates and the PP move along the bars during assembly and disassembly of the GPHE. The two bars are connected to the FP and the support column. (Alfa Laval internal database)

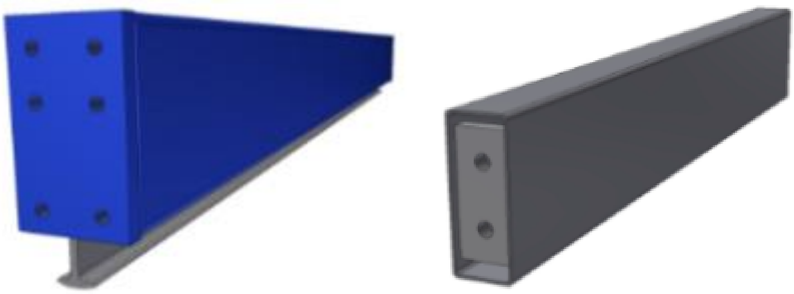

Figure 2.12 CB and GB (Alfa Laval internal database).

2.3.2.5 Support column

The support column (Figure 2.13) is the rear connection point of the CB and GB. The support column is attached to the ground. (Alfa Laval internal database)

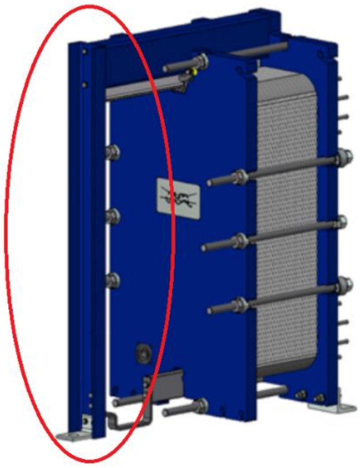

Figure 2.13 Support column (Alfa Laval internal database).

2.3.2.6 Pressure plate holder

The pressure plate holder is a component that enables the PP to move easily along the CB, which is necessary during closing and opening of the GPHE. The pressure plate holder includes a wheel, see "roller assembly" in Figure 2.14. (Alfa Laval internal database)

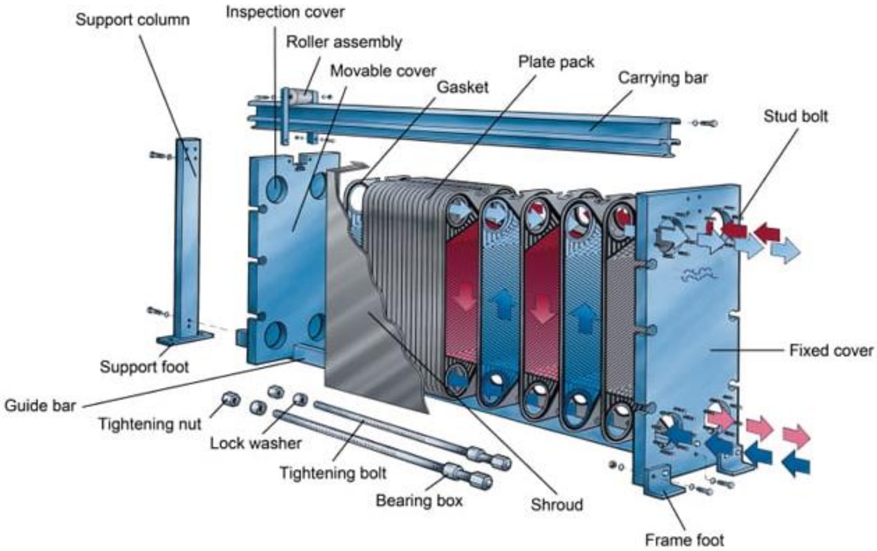

Figure 2.14 GPHE components (Alfa Laval, 2023g).

2.4 Pressure vessel standards

The three main standards that are necessary to take into consideration when designing a new GPHE at Alfa Laval are American Society of Mechanical Engineers (ASME), Pressure Equipment Directive (PED) and Alfa Laval Standard (ALS).

2.4.1 **American Society of Mechanical Engineers (ASME)**

ASME is a non-profit professional organization that guarantees quality of products through development of codes, standards, and certifications. (ASME, n.d.a)

> *"ASME serves a wide-ranging engineering community through quality learning, the development of codes and standards, certifications, research, conferences and publications, government relations, and other forms of outreach." (ASME, n.d.d)*

ASME's Boiler and pressure vessel code (BPVC) standard is the single largest source of technical data used for manufacturing, construction, and operation of boilers and pressure vessels. The BPVC standard is revised every two years with a new edition. (ASME, n.d.b)

2.4.2 **Pressure Equipment Directive (PED)**

All pressure equipment that is subjected to a maximum pressure greater than 0.5 bar adheres to the PED. In addition to the vessel, the piping, safety accessories, and pressure accessories must comply with the PED. (PED, 2014)

2.4.3 **Alfa Laval Standard (ALS)**

Alfa Laval's internal standards and requirements are used to meet both demands for international standards and to fulfill requirements set up within the Alfa Laval organization. ALS exists within all areas of Alfa Laval's development and is made to align the work of individuals and departments in the organization. The standards apply to material standards, technical delivery requirements, surface treatment standards, etc. (Alfa Laval internal database)

2.5 GPHE assembly process

The assembly process of the current GPHE design is standardized for most Alfa Laval GPHEs. The components of a standard GPHE frame are represented in Figure 2.15. The assembly process of Alfa Laval's current GPHE design can be summarized in the following most important steps:

1. Gaskets are put on each channel plate.
2. Feet are mounted on the FP and PP (Figure 2.16).
3. GB and CB are assembled on the FP (Figure 2.17).
4. The PP is put on the CB and is aligned with the GB (Figure 2.18).
5. The CB and GB are connected to the support column (Figure 2.19).
6. The channel plates are placed in between the FP and PP (Figure 2.20 and Figure 2.21).
7. Four tightening bolts are added to the GPHE. Two on each side of the GPHE (Figure 2.22).
8. The plate package is tightened to A-measurement (Figure 2.23).
9. The remaining bolts are put on the GPHE (Figure 2.24).
10. Pressure test and inspections are made on the GPHE.

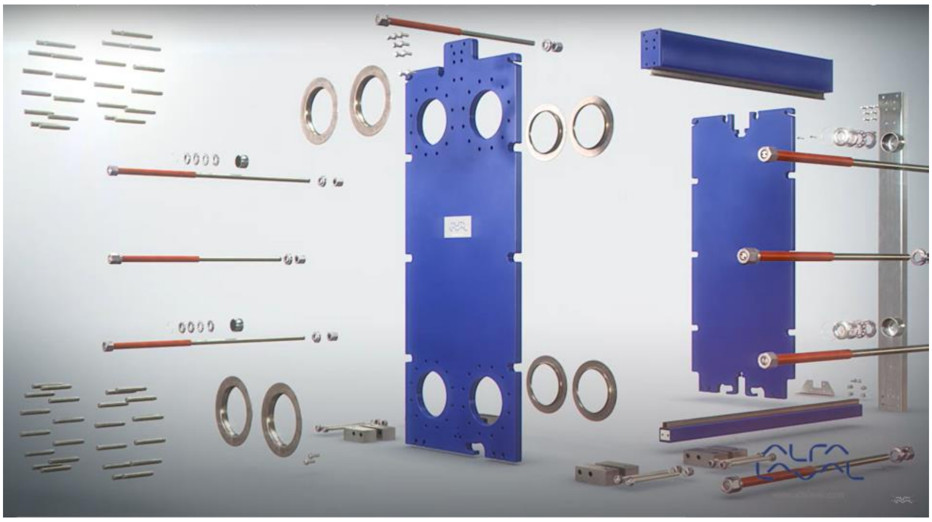

Figure 2.15 Frame components before assembly (Alfa Laval, 2017).

Figure 2.16 Step 2, linings, feet and stud bolts have been placed on the FP (Alfa Laval, 2017).

Figure 2.17 Step 3, CB and GB are mounted on the FP (Alfa Laval, 2017).

Figure 2.18 Step 4, PP is mounted on the CB and GB (Alfa Laval, 2017).

Figure 2.19 Step 5, support column is mounted (Alfa Laval, 2017).

Figure 2.20 Step 6, one channel plate with gasket placed inside the GPHE frame (Alfa Laval, 2017).

Figure 2.21 Step 6, whole plate package placed inside the GPHE frame (Alfa Laval, 2017).

Figure 2.22 Step 7, four tightening bolts are mounted on the GPHE (Alfa Laval, 2017).

Figure 2.23 Step 8, plate package tightened to A-measurement (Alfa Laval, 2017).

Figure 2.24 Step 9, all bolts mounted and tightened on the GPHE (Alfa Laval, 2017).

2.6 Service of GPHE

Service of GPHEs is crucial to maintain the performance and longevity of the PHEs. By regularly and proactively maintaining the PHE, customers can make sure that they can save money and time, optimize the productive time of their activities, prolong the lifetime of their equipment, and reduce emissions. (Alfa Laval, 2024) This can be achieved when service maintenance prevents corrosion, potential leakage, and fouling (dirty plates), as explained by one of Alfa Laval's development engineers. Alfa Laval has more than 100 service centers worldwide and the ability to provide field service for PHEs (Alfa Laval, 2022).

> *"Every year, Alfa Laval install and service millions of heat exchangers, reducing capacity needs by 100 GW. To put that into perspective, the global wind power capacity from newly installed wind turbines was 93 GW in 2021." (Alfa Laval, n.d.n)*

Up to 2.5% of the world CO_2 emissions could be prevented if all heat exchangers were regularly serviced and were optimized for their purpose. Heat exchangers are often considered products that are unnecessary to service. However, with regular maintenance of heat exchangers, the PHE maintains a better performance (Figure 2.25) resulting in energy savings, cost savings and emission reduction. If not serviced properly, the channel plates become dirty, resulting in reduced heat transfer capacity between the fluid streams. Improper service also increases the risk of leakage due to exhausted gaskets, thus leading to operational down time. (Alfa Laval, 2023h)

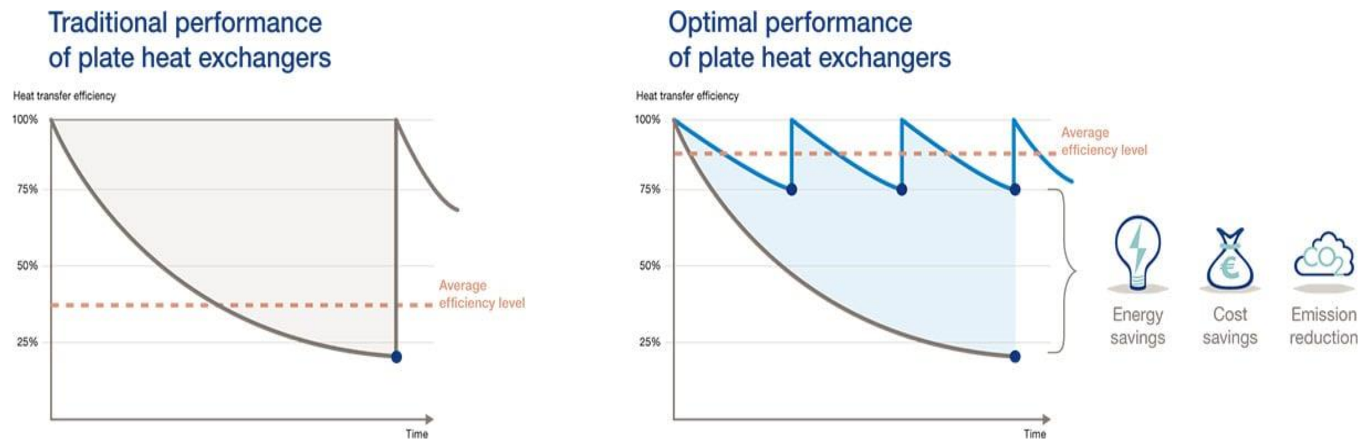

Figure 2.25 Rarely serviced PHE compared to regular serviced PHE (Alfa Laval, 2023h).

3. Methodology

This chapter describes the choice of method and explains the theory of the methods used in this thesis.

The development methodology used in this master thesis was based on the methods outlined in Ulrich and Eppinger's book *Product Design and Development* (Ulrich & Eppinger, 2012) and was complemented by Double Diamond (Design Council, n.d.). While the Double Diamond focuses on the main strategy of a development project, i.e., diverge and then converge, Ulrich and Eppinger offer well developed methods that are easy to implement, i.e., the method of establishing target specifications, the concept scoring matrix method for selecting concepts, and an overall good project structure.

All development projects have their own character which results in a need to adapt methods to the project (Ulrich & Eppinger, 2012, p.7). A well-defined development method is necessary for the development process' quality assurance, coordination, planning, management, and improvement (Ulrich & Eppinger, 2012, p.12). By implementing the theoretical framework, and methods suggested by the Double Diamond framework and Ulrich and Eppinger, alongside Alfa Laval's process to gather input information and reviewing the output, a method for this specific thesis project was developed and used.

3.1 Double Diamond

The Double Diamond was created by the UK Design Council in 2004. The aim of the Double Diamond is to describe any design and innovation process and assist developers in various industries. (Design Council, n.d.b) The Double Diamond is based on the concept of first exploring a problem widely through divergent thinking to then formulate solutions and how to mitigate the identified problems through convergent thinking. The framework of the Double Diamond consists of four phases: Discover, Define, Develop, and Deliver (Figure 3.1). The framework is intended to be used as an iterative process where some steps will be performed several times during the development process as new information becomes available and conditions change. By implementing an iterative process, the chances of avoiding errors and risks increase. The framework also recommends the users to: collaborate with others to find better solutions, to focus on the end-customers' needs and strengths of the developed product, as well as to communicate inclusively with all stakeholders of the project. (Design Council, n.d.a)

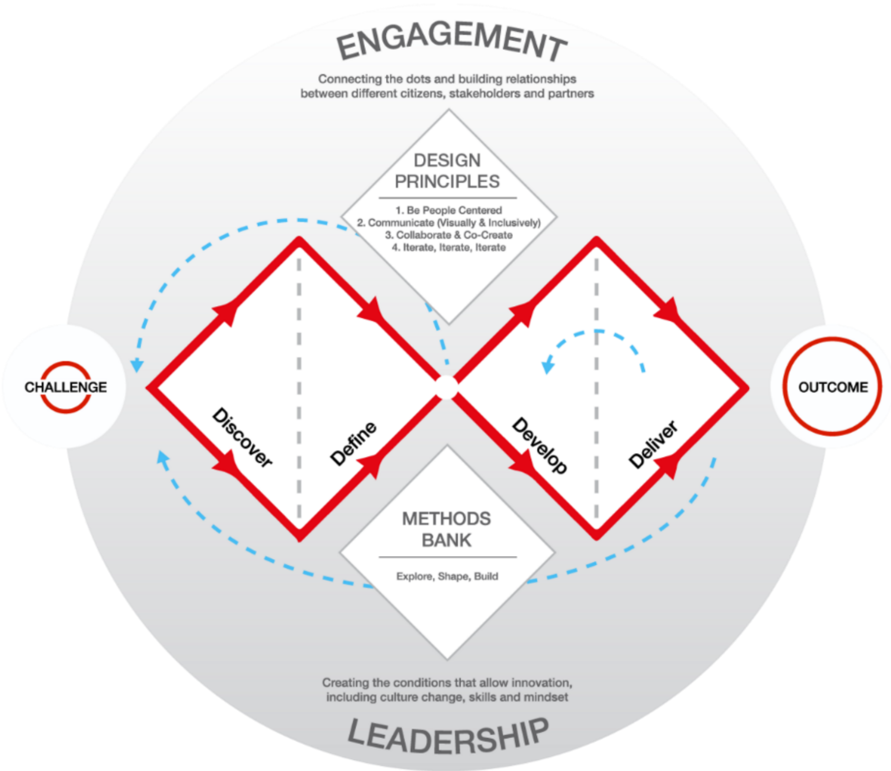

Figure 3.1 Double Diamond framework (Design Council, n.d.a).

In this project, the Double Diamond phases Discover, Define, Develop, and Deliver, were iterated. During the iterations, concepts were generated using only the most essential needs and requirements to maintain as much design freedom as possible.

3.2 Ulrich and Eppinger's development process

It is necessary for most firms today to be able to quickly progress from idea to finished product. Ulrich and Eppinger's development process was created to take several factors into account during the development process. Their book therefore focuses on unifying marketing, design, and manufacturing methods. (Ulrich & Eppinger, 2012, p.2-3)

The development process outlined by Ulrich and Eppinger includes structured methods that provide a step-by-step approach in addition to templates for documentation of key information. (Ulrich & Eppinger, 2012, p.7) The development process is divided into six phases: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up (Figure 3.2). (Ulrich & Eppinger, 2012, p.18-22) As the aim of this thesis is to develop new concepts for a new range of Alfa Laval GPHEs, the thesis will focus on the planning and concept development phases.

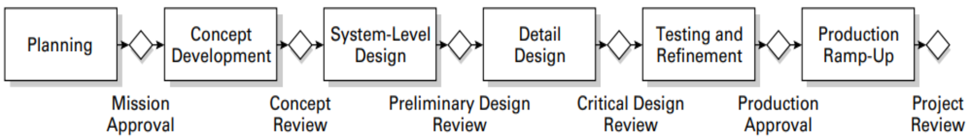

Figure 3.2 Product design and development process (Ulrich & Eppinger, 2012, p.22).

3.3 Master thesis process

The process selected for this thesis project was a twelve-step process (Figure 3.3) with the steps: product planning, identifying customer needs, product specification, concept generation, design review one, refined concepts, calculation analysis, defined concepts, concept selection, design review two, FEA, and BPVC review.

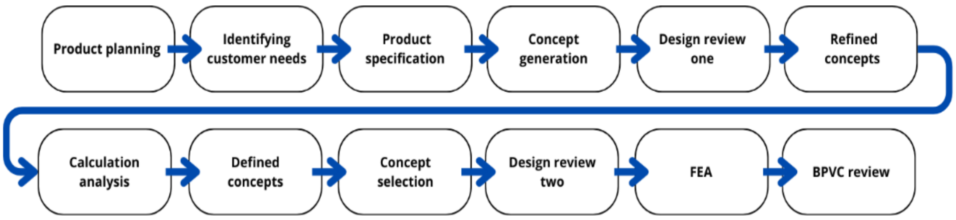

Figure 3.3 Master thesis process.

3.3.1 Product planning

According to Ulrich and Eppinger, the purpose of the product planning phase is to create a frame for what the project aims to accomplish regarding function, benefit, stakeholders, and costs. One way to do this is with a mission statement. (Ulrich & Eppinger, 2012, p.67) Additionally, an effective way to ensure that all issues regarding the product are addressed is to list and analyze all stakeholders, i.e., all groups of people that are affected by the product's failure or success. (Ulrich & Eppinger, 2012) Taking these theoretical aspects of the product planning phase into consideration, the production planning phase of this thesis project included formulation of a mission statement as well as creation of a Gantt chart and a list of all stakeholders. These activities were performed to better understand the scope of the project.

3.3.2 Identifying customer needs

The "identifying customer needs" phase is meant to ensure that the development process focuses on the customer needs and aids in uncovering latent, hidden, and explicit needs. The identified needs are then used to formulate product specifications. As explained by Ulrich and Eppinger, there is a difference between needs and specifications; while needs are independent from the product that is developed and are not specific to the concept that is developed, specifications, are directly linked to the selected concept. (Ulrich & Eppinger, 2012, p.74-75)

According to Ulrich and Eppinger, it is important to express the needs in terms of what "the product has to do" and not how "the product might do it". Another important aspect to consider is to keep the stated needs at the same level of detail as the raw data it is based on. (Ulrich & Eppinger, 2012, p.82-83)

The recommended way of gathering needs, according to Ulrich and Eppinger, is to listen directly to the end-users. However, for this thesis project customers were hard to reach and therefore employees at Alfa Laval that work closely to current customers have been interviewed to gather the needs for the large high-pressure GPHE frame. The interviews were held as one-on-one interviews in a semi-structured manner; initially, open ended questions about the product were asked, allowing the interviewees to elaborate their answers which were then followed up by questions regarding hidden needs and department specific requirements.

For this project, the process of identifying and organizing needs was as follows:

1. Gather data by interviewing stakeholders in Alfa Laval's organization.
2. Interpret the interview content into needs.
3. Organize the needs in groups consisting of similar needs.
4. Label each group of needs.
5. Discuss the needs with Alfa Laval development engineers to establish relative importance between the needs.

3.3.3 **Product specification**

In this step, the customer needs are translated into product specifications with precise targets. A specification consists of a metric and a value. (Ulrich & Eppinger, 2012, p.92-93) The first set of specifications are called target specifications and are set directly after the identification of the needs. The target specifications represent the aspiration of the development team. (Ulrich & Eppinger, 2012, p.93-94) It is important that the specifications are measurable and as precise as possible to enable follow up on the specifications to decide if the specifications are fulfilled or not. (Ulrich & Eppinger, 2012, p.95)

For this thesis project, the process of establishing target specifications was:

1. Select the most important needs.
2. Prepare a list of metrics of the selected needs.
3. Set acceptable target values.

3.3.4 **Concept generation**

The concept generation is inexpensive and not time demanding compared to other phases in the development process. It is, however, an especially important step. To avoid missing any good concepts due to narrow thinking, it is essential to explore all solutions. Bad concepts are hard to implement and improve later on in the development process. (Ulrich & Eppinger, 2012, p.118)

When the physical form, rather than the working principles (the technology), is the reason for the problem, the approach of decomposing the problem into sub-problems focusing on key customer needs is useful (Ulrich & Eppinger, 2012, p.123). Furthermore, when investigating the subsequent solutions, the preferred approach, according to Ulrich and Eppinger, is to first investigate individually and then discuss with the team. This approach leads to more and better concepts compared to if the concept generation had started as a team activity. However, the team discussion is needed to build consensus in the group and to refine the concepts. (Ulrich & Eppinger, 2012, p.128)

When brainstorming possible solutions, it is important to not discard ideas early on in the concept generation process. Instead, suggestions for improvements should be expressed to encourage new ways of solving problems. It is also important to generate many concepts to be sure that the whole design space has been explored. Additionally, generating many solutions often serves as inspiration for even more ideas. (Ulrich & Eppinger, 2012, p.128)

For this thesis project, the concept generation phase was, in alignment to Ulrich and Eppinger's theory, performed to analyze what new concepts might satisfy the established needs and specifications. Furthermore, this project's concept generation phase was divided into six steps:

1. Clarify problem.
2. Problem decomposition.
3. Search externally for inspiration to solutions.
4. Search internally for inspiration to solutions.
5. Explore solutions systematically.
6. Combine solutions into concepts.

The external search was conducted through online searches for different heat exchanger types as well as equipment with the purpose of tightening. Also, a patent search was made to investigate different kinds of PHE designs.

The first step of the internal search was performed by searching Alfa Laval's internal databases and to find solutions to the sub-problems. The second step of the internal search was to individually generate concepts based on the solutions for the sub-problems. The third step was to invite a group of Alfa Laval engineers, with different knowledge, to brainstorm around the initial ideas to further get access to company knowledge.

3.3.5 **Design review one**

For this project, the concept selection was performed during two different occasions: design review one and design review two. The design reviews were one-hour meetings held together with six Alfa Laval engineers with different backgrounds and areas of expertise.

Design review one was performed after the initial frame concepts had been generated. At design review one, the most interesting concepts were chosen based on a team discussion. This was deemed an appropriate selection method since the concepts from design review one were significantly different from each other. Furthermore, suggestions for concept improvements and important aspects to consider regarding the concepts were also discussed during design review one.

3.3.6 **Refined concepts**

During design review one, several concepts were selected to move forward with. Since the selected concepts were on a low level of detail, this part of the development process was made to further investigated the selected concepts to refine their functions and designs. The refinement of the concepts was done to be able to perform the next step of the development process, i.e. calculate the approximate dimensions of the concept designs' components.

3.3.7 **Calculation analysis**

In this part of the development process, the approximate dimensions of the concepts' main components were calculated using traditional solid mechanics, for example by using formulas for: buckling, shear stress, tension/compression stress and bending. To prevent plasticization of the materials, the calculated stress levels in the components were compared to the materials' yield stress to determine the dimensions of the components.

3.3.8 **Defined concepts**

After the concept components' dimensions had been calculated, the refined concepts were defined by CAD models that showcased the concepts in their required size. Furthermore, the defined concepts were investigated using the CAD tool to estimate weight, the maximum height, and the required space of each of the concepts.

3.3.9 Concept selection

In this part of the development process, according to Ulrich and Eppinger, the generated concepts should be evaluated with respect to the needs identified during the product planning phase. The following question is answered: What are the different concepts strengths and weaknesses and what concepts are the best to further develop and investigate? (Ulrich & Eppinger, 2012, p.144)

A common method to use during the concept selection phase, as explained by Ulrich and Eppinger, is the concept scoring method. This method is preferred when a precise answer is needed and is usually performed once the concepts have been refined to some extent. Often, a reference concept is selected to which all the other concepts are compared to. During concept scoring, each criterion is weighted based on its importance. The weighting can be made by allocating 100 percentage points among the criteria. (Ulrich & Eppinger, 2012, p.154-155) Then, the result of the scoring matrix is analyzed through a sensitivity analysis. The sensitivity analysis is performed by varying the weights of the concept scoring criteria and the ratings that the concepts received from the concept scoring. This analysis showcases how different parameters affect the result of the scoring matrix. Thus, the sensitivity analysis provides useful insights, regarding the concepts, to consider when deciding what concept to move forward with. (Ulrich & Eppinger, 2012, p156-157)

During design review two of this thesis project, the concept selection was performed using a concept scoring matrix. The concept scoring method was deemed a suitable selection method as there were many criteria with varying importance to consider. The selection criteria were chosen based on the needs identified during the product planning phase. Furthermore, the weighting of the selection criteria was determined by consulting the six Alfa Laval engineers during design review two. The reference concept in the scoring matrix was the current large high-pressure GPHE design.

For this thesis project, the process of the concept scoring matrix can be summarized in four steps:

1. Prepare selection matrix criteria.
2. Set weight of criteria.
3. Rate the concepts.
4. Perform sensitivity analysis.

3.3.10 **Design review two**

During the design review two, the concept scoring grading was performed. During the concept scoring grading session, additional comments were given to the defined concepts regarding strengths, weaknesses, and suggestions for improvements. In the end of design review two, a final concept was chosen to move forward with.

3.3.11 **FEA**

During this step in the development process, a FEA was performed of the final concept to verify the calculations done with traditional solid mechanics, investigate deflections of the final concept's components, and locate the weak spots of the final concept's design. Since the complexity of the final design was high, FEA was deemed a good tool to analyze the concept.

3.3.12 **BPVC review**

For the BPVC review, an interview was held with a BPVC engineer who was an expert within regulatory requirements. During the interview, the concepts generated in this thesis were discussed in regard to the BPVC standard.

4. Product planning

This chapter presents the stakeholder analysis of the project and provides a mission statement summarizing the company's inputs and desires for the project.

4.1 Stakeholders

In the following sub-sections, the different stakeholders in this thesis project are defined and briefly analyzed. The information was gathered from development engineers, reflecting their perspectives on the tasks and requirements of each stakeholder.

4.1.1 **End User**

This stakeholder group includes the end users, i.e., those who will use the product. It is important for the end user that the product delivers what the user has requested, and that the product is easy and cheap to own and use.

4.1.2 **Logistic**

The downstream logistic is responsible for transporting the finished product to customers as well as inhouse logistics. It is necessary for this stakeholder that the product and its parts are possible to transport to customers in the most efficient way, and if possible, using today's logistical solutions.

4.1.3 **Service Department**

The service organization is responsible for servicing customers' GPHEs to maintain the performance and making sure that the GPHEs can be used for their entire planned lifetime. The service department wants the GPHEs to be as quick and simple to service as possible. It is also a desire that service could be performed using standard tools available at the customers' sites.

4.1.4 Operation Department

The production department is responsible for producing the GPHE and deciding on what is possible to produce as well as suggesting design changes to simplify the production method. To keep both the cost and number of required production changes down, the operation department often want low production series to allow for incorporation of the new products in the current production system.

4.1.5 Suppliers

Alfa Laval has many suppliers of components and material. The suppliers can set requirements, in the form of limitations to their capabilities and ambition of producing certain things. This can affect what Alfa Laval can produce.

4.1.6 Research and Development

The research and development department wants a design that is efficient and a concept that works for its intended purpose. Furthermore, they want to minimize changes and maximize the reutilization of already developed components and details to avoid larger development projects and component testing.

4.1.7 Finance Department

The finance department checks that the profit of producing the heat exchanger is higher than the cost. They are also responsible for the budgeting of the overall development projects for GPHEs. It is necessary that the financial department sees the project as a lucrative task or as a new market opportunity for a project to get funding.

4.1.8 Governmental and national agencies

Governments and states set requirements in the form of regulations and laws to guarantee that a company’s products are good and safe to use. Heat exchangers are classified as pressure vessels which results in that Alfa Laval heat exchangers need to fulfill certain regulations, such as ASME and PED.

4.2 Mission statement

The mission statement (Table 4.1) was based on the task description of this thesis project as well as discussions with the supervisor at Alfa Laval and the analysis of the project's stakeholders. Additionally, the preliminary Gantt chart of the project is available in Appendix A.

Table 4.1 Mission statement for large high-pressure GPHE frame project.

Mission statement	
Product description	Mechanical GPHE frame, which is openable, sealed, robust, capable to be used for high design pressures and manageable in terms of transportation, service, and manufacturing.
Benefit proposition	- High efficiency. - Lightweight design. - Easy maintenance. - Small storage area. - Sustainable design. - Large high-pressure GPHE.
Primary market	- Energy solutions.
Secondary market	- All kinds of industries and processes.
Assumptions and constraints	- The plate package design shall not change. - The GPHE shall be able to open and close. - Low scale production volumes.
Stakeholders	- End User. - Logistic Department. - Service Department. - Marketing Department. - Operation Department. - Component suppliers. - Research and Development. - Finance Department. - Governmental and national agencies.

5. Identification of needs

This chapter summarize the process of gathering the needs for the project and presents the needs in an organized list.

5.1 Interviews

There were two one-on-one interviews held during this step of the project. The interviewees were one product manager for large GPHEs and one senior development engineer with experience from new product development (NPD). Initially, the plan was to also interview a person with insight into the service organization and one person with insight into the operations. However, the service and operations personnel were not available at the time of this phase. Instead, the input from these stakeholders were later gathered during the design reviews of the generated concepts. See Appendix B for summaries of the interviews conducted.

5.2 Identification of customer needs

All the gathered needs were organized and thereafter graded in a scale of “1”, ”2” and “3”, based on importance of the need. An explanation of the different grades is found in Table 5.1. The importance rating was set together with Alfa Laval engineers with earlier experience of similar projects. The needs’ significance was set based on a successful outcome to this project’s objective. The needs without any mark were considered redundant and limitary for this specific project.

Some needs have high significance for the finished product but are only denoted as "important to consider" for this project. For example, fulfilling pressure vessel standards is essential for selling the final product but was not considered a must for achieving this project's objective.

Table 5.1 Importance rating definitions.

Rating	*Definition*
1	Important to consider
2	Important for the convenience of the product
3	Critical to consider

None of the collected needs were denoted as latent needs (needs that customers take for granted but do not mention as needs). One reason for this could be that the needs were based on data from stakeholders at Alfa Laval, who included latent needs in their responses about important aspects to consider.

5.3 Organization of needs

All needs deemed relevant for this project are included in Table 5.2, along with their corresponding importance. To see all needs identified in the interviews, see Appendix C.

Table 5.2 Needs corresponding importance.

No.		*Need*	*Importance*
1	The frame	fulfills ASME, PED and/or ALS regulations demands	1
2	The frame	can be lifted	2
3	The frame	can be connected to the ground	2
4	The frame	can withstand lateral loads due to inclined ground	1
5	The frame	can compress the plate package to A-measurement	3
6	The frame	can maintain a watertight test pressure	3
7	The frame	allows for easy release of compression of the plate package	2
8	The frame	allows for easy insertion and removal of the channel plates when the GPHE is opened.	2
9	The frame	can be serviced with standard customer tools	1
10	The frame	can carry the plate package above the ground	2
11	The frame	can maintain the straight alignment along the orthogonal axis of the plate package	3
12	The frame	is compatible with current channel plate design	2
13	The frame	has acceptable tolerances in its interface with the plate package	3
14	The frame	can be produced with economical feasible methods	1
15	The frame	can be produced with Alfa Laval's and suppliers' current production capabilities	1
16	The frame	components are easy to handle in Alfa Laval production facilities	2
17	The frame	has a shape that is manageable during production	1
18	The frame	can be transported by road	2
19	The frame	preserves the characteristics of a GPHE	3
20	The frame	can withstand heat	1
21	The frame	can withstand freezing temperatures	1
22	The frame	can withstand a corrosive environment	2
23	The frame	can withstand corrosive GPHE process mediums on its surfaces in contact with the plate package	2
24	The frame	has a lifetime of 40 years	1

6. Product specification

This chapter translates the most important needs into product specifications, including metrics and acceptable values.

6.1 Preparation of metric list

The gathered needs with the highest importance, i.e., an importance rating of level 3, were the needs which were seen as requirements for the project. All the needs that received rating of 3 can be found in Table 6.1. The remaining needs were assessed during the second design review where the defined concepts were benchmarked against each other.

Table 6.1 Most important needs gathered.

No.		***Need***
5	The frame	can compress the plate package to A-measurement
6	The frame	can maintain a watertight test pressure
11	The frame	can maintain the straight alignment along the orthogonal axis of the plate package
13	The frame	has acceptable tolerances in its interface with the plate package
19	The frame	preserves the characteristics of a GPHE

Need number 5 was measured in stress and deformation during plate package compression. Need number 6 focused on the stress and the deformation during operation of the GPHE at test pressure. Need number 11 was already satisfied by the current CB and GB. Since these two bars are not considered problematic in the current design, they will not be prioritized in this project. Regarding need number 13, the deflection of the FP during test pressure was controlled to prevent plate package from leaking. Regarding need number 19, the heat exchanger must use channel plates with gaskets and be easy to open and close. Since this project was limited to the frame of the GPHE, the plate package was not changed.

6.2 Defined product specifications

The product specification can be found in Table 6.2. Metrics 1 and 2 use the unit of yes/no (Table 6.2), which will be further specified in the calculation part in Section 10.1. From section 10.1, the calculation generated that approximately 2 MN was required to tighten the plate package to A-measurement and approximately 1* N to withstand the test pressure. For these two metrics to be approved, no part of the GPHE can plasticize.

Table 6.2 Product specification.

Metric No.	***Need Nos.***	***Metric***	***Unit***	***Acceptable Value***
1	5	The frame can compress the plate package to A-measurement.	Yes/No	Yes
2	6	The frame can withstand the test pressure.	Yes/No	Yes
3	11	The frame can keep the plate package aligned along the axis orthogonal to the plate surface.	Yes/No	Yes
4	6,13	Maximum frame deflection during test pressure.	mm	<1
5	19	The frame can be opened and closed.	Yes/No	Yes

7. Concept generation

This chapter decomposes the problem based on key product needs into sub-problems, summarizes the generated solutions for each sub-problem, and finally, provides a description of the 13 generated GPHE frame design concepts.

7.1 Problem decomposition

The GPHE's function was decomposed into seven sub-problems based on the key needs (Table 5.2) of the GPHE's frame (Table 7.1).

Table 7.1 Decomposed sub-problems.

Sub-problem No.	*Metric*
1	Make the GPHE stand stable on the ground.
2	Tighten the plate package to A-measurement (low stress part).
3	Withstand the design pressure (high stress part).
4	Align the plate package.
5	Make it possible to open the GPHE in a controlled manner.
6	Support the channel plates.
7	Make the GPHE robust.

7.2 Solution search

A solution search was made to find inspirations for concept ideas. The solution search included an internal search in Alfa Laval's database and an external search of competitors GPHEs, shell-and-tube heat exchangers, solutions on desired functions such as lightweight strength, and a patent search. The result of the solution search is found in Appendix D.

7.3 Solution generation to sub-problems

To address each of the sub-problems, a brainstorming session was performed. During the brainstorming session, multiple solutions to each of the sub-problems in Table 7.1 were identified. The sub-problems and corresponding brainstormed solutions are presented in Table 7.2.

Table 7.2 Brainstormed solutions to sub-problems.

Sub-problem	Solutions
Make the GPHE stand stable on the ground	- Feet. - Support wire to the surrounding walls or ground. - Connection to the ceiling. - Cast fundaments into the foundation. - Cast the GPHE into the foundation. - Shapes/holes in the foundation where the GPHE is placed into.
Tighten the GPHE to A-measurement (low stress part)	- Wire that is tightened straight between FP and PP. - Wire that is tightened around the whole GPHE. - Pressing the FP and PP together with a pressing tool. - Punch the FP and PP together. - Pressing the FP and PP with together with the weight of the FP and PP (Assemble the GPHE horizontally). - Tightening bolts. - Vacuum in the plate package.
Withstand the design pressure. (high stress part)	- Many small bolts. - Few big bolts. - Many thin wires. - Long thin wire that is mounted in several layers on top of each other. - Few thick wires. - Connect bolts or wire with surrounding support features. - Cast a support structure around the frame. - Support wire wrapped around the whole GPHE. - Composite materials as reinforcement. - Whole sheets of thick metal on the sides of the GPHE. The thick metal sheets would replace the function of the current tightening bolts as the plates would maintain the plate package compressed. - Welded framework structure on top of the FP and PP.
Align the plate package	- Guiding bar and carrying bar. - Guiding bars on the sides. - Guiding the plate package with walls around it.
Make it possible to open the GPHE in a controlled manner	- Bolts released. - Wire released. - Remove supports around the GPHE.
Support the channel plates	- Carrying bar. - Support structure underneath the channel plates.
Make the GPHE robust	- Frame reinforcement. - Thicker FP and PP. - Combine several thinner frame plates (FPs or PPs) into one thick. - Support construction of beams.

7.4 Generated concepts

13 different frame concepts were generated by combining brainstormed solutions to the sub-problems. Each concept aimed to enhance manufacturability, distribution, or maintenance of the GPHE.

The frame components with the presumed biggest influence on the design were the PP, FP, and tightening bolts. Therefore, the generated concepts mainly focused on suggesting alternative solutions for these components and the functions they were fulfilling.

7.4.1 **Double plate concept**

The double plate concept focused on reducing the weight and thickness of the frame's plate by splitting the FP and PP into two pieces (Figure 7.1). Splitting each plate into two pieces makes the plates easier to handle and produce individually.

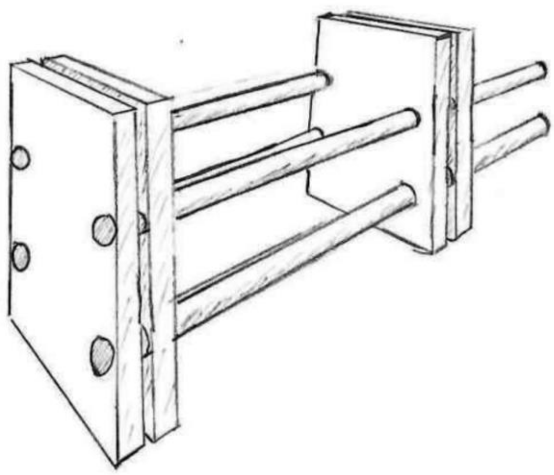

Figure 7.1 Double plate concept.

7.4.2 **Varying thickness plate concept**

The varying thickness plate concept focused on minimizing the weight of the FP and PP by adapting the thickness of the plates. In today's design, the thickness is uniform over the whole FP and PP. However, the thickness in the corners of the plate do not require the same thickness as the middle. Therefore, for this concept, the areas of the FP and PP that generally has a large deflection were made thicker and the areas exposed to less stress were kept thinner (Figure 7.2), resulting in a more weight efficient design.

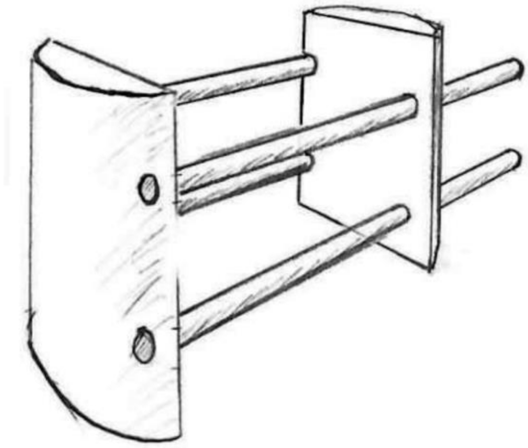

Figure 7.2 Varying thickness plate concept.

7.4.3 Truss structure concept

The truss structure concept was a further development of the varying thickness plate concept. By using a truss structure within the FP and PP, instead of a solid section, the component could potentially become even lighter (Figure 7.3).

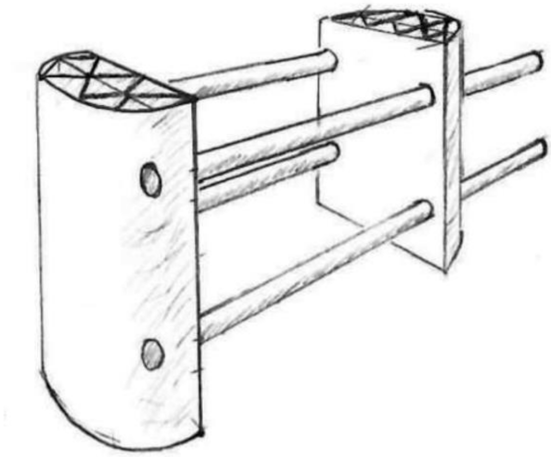

Figure 7.3 Truss structure concept.

7.4.4 **Reinforced concept**

The reinforced concept was based on using regular large GPHE FPs or PPs and then reinforcing it with a framework structure (Figure 7.4). By using a framework structure to reinforce the PP and FP, the FP and PP could be made lighter.

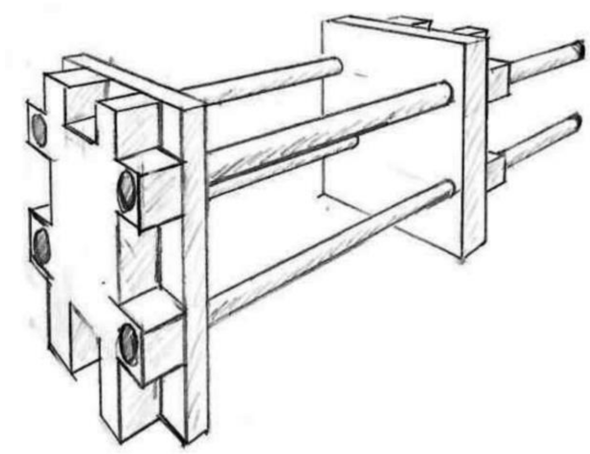

Figure 7.4 Reinforced concept.

The framework structure can be designed in different ways, another possible design is shown in Figure 7.5.

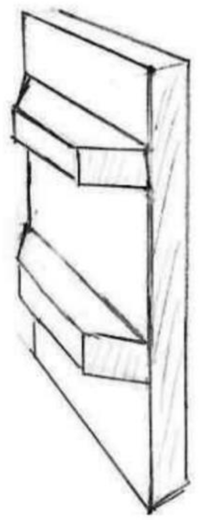

Figure 7.5 Alternative reinforcement structure.

7.4.5 Modular concept

The modular concept divides the GPHE frame in two main modules, a plate package module with the main task to tighten the plate package to A-measurement (Figure 7.6) and a frame module with the main task to withstand the design pressure (Figure 7.7). The plate package module would be placed inside the frame module (Figure 7.8). The concept was based on that the plate package module would be designed to just be able to tighten the plate package (not be classified as pressure vessel components) while the frame module would be designed to endure the design pressure. The largest forces are obtained when the GPHE is pressurized during operation, not when the GPHE is tightened to A-measurement. Thus, it seemed like a good solution to tighten the GPHE with smaller components in the plate package module and then use more robust components to withstand design pressure in the frame module. By implementing this modular design solution, it would probably be possible to reduce the weight of some of the components as well as ease service procedures. Another aspect of the modular concept was to make the service procedure more efficient. Today, to gain access to the channel plates, it is necessary to remove all tightening bolts and take out each channel plate individually. Therefore, a modular structure would lead to easier separation of the plate package module, thus allowing for the entire plate package to be sent to an Alfa Laval service center. At the service center the plate package can be served, leak tested and then transported back to the customer. This would potentially reduce the operational downtime during service.

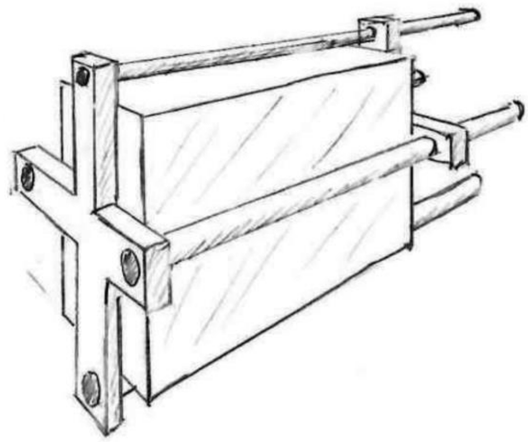

Figure 7.6 Plate package module.

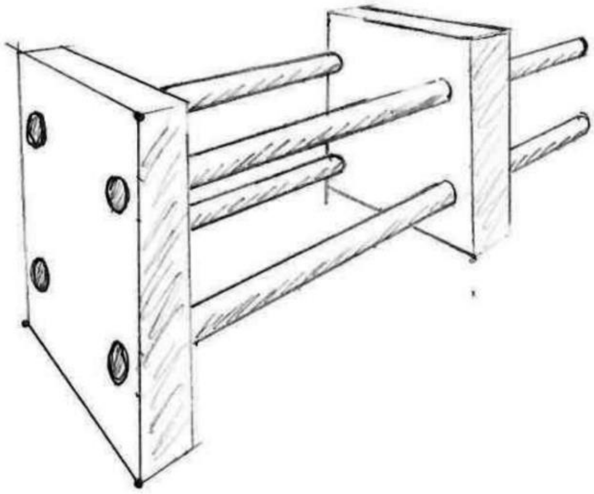

Figure 7.7 Frame module.

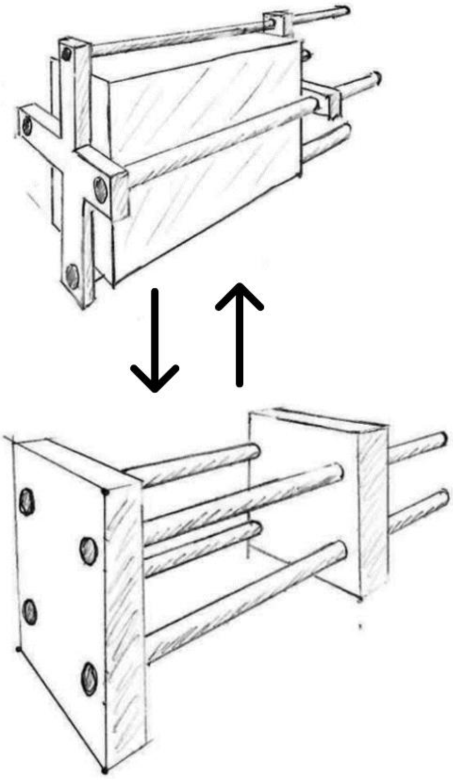

Figure 7.8 Plate package module is placed between the FP and PP of the frame module.

7.4.6 **Side-plate concept**

This concept was made to exchange the thickest tightening bolts to side-plates (Figure 7.9), like the FP and PP. One advantage of this concept would be during service and assembly, where only one side-plate would need to be removed instead of many bolts. One disadvantage with changing bolts to plates would be that it would increase the weight of the GPHE.

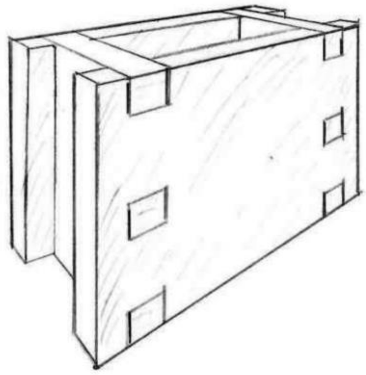

Figure 7.9 Side-plate concept.

7.4.7 **Composite tube concept**

In this concept, the thickest tightening bolts were exchanged to high strength composite tubes (Figure 7.10). In Figure 7.10, the dark bolts represent the carbon tubes, and the white bolts represent normal tightening bolts required to tighten the plate package to A-measurement. This concept would reduce the weight of the GPHE as well as make service procedure easier due to lighter components.

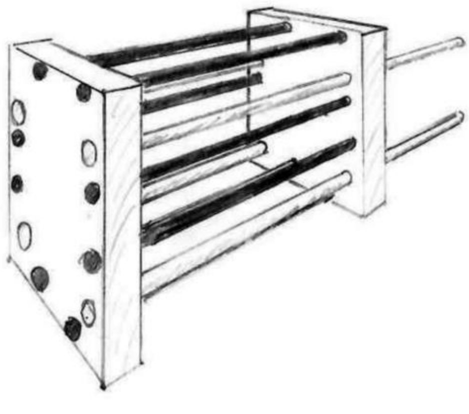

Figure 7.10 Composite tube concept.

7.4.8 **Composite plate concept**

In this concept, the thickest tightening bolts were exchanged to high strength composite plates (Figure 7.11). In Figure 7.11, the dark shaded areas represent the carbon plates, and the white bolts represent normal tightening bolts required to tighten the plate package to A-measurement. This concept would reduce the weight of the GPHE as well as make service procedure easier due to lighter components.

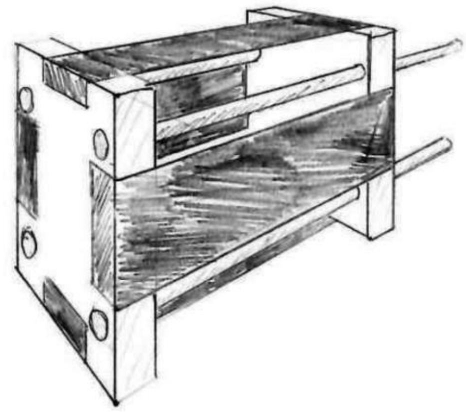

Figure 7.11 Composite plate concept.

7.4.9 **Thick-wire concept**

In this concept, the tightening bolts were exchanged to thick wires (Figure 7.12). Wires have high tension strength and are possible to bend, making the variety of possible setups large. Potential benefits of this concept would be easier service procedures.

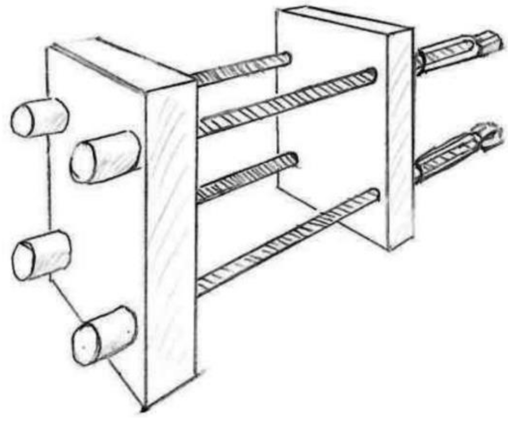

Figure 7.12 Thick-wire concept.

7.4.10 **Thin-wire concept**

The thin-wire concept was based on the idea of exchanging the thick tightening bolts with thin wires. The difference between thin and thick wires is the possibility for the thin wires to bend more, allowing for more flexibility in wire setup, as illustrated by the blue wire in Figure 7.13. Furthermore, a thin wire would be easier to handle in assembly and service as well as easier and cheaper to produce compared to thicker wires and large tightening bolts.

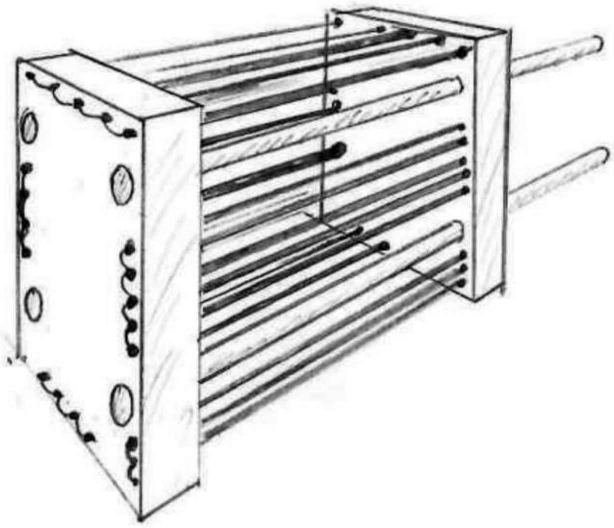

Figure 7.13 Thin-wire concept.

7.4.11 **Horizontal concept**

The horizontal concept was made in two versions.

The first version of the horizontal concept led to reduced length of the tightening bolts by using the FP's weight to compress the plate package, and thereafter mount the tightening bolts. After assembly of bolts, the GPHE would be raised from a horizontal position to a vertical. Therefore, the tightening bolts would not need to be as long as if the GPHE had been assembled standing vertically.

The second version of the horizontal concept included both assembly and use of the GPHE in a horizontal setup (Figure 7.14). Having a horizontal setup would make it possible to skip the PP and instead use the floor. Bolts could also be directly screwed into the floor to tighten the GPHE, reducing both the weight of the GPHE and the number of components.

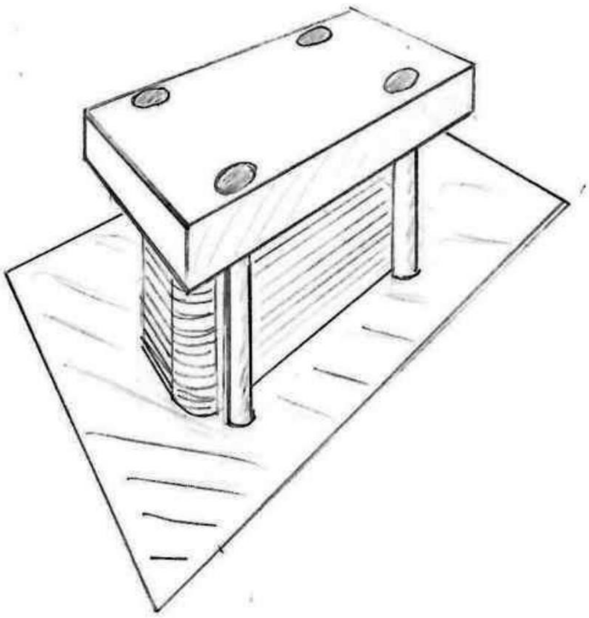

Figure 7.14 Horizontal concept.

7.4.12 Support concept

The support concept relies solely on external support for compressing the plate package and withstand the design pressure (Figure 7.15), thus removing the need for bolts, wire ropes or anything else in between the FP and PP. The external supports would be able to move along a railway solution to be able to compress and release compression on the plate package. An advantage of this concept would be simplified service procedure, reducing operational downtime, and increasing accessibility of the channel plates.

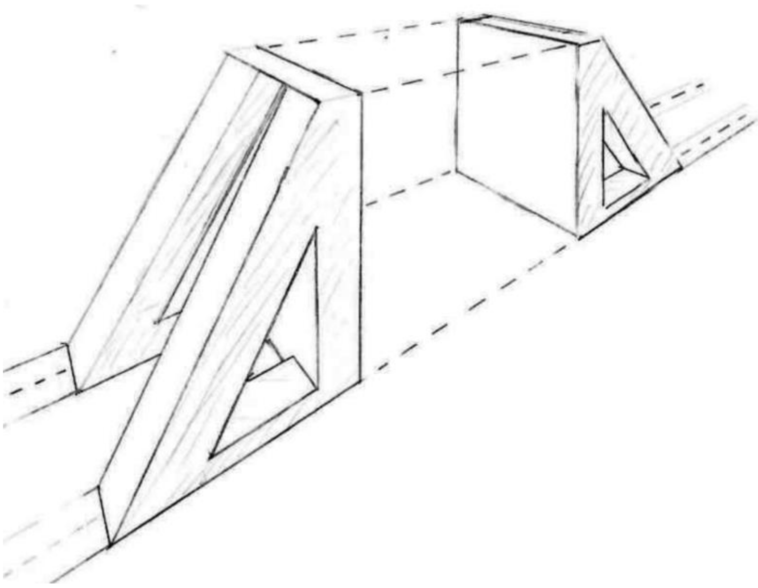

Figure 7.15 Support concept.

7.4.13 Angled bolt concept

The concept with angled bolts had a service focus. Today, the tightening bolts need to be removed by lift from the opened GPHEs (Figure 7.16) during service. The lifting of the bolts is complicated and introduces risks during the service procedure. This concept suggests that the bolts should be angled toward the ground or to the side of the GPHE (Figure 7.17) to allow access to the plate package. To enable the angling of the tightening bolts, a beam would be mounted on the FP. (Figure 7.18). This solution would reduce the weight needed to be lifted by 50% as only one of the bolts' ends would be required to be lifted.

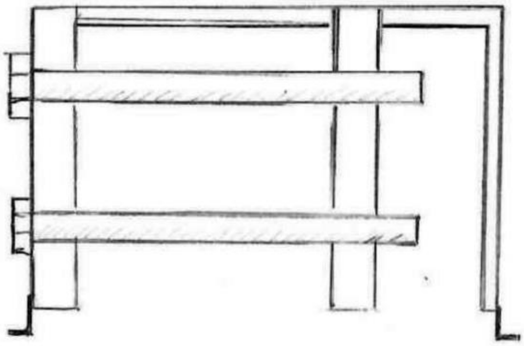

Figure 7.16 Opened GPHE.

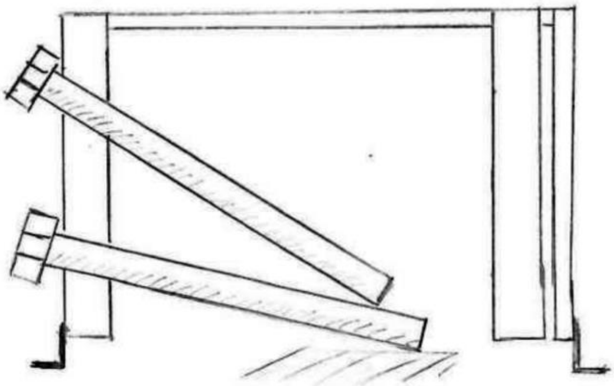

Figure 7.17 Open GPHE with angled bolt concept.

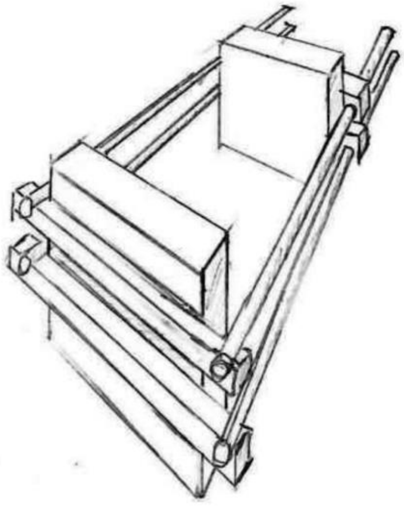

Figure 7.18 Front view of the angled bolt concept.

8. Design review one

This chapter summarizes the content of the first design review and describes the selection process for determining which concepts to move forward with.

A design review meeting was held after the initial concepts were generated. Five Alfa Laval engineers, in various roles but with long and diverse experience of development projects, attended the meeting: one project manager, one development engineer from existing product development, two product development engineers from NPD, and one specialist within technology development. The aim of the meeting was to discuss the list of requirements, the generated concepts, and together brainstorm additional design concepts.

There was no new concept discussed or suggested during the design review. However, some design considerations were suggested regarding the presented concepts. Regarding the thick-wire concept design, it was noted important to consider the friction that can come from the wire moving against the FP and PP during tightening of the wire. A proposed solution to this problem was to tighten the wire simultaneously in both ends of the wire to minimize the movement of the wire when in contact with FP and PP. Another suggesting to the thick-wire concept would be to use lifting webbing (or similar) instead of wires.

Three concepts were selected as particularly promising to move forward with, based on the team's judgment during the meeting. The selected concepts were the:

- Thick-wire concept
- Modular concept
- Support concept

These concepts were deemed the most promising due to their novelty and potential to achieve the objective of enhanced manufacturability, distribution, maintenance of the GPHE.

9. Refined concepts

This chapter presents the further development of the selected concepts, where the main functions of these concepts are clarified.

9.1 Thick-wire concept

The thick-wire concept was deemed to have high potential, as wires, thanks to their ability to bend, can be used in more versatile ways compared to tightening bolts. However, one challenge, noted in the first design review, was how to tighten the wires without causing high friction forces between the wires and the structural plates. To prevent high friction forces, the aim was to have a solution where the primary movement of the wire would be made when the wire is not in contact with FP and PP. Thus, three concepts on how to tighten the wire were proposed:

1. Wires are mounted with one nut at the FP and another one at the PP (Figure 9.1). The wires will be tightened similarly to how tightening bolts are being tightened today.
2. Wires bend around the FP while having a disk on the PP with bolts (Figure 9.2 and Figure 9.3). Tightening the ends of the wire simultaneously.
3. Wires bending around both the FP and PP and placing turnbuckles on the sides of the GPHE (Figure 9.3 and Figure 9.4).

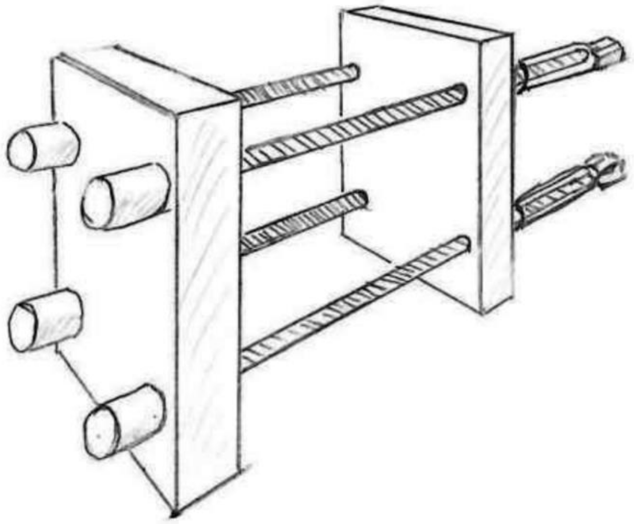

Figure 9.1 Wire solution 1.

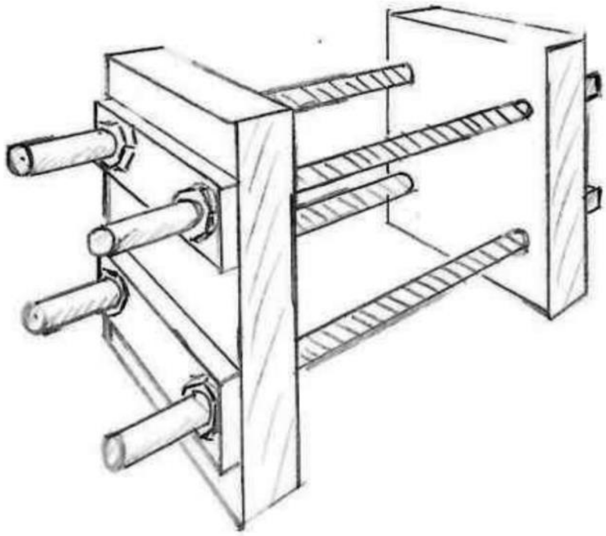

Figure 9.2 Wire solution 2, seen from the back.

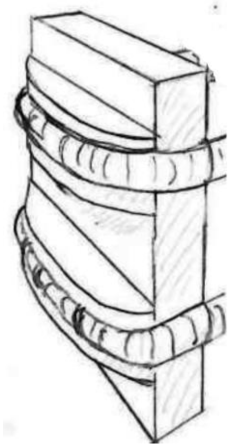

Figure 9.3 Wire solution 2 and 3, seen from the front.

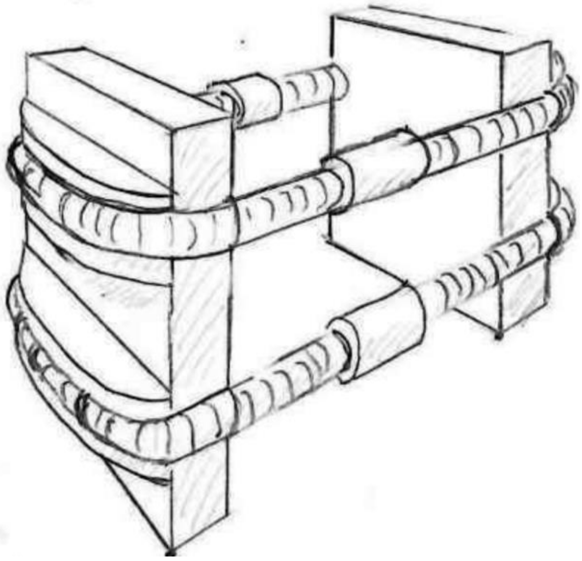

Figure 9.4 Wire solution 3, illustrating the turnbuckle placement on the sides.

A subsequent discussion with two engineers, regarding the three wire tightening concepts, resulted in that the continued analysis focused on the third alternative. The third alternative was selected thanks to its tightening function that differed the most compared to the current solution as well as due to the large contact surface area between the wire and the FP and PP. It was seen as interesting to research how the larger contact surface between the wire and FP and PP would affect the stresses in the plates. Further, semicircle shaped shelves were developed as a possible solution to accomplish a good interface between the wires and the FP and PP (Figure 9.3).

The use of turnbuckles will limit how much the wire can be tightened. Therefore, the considered solution was to tighten the plate package to A-measurement with tightening bolts and then assemble the wires.

9.2 Modular concept

The modular concept consisted of two modules: the plate package module and the frame module. The main part of this concept was to separate the functions of tightening the GPHE to A-measurement and the function of enduring the design pressure of the GPHE. By separating the functions, it would be possible to use an identical plate package module and instead design the frame module to be able to withstand various operational demands. Therefore, for example, one plate package could be combined with five different kinds of frame modules designed for different operational demands.

During the refinement process of the modular concept, an additional concept was developed as a further development of the modular concept. Therefore, the modular concepts became two different concepts: Modular concept alternative 1 and modular concept alternative 2.

9.2.1 **Modular concept alternative 1**

The modular concept alternative 1 was based on the original concept design (Figure 7.8). The idea was to use a plate package module placed within the frame module. This require the tightening bolts of the plate package module to be fitted inside the frame module. There were three different solutions to how the plate package could be compressed and still be able to fit in between the frame module plates:

1. Compressing the plate package with a pressing tool and then attach bolts.
2. Tightening the plate package with long bolts and then switch the longer bolts one by one to shorter bolts.
3. Utilizing larger FP and PP for the plate package module compared to the FP and PP of the frame module. This allows for the use of longer tightening bolts, as the bolts do not need to be positioned between the FP and PP of the frame module.

The second solution was selected as it was deemed as the most suitable for this concept as well as easiest to implement and the cheapest to manufacture.

9.2.2 Modular concept alternative 2

A new interesting modular concept was also developed, which resulted in an additional concept: the modular concept alternative 2. The new modular concept would share the same plate package module as the modular concept alternative 1, but the frame module would be made of beams connected by tightening bolts on the FP and PP (Figure 9.5). Since the frame module would be made of beams, the tightening bolts used to compress the plate package could be long.

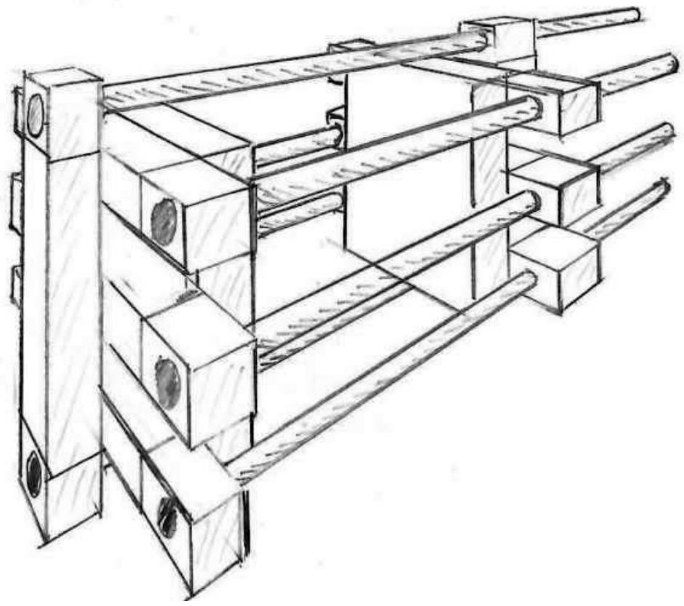

Figure 9.5 Modular concept alternative 2.

9.3 Support concept

The support concept had the original idea of not needing bolts at all, and only compress the GPHE using external supports. Compressing the GPHE would require the frame to move several meters and be able to carry a load equivalent to several big bolts. Initially, there was consideration to utilize external walls in this concept. However, after further evaluation, the decision was made to focus solely on solutions that rely on flooring since many large GPHEs are placed in an outside environment.

One considered solution was to use a rack-wheel solution to tighten the plate package to A-measurement and then securing the frame by screwing bolts into the foundation. The securing of the frame was approximated using full shear loading (Equation 9.1) which resulted in the total shear stress, when using M1* bolts, being 4430 MPa (Equation 9.2). The force F used in the calculation was the force required to withstand the test pressure. The material was considered to have yield stress of 355 MPa which was reduced by 20% to obtain a safety margin towards plasticity. The calculated number of bolts needed on each side of the GPHE was sixteen M1* bolts (Equation 9.3). However, since 32 bolts would be screwed to the floor for each GPHE, a special made flooring, that is able to withstand the large forces, would be required.

Equation 9.1. Shear stress.

$$\tau = F/A \qquad (9.1)$$

Equation 9.2. The total shear stress when using M1* bolts is 4430 MPa.

$$\frac{F^*}{(\frac{M1^*}{2})^2 * pi} = 4430 \qquad (9.2)$$

Equation 9.3. Number of M1* bolts required to withstand the shear stress is 16 bolts.

$$\frac{4430}{355 * 0.8} = 15.59 \qquad (9.3)$$

This concept was considered hard to evaluate and realize by Alfa Laval engineers, which resulted in this concept being abandoned.

The second considered solution abandoned the idea of the support being able to move. Instead, this solution became more similar to the modular concepts. The solution considered was to cast the support into the floor, making it fixed to the ground and not possible to move. To be able to place the plate package between the fixed supports, the plate package would be required to be over-compressed beyond the A-measurement. Once the plate package had been placed in position, the compression would be released, thus allowing the plate package to expand and come in contact with, and be supported by, the fixed supports (Figure 9.6). However, over-compressing the plate package is not usually performed due to the risk of deforming the channel plates. The plates are considered to start deforming with an over-compression of about 1-2%. The A-measurement for the large GPHEs is about four meters, and 1-2% of this is about four to eight centimeters which was assumed to be enough to put the plate package module in place between the fixed supports.

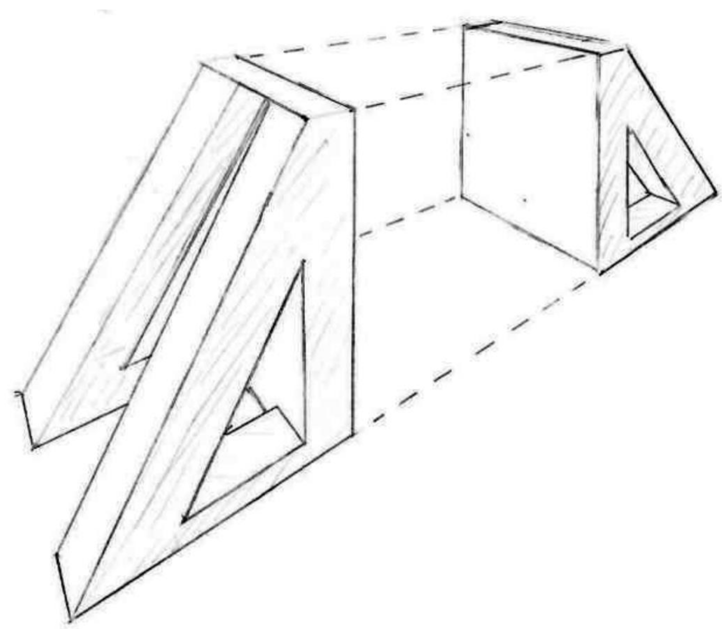

Figure 9.6 Support concept.

10. Calculation analysis

This chapter describes the results of the traditional solid mechanics calculations made for the selected concepts. The analysis focuses on larger components, such as the FP, PP, and the tightening bolts.

10.1 Calculation cases

In this calculation analysis, two different load cases were considered:

1. The frame compresses the plate package to A-measurement.
2. The frame withstands test pressure during operation of the GPHE.

10.2 Assumptions

The tightening bolts were assumed to be made of a material with a yield stress of 730 MPa. The wire material was a high-tensile non alloy steel with unspecified yield stress. All other components (FP, PP, and beams) were assumed to be made by steel S355 with the yield stress of 355 MPa.

Since the pressure vessel standards' way of calculating would be difficult to learn during the time of this master thesis project, the selected calculation approach for this thesis was not standardized. Instead, a more general approach of traditional solid mechanics was used to calculate the approximate dimensions of the components.

The threshold value of the stress, for which the stress in the component was to be below, was selected to be 80% of the material's yield stress. This incorporated a 20% safety margin in the calculations.

10.3 Forces

In the assembly of the GPHE, tightening bolts are used to compress the plate package. The force (F_a) of compressing the plate package to A-measurement is equivalent to the pressure to compress one channel plate gasket multiplied by the length of one gasket and by the width of one gasket. The equation provided by Alfa resulted in an F_a equal to 1,888,120 N.

Alfa Laval also provided an equation that express the force (F_p) when the GPHE operates under test pressure. This equation considered the force needed to endure the test pressure as well as the force needed to maintain the compression of the plate package. The force of enduring test pressure was derived from the surface area of one channel plate multiplied by the test pressure and the static pressure from the water column inside of the GPHE. The force needed to keep the plate package compressed was derived by multiplying the pressure needed to maintain one gasket compressed by the length of one gasket and by the width of one gasket. The resulting F_p equaled 1* N.

The forces used during the calculation analysis are specified in Table 10.1.

Table 10.1 Load cases considered in the calculation analysis.

Load case	*Force*	*Defined variable*
Compress to A-measurement	1,888,120 N	F_a
Withstand test pressure	1* N	F_p

10.4 Bolts

The bolt calculations were based on the tensile stress described in Equation 10.1. The stress level was required to be below 80% of the material's yield stress of 730 MPa. The required number of bolts for each bolt size was documented. For the detailed calculations regarding the bolts, see Appendix E.1.

Equation 10.1 Tensile stress (Björk, 2017).

$$\sigma = \frac{F}{A} \qquad (10.1)$$

The required number of bolts needed to tighten the plate package for each bolt size is presented in Table 10.2. Four M36 bolts were selected as suitable to use to tighten the plate package in each of the refined concepts. The decision to use four M36 bolts was made since it enabled an easy manufacturing process due to the low number of bolts and a bolt size that allowed for manual lifting by one person.

Table 10.2 Minimum number of bolts to tighten the GPHE plate package to A-measurement.

Bolt size	***Number of bolts required***
M100	1
M72	1
M64	1
M48	2
M39	3
M36	4
M30	5
M20	11

The required number of bolts needed to withstand test pressure is presented in Table 10.3. To withstand the test pressure, in the modular concept alternative 1 and modular concept alternative 2, eight M1* bolts were decided to be used. Even though M1*s are heavy and require lifting equipment for assembly to the GPHE, they were deemed the most suitable bolt size. The smallest bolt size, the M1.2*, would not require any lifting equipment, but would result in a very high number of required bolts, thus leading to demanding assembly and disassembly processes. A slightly smaller bolt size, compared to the M1*, would be the M1.1*. However, even the M1.1* would require lifting equipment in addition to a higher number of required bolts. Therefore, the M1* bolt size was decided to be used in the refined concepts using tightening bolts to withstand test pressure.

Table 10.3 Number of bolts to withstand the test pressure.

Bolt size	***Number of bolts required***
M1*	8
M1.1*	15
M1.2*	85

10.5 Thick-wire concept

The components of the thick-wire concept that were included in the calculations were:

- Tightening bolts for tightening the plate package.
- Wire rope.
- FP and PP.

10.5.1 **Tightening bolts for tightening the plate package**

As described in section 10.4, four M36 tightening bolts were used to tighten the plate package to A-measurement.

10.5.2 **Wire rope**

There are many different types of wire ropes available, each designed for different purposes (Bergen Cable Technology, 2023). Wire data was collected from STEEL WIRE ROPE (SWR) who specialized in wire ropes for different industries, e.g. marine, machinery, construction, engineering, and manufacturing (SWR, n.d.). The wire rope calculations were made by dividing F_p with the wires' design loads (collected from SWR) to get the required number of wire ropes for each wire size to withstand the force.

The selected wire rope was the Spiral Strand Rope (OSS) (Figure 10.1). The main properties of the OSS wire are high axial stiffness, high strength to weight ratio, high fatigue resistance, and torque balance. (Teufelberger, n.d.) The calculated required number of wires required to withstand test pressure, are presented in Table 10.4. A alternative wire to the OSS wire is described in Appendix F.

Figure 10.1 OSS wire (SWR, n.d.b).

Table 10.4 OSS wire.

Wire diameter	*Number of wire ropes required to withstand test pressure*
D1*	6
D1.1*	8
D1.2*	64

Wires have different bend radii depending on wire pattern and size. The recommended bending radius for the wire types 6x19, 7x19 and 19x7 are about ten times the rope diameter. (Strandcore, n.d.) The specific recommended bending radius for the selected OSS wires was not found.

Similarly to the reasoning behind the choice to use eight M1* tightening bolts, described in Section 10.4, eight OSS wires with a diameter of D1.1* mm were chosen to be used to withstand the test pressure in the thick-wire concept.

10.5.3 **FP and PP**

The required thickness of the FP and PP was calculated by comparing the von Mises stress (Equation 10.2), which considered the bending stress (Equation 10.3) and shear stress (Equation 10.4), to 80% of the material's yield stress of 355 MPa. The load case considered in this calculation was a point load on a beam between two supports (Figure 10.2). The semicircles were not considered in the calculations. For the detailed calculations made for the FP and PP, see Appendix E.2. The selected thickness of the FP and PP was 1* mm, which was the minimum required thickness to have a stress level below 80% of the materials yield stress.

Equation 10.2 Von Mises stress (Björk, 2017).

$$\sigma_v = \sqrt{\sigma^2 + 3 * \tau^2} \qquad (10.2)$$

Equation 10.3 Bending stress (Björk, 2017).

$$\sigma = \frac{M_b}{W_b} \qquad (10.3)$$

Equation 10.4 Shear stress (Björk, 2017).

$$\tau = \frac{F}{A} \qquad (10.4)$$

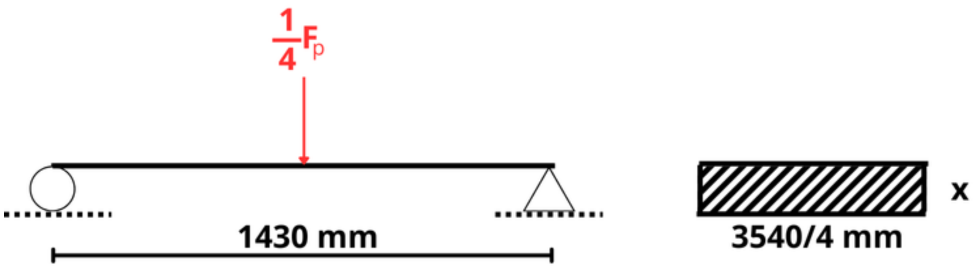

Figure 10.2 Horizontal load case for FP and PP.

10.6 Modular concept alternative 1

The components of the modular concept alternative 1 included in the calculations were:

- Tightening bolts for tightening the plate package.
- Tightening bolts for withstanding test pressure.
- The FP and PP of the plate package module.
- The FP and PP of the frame module.

10.6.1 **Tightening bolts for tightening the plate package**

As described in section 10.4, four M36 tightening bolts were used to tighten the plate package to A-measurement.

10.6.2 **Tightening bolts for withstanding test pressure**

As described in section 10.4, eight M1* tightening bolts were used to withstand the test pressure.

10.6.3 **FP and PP of the plate package module**

The thickness calculations of the plate package modules FP and PP were performed using Equation 10.2, Equation 10.3, and Equation 10.4. These calculations were conducted in a manner similar to those in section 10.5.3, but instead applied to the load case presented in Figure 10.3. For detailed calculations of the FP and PP in the plate package module in modular concept alternative 1, see Appendix E.3. The selected thickness of the FP and PP in the plate package module was the minimum required thickness of 79 mm.

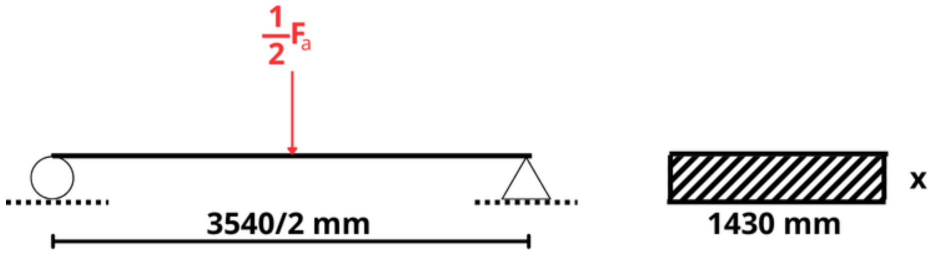

Figure 10.3 Vertical load case for FP and PP.

10.6.4 **FP and PP of the frame module**

This case was assumed to be the exact same as the one described for the thick-wire concept in section 10.5.3. The required thickness of the FP and PP of the frame module in modular concept alternative 1 was therefore 1* mm.

10.7 Modular concept alternative 2

The components of the modular concept alternative 2 included in the calculations were:

- Tightening bolts for tightening the plate package.
- Tightening bolts for withstanding test pressure.
- FP and PP of the plate package module.
- Beams of the frame module.

10.7.1 **Tightening bolts for tightening the plate package**

As described in section 10.4, four M36 tightening bolts were used to tighten the plate package to A-measurement.

10.7.2 **Tightening bolts for withstanding test pressure**

As described in section 10.4, eight M1* tightening bolts were used to withstand the test pressure.

10.7.3 **FP and PP of the plate package module**

As explained in section 10.6.3, the required thickness of the FP and PP of the plate package module was 79 mm.

10.7.4 **Beams of the frame module**

HEM beams were selected for the frame module of the modular concept 2 alternative. The HEM beam is a rigid beam type with strong bending strength. For the modular concept alternative 2, eight horizontal HEM beams, four of which were placed on the FP and four on the PP, were connected using the eight M1* tightening bolts. Each HEM beam had solid pieces of steel at its ends where the tightening bolts would connect (Figure 10.4). Data for HEM beams was gathered from "Tibnor konstruktionstabeller" (Tibnor, 2021).

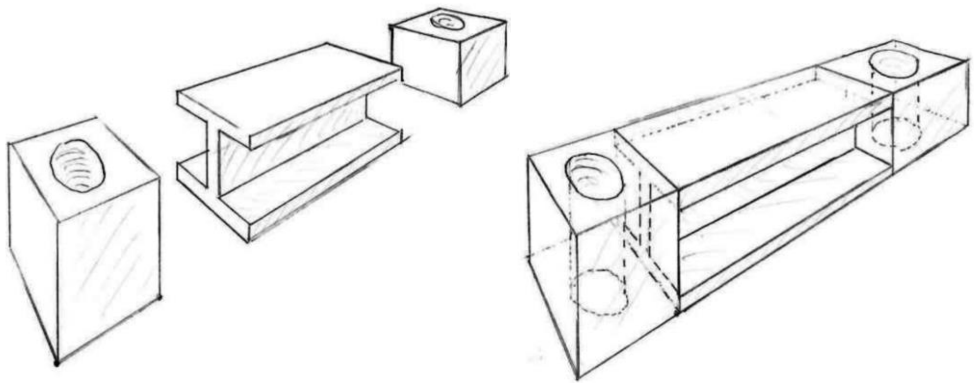

Figure 10.4 Structure of the beams in the frame module of modular concept alternative 2.

The required beam dimension was calculated by comparing the von Mises stress (Equation 10.2) to 80% of the material's yield stress of 355 MPa. Equation 10.3 was used for the bending stress and Equation 10.4 for the shear stress. The load case considered in this calculation can be seen in Figure 10.5. For detailed calculations of the beams in the frame module in modular concept alternative 2, see Appendix E.4. The smallest HEM beam that was able to withstand the test pressure during the set circumstances was the HEM1* beam, hence the four beams on the FP and the four beams on the PP were decided to be of the size HEM1*.

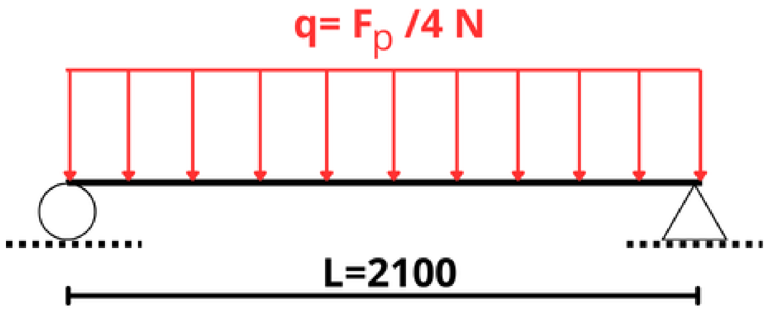

Figure 10.5 Horizontal load case for beams.

10.8 Support concept

The components of the support concept included in the calculations were:

- Tightening bolts for withstanding compression of plate package
- FP and PP compressing the plate package
- Support structure
- Interface between support structure and FP/PP

10.8.1 **Tightening bolts for withstanding compression of plate package**

As described in section 10.4, four M36 tightening bolts were required to be used to tightening the plate package to A-measurement.

10.8.2 **FP and PP for compressing the plate package**

The required thickness of the FP and PP was calculated by comparing the von Mises stress (Equation 10.2) with 80% of the material's yield stress of 355 MPa. Equation 10.3 was used for the bending stress and Equation 10.4 for the shear stress.

The load case considered is seen in Figure 10.6. For detailed calculations of the FP and PP for compressing the plate package in the support concept, see Appendix E.5. The selected thickness of the FP and PP in the support concept to compress the plate package was set to 71 mm as it was the smallest thickness that withstood the force of compressing the plate package.

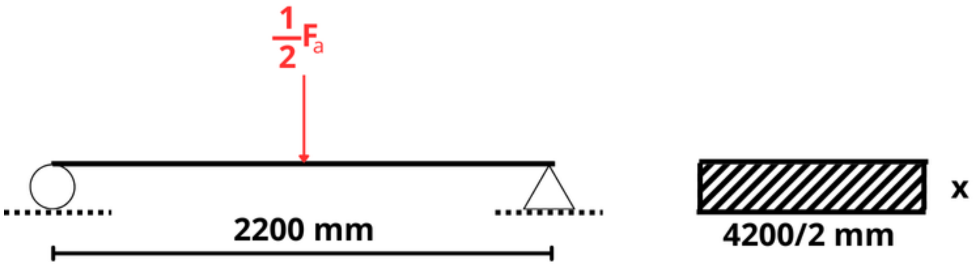

Figure 10.6 Horizontal load case for FP and PP.

10.8.3 Support structure

To get a feeling of the optimal structure of the supports, a topology optimization of the support structure was performed using Autodesk Inventor. In the topology optimization, the test pressure was applied to a preserved surface supporting the plate package. A fixed support was applied to the surface facing the floor. The analysis setting was set to a 60% mass reduction of the original mass. The setup of the optimization is found in Figure 10.7 and the optimization results are presented in Figure 10.8.

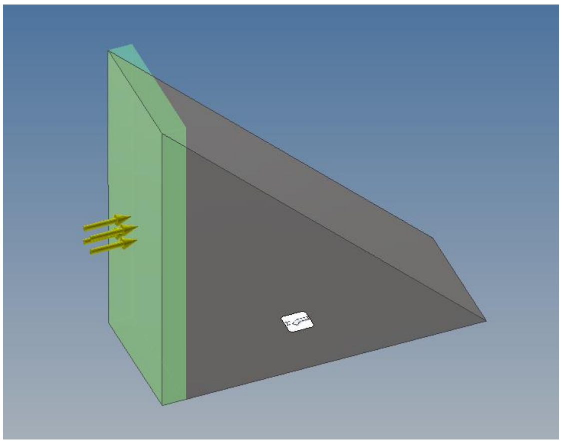

Figure 10.7 Set up for topology analysis of the support structure.

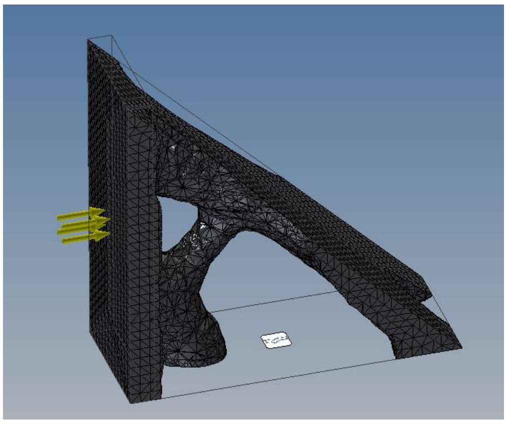

Figure 10.8 Result of topology analysis.

An external search for similar solutions was also conducted. The structure of buffer stops for trains has a similar purpose, see Figure 10.9. When designing the support structure, the buffer stop was used as inspiration alongside the topology optimization.

Figure 10.9 Buffer stops for train (Voestalpine Track Solutions, n.d.).

Calculations were performed for the following four structure cases, see Figure 10.10. Two different angles between the top beams were considered: a 45-degree angle and a 60-degree angle, as illustrated in Figure 10.11.

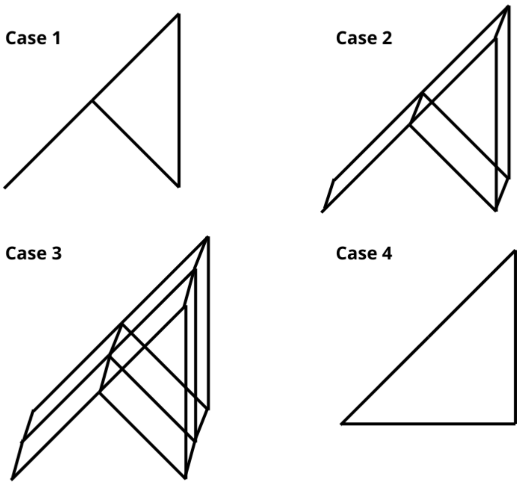

Figure 10.10 Structure cases 1, 2, 3, and 4.

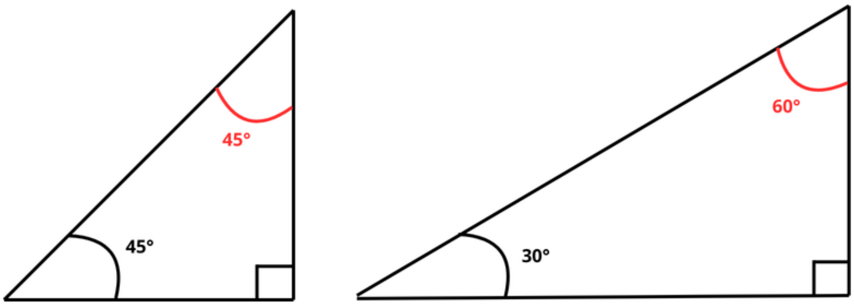

Figure 10.11 Top corner with an angle of 45 degrees and 60 degrees.

Because of the VKR profile's good resistance against buckling, VKR beams were deemed suitable to use in the support structure. Data for the VKR beam was gathered from "Tibnor konstruktionstabeller" (Tibnor, 2021).

The calculations considered buckling and shear stress of the support structure. The buckling was calculated using Equation 10.5 and the shear stress was calculated using Equation 10.4. By setting the P_k value to the actual force, the minimum required moment of inertia was calculated. Similarly, by setting the shear stress to 80% of the material's yield stress, the minimum cross-section area was calculated. The resulting moment of inertia and cross-section area needed for each case with a 45-degree and 60-degree top angle are found in Table 10.5. For the detailed calculations of the support structure, see Appendix E.5.

Equation 10.5 Buckling force (Sundström et al, 2008).

$$P_k = \frac{4 * \pi^2 * E * I}{l^2} \qquad (10.5)$$

Table 10.5 Required moment of inertia (I) and cross-section area (A) for different designs of the support structure.

Structure case	*I [mm4*10^4]*	*A [mm2]*
1 – 45 degrees	1*	1*
2 – 45 degrees	1*	1*
3 – 45 degrees	1*	1*
4 – 45 degrees	1*	1*
1– 60 degrees	1*	1*
2 – 60 degrees	1*	1*
3 – 60 degrees	1*	1*

To withstand the moment of inertia in case 2 with a 45-degree angle, a 1x1* [mm x mm] VKR profile with a thickness of at least 1* mm must be used. However, this beam has a cross-section area of 1* mm^2 which is not close to the needed cross-section area of 1* mm^2. For case 2 with a 60-degree angle, the needed cross- section area was reduced to 1* mm^2. However, the reduction of the required cross-section area was deemed to not outweigh the prolongation of the beams by two meters and the prolongation of the whole GPHE by four meters. An alternative solution would be to instead have three support beams, as in case 3. However, case 3 led to decreased access to the fluid ports of the FP. Therefore, to enhance access to the fluid ports of the GPHE, while at the same time minimizing occupied space, structure case 2 with a 45-degree top angle was selected for further development.

The beam used for this structure would be a 1x1* [mm x mm] VKR profile with a wall thickness of 1* mm. The moment of inertia of this beam exceeds the required value, but it was dimensioned based on the necessary cross-sectional area. An alternative solution could be to use VKR beams with smaller dimensions but a solid cross-section. However, using large beams with a solid cross-section would result in difficulties when welding and attaching the beams in the support structure.

10.8.4 Interface between support structure and FP/PP

Most importantly, the interface between the support structure and FP/PP must withstand the test pressure. Two alternatives were considered for the interface between the support structure and the FP/PP (dotted line in Figure 10.12). The first alternative was to use solid plates and the second alternative was to use a framework of HEM1* beams.

10.8.4.1 Solid plates

Using four support points, two on the bottom and two on the top, on each solid plate resulted in an unreasonably thick solid plate. Therefore, the calculations were performed again using six support points, two on the bottom, two in the middle and two on the top, on each plate. In Figure 10.12, the structure is illustrated from the side showing the support structure supporting the interface.

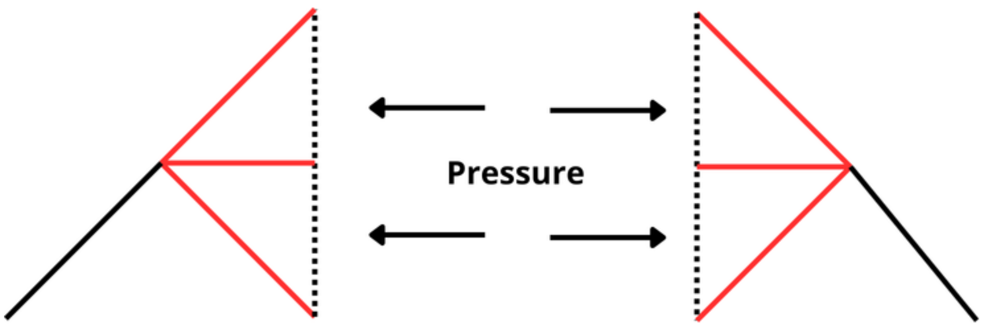

Figure 10.12 The support structures seen from the side, having three supports against the pressurized surfaces.

Similarly to Section 10.5.3, the thickness of the two solid plates was derived using Equation 10.2, Equation 10.3 and Equation 10.4 alongside the load case seen in Figure 10.13. For the detailed calculations of the required thickness of the solid plate, see Appendix E.5. The minimum thickness, required to withstand the test pressure, of the solid plates in the support concept was 1* mm.

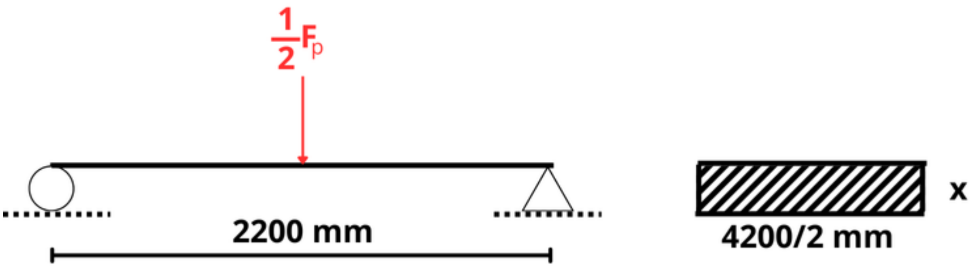

Figure 10.13 Horizontal load case for solid plate.

10.8.4.2 Frameworks of HEM beams

To enable easy access to the port holes, two vertical beams were assessed as the maximum number of vertical beams. Then, the required number of horizontal beams needed to withstand the test pressure was investigated. After that, the required number of support points on the vertical beams was examined.

The horizontal beam was calculated using the same calculation approach as in section 10.7.4 with the load case seen in Figure 10.14. For the detailed calculations of the required number of horizontal HEM1* beams in the framework interface of the modular concept, see Appendix E.5. The calculations showed that, to withstand the test pressure, at least five horizontal HEM1* beams were required to be used on each side of the plate package.

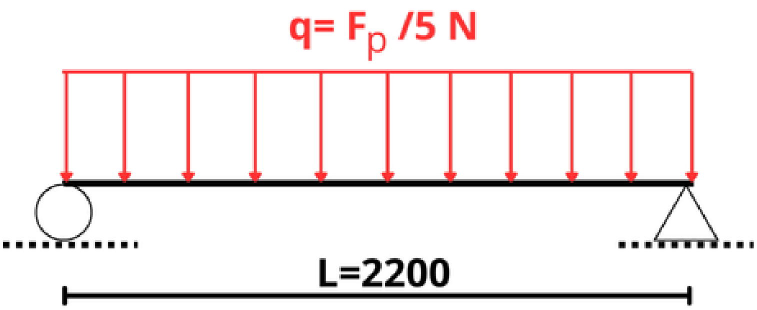

Figure 10.14 Horizontal load case for framework of HEM1* beams.

The required number of support points on the vertical beam was evaluated using the same calculation approach as in section 10.7.4 alongside the load case seen in Figure 10.15 where x denotes the number of required additional supports. For the detailed calculations of the support points of the vertical beams in the HEM beams framework structure, see Appendix E.5.

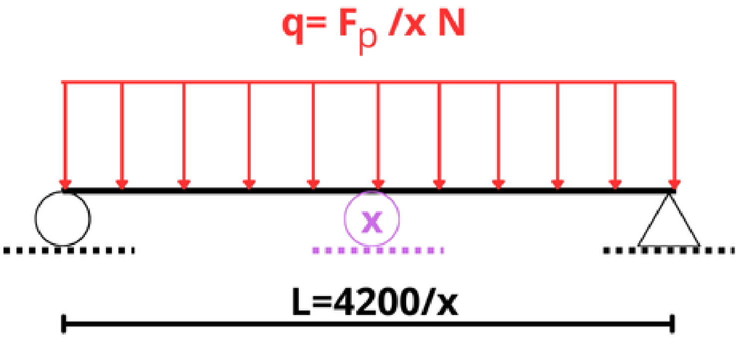

Figure 10.15 Vertical load case for framework of HEM1* beams.

Firstly, when investigating the required number of support points of the vertical beams, the case in which no additional support points were added, i.e. x=0, was examined. The von Mises stress was above 80% of the material's yield stress and therefore not OK. Thereafter, one support (x=1) in the middle of the vertical beam was investigated. For x=1, the von Mises stress was below 80% of the material's yield stress and therefore OK.

The decision was made to use five horizontal and two vertical HEM1* beams to make up the structure of the framework (Figure 10.16). The framework structure requires six support points (red dots in Figure 10.16) for the vertical beams: two support points on the top, two support points in the middle, and two supports points on the bottom (Figure 10.12).

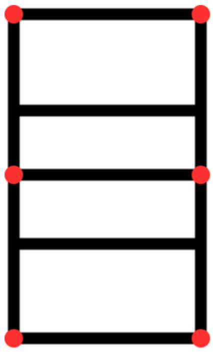

Figure 10.16 Framework structure of the FP/PP with HEM beams.

10.9 Summary of calculated dimensions

All the component dimensions calculated in Chapter 10 are presented in Table 10.6.

Table 10.6 Calculated component dimensions for the refined concepts.

Concepts / ***Components***	***Thick-wire concept***	***Modular concept alt 1***	***Modular concept alt 2***	***Support concept***
Bolts - compress plate package	4 pcs M36	4 pcs M36	4 pcs M36	4 pcs M36
Bolts – withstand test pressure	-	8 pcs M1*	8 pcs M1*	-
Wire rope	8 pcs D1.1* ⌀ OSS	-	-	-
Support structure	-	-	-	1x1x1* VKR, top angle 45 degrees, case 2
Compress plate package	-	79 mm (FP and PP)	79 mm (FP and PP)	71 mm (FP and PP)
Withstand test pressure	1* mm (FP and PP)	1* mm (FP and PP)	4 pcs HEM1* (beams)	5 horizontal beams and 2 vertical beams (HEM1* framework)

11. Defined concepts

This chapter presents CAD designs of the refined concept designs, thus defining the concepts. It further presents data collected from the CAD tool, including weight, storage area, and height for each defined concept.

11.1 Thick-wire concept

The thick-wire concept will be constructed by a FP and a PP with a thickness of 1* mm, four M36 tightening bolts and eight D1.1* mm OSS wires. The thick-wire concept (Figure 11.1) uses wires that are bent around the FP and PP.

The tightening mechanism is performed by first tightening the GPHE to A-measurement by using four M36 tightening bolts placed in the FP and PP corners. When the plate package has been compressed to A-measurement, the D1.1* mm OSS wires are put onto the GPHE's semicircle shelves. The wires are tensioned on both sides of the GPHE simultaneously using turnbuckles.

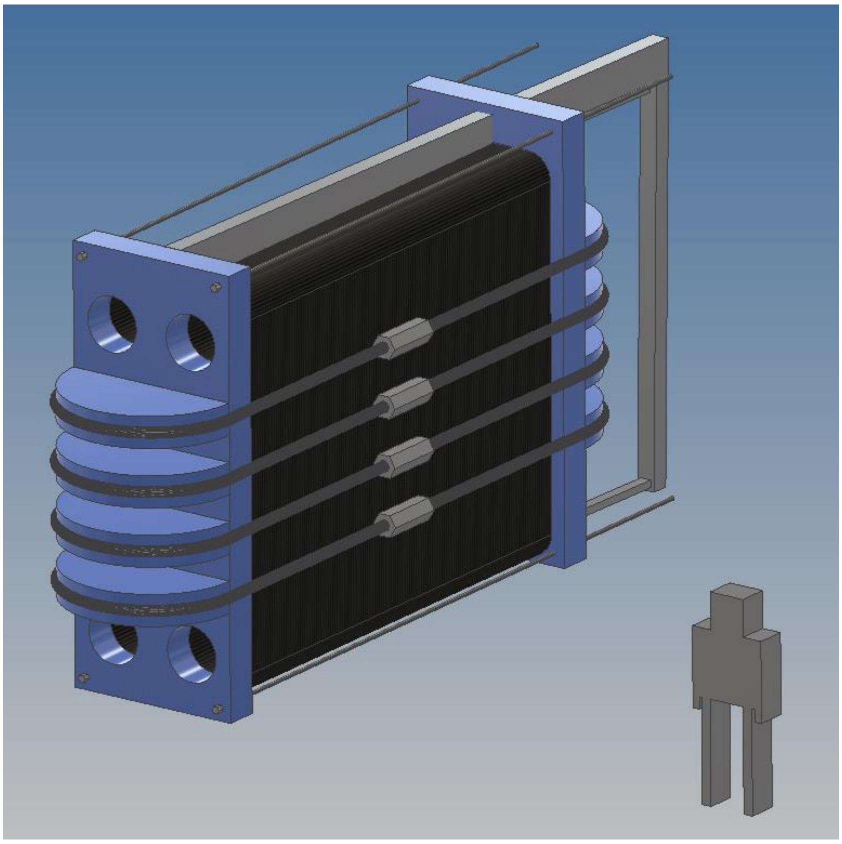

Figure 11.1 Thick-wire concept.

11.2 Modular concept

11.2.1 **Modular concept alternative 1**

Modular concept alternative 1 uses plates in the frame module (Figure 11.2). Furthermore, the concept uses four M36 bolts in the plate package module to tighten the plate package to A-measurement and eight M1* tightening bolts in the frame module to withstand the test pressure. The thickness of the FP/PP in the plate package module is 79 mm and the thickness of the FP/PP in the frame module is 1* mm.

To allow the plate package module to be inserted and removed from the frame module, the plate package module uses two sets of tightening bolts: one set of long bolts and one set of short bolts. When compressing the plate package, the long tightening bolts are used to compress the plate package to A-measurement. When A-measurement has been reached, the long bolts are exchanged into the shorter tightening bolts. Furthermore, when releasing the plate package from A-measurement, the short tightening bolts are exchanged to the set of long bolts to enable the plate package to expand (Figure 11.3).

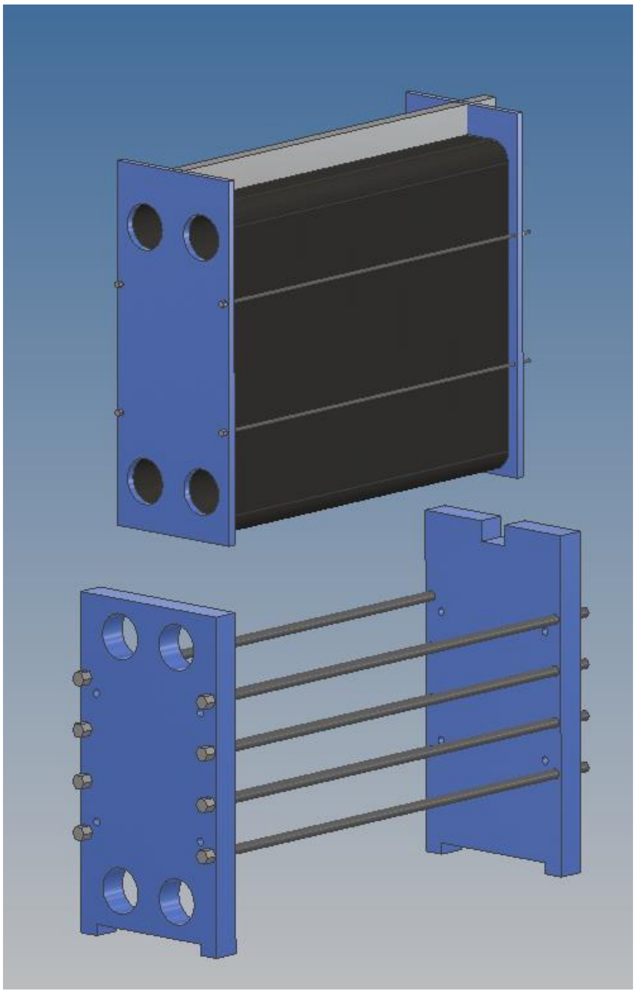

Figure 11.2 Modular concept alternative 1 when the plate package module is separated from the frame module.

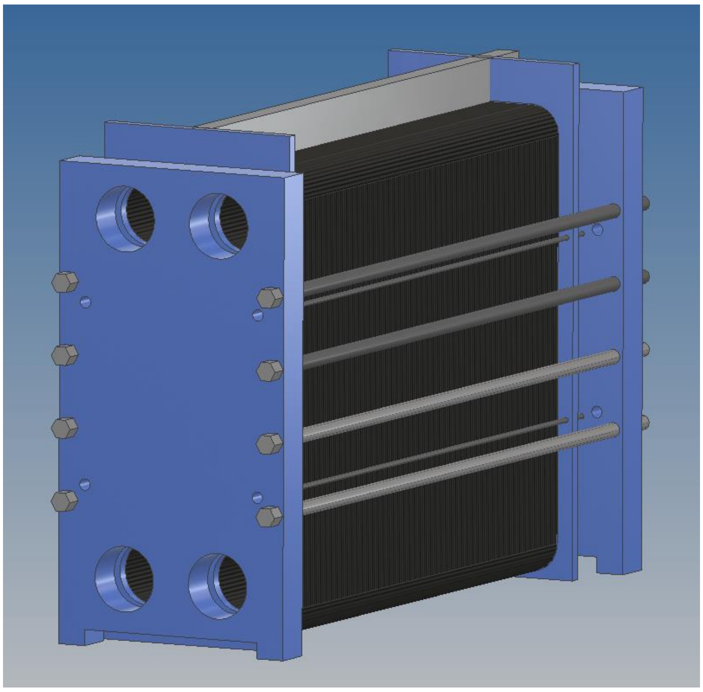

Figure 11.3 Modular concept alternative 1 when plate package module is combined with the frame module.

11.2.2 Modular concept alternative 2

Modular concept alternative 2 uses beams in the frame module (Figure 11.4). The thickness of the FP/PP in the plate package module is 79 mm. The plate package is tightened to A-measurement with four M36 tightening bolts. Four HEM1* beams are placed on the FP and four HEM1* beams are placed on the PP (Figure 11.4). The HEM1* beams on the FP are connected to the HEM1* beams on the PP by eight M1* tightening bolts.

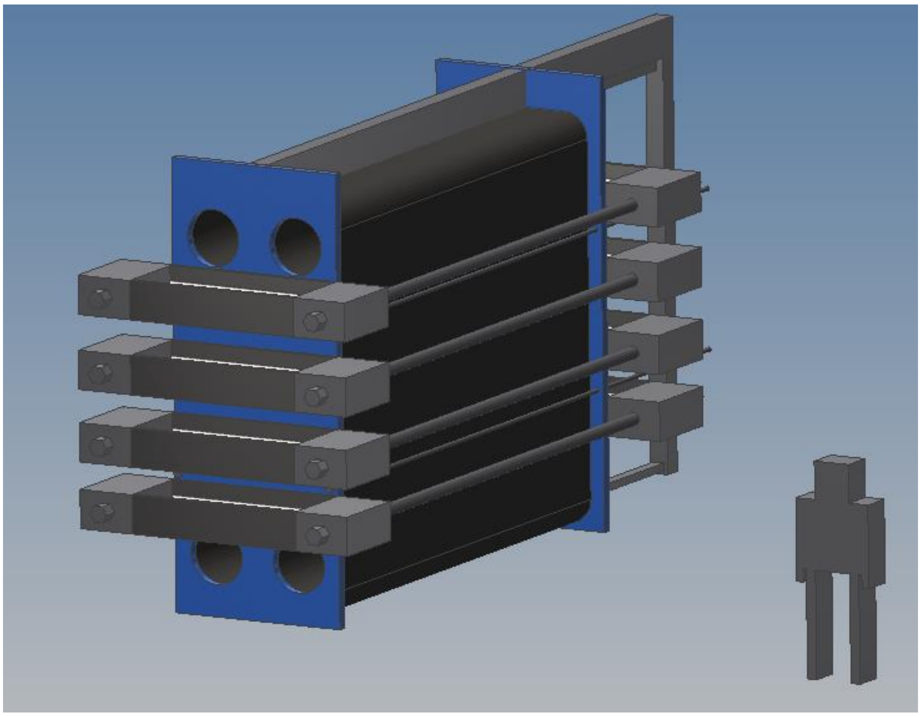

Figure 11.4 Modular concept alternative 2.

11.3 Support concept

The tightening of the plate package is performed using four M36 tightening bolts. The plates, used to tighten the plate package, has a thickness of 71 mm. The support structures are cast into the ground. Furthermore, the support concept has enlarged plates that allow the use of long tightening bolts even when the module is placed in between the two supporting structures (Figure 11.5). The support structures are made of 1x1* mm VKR beams with a wall thickness of 1* mm and the framework that supports the thin plate is made of HEM1* beams (Figure 11.6 and Figure 11.7).

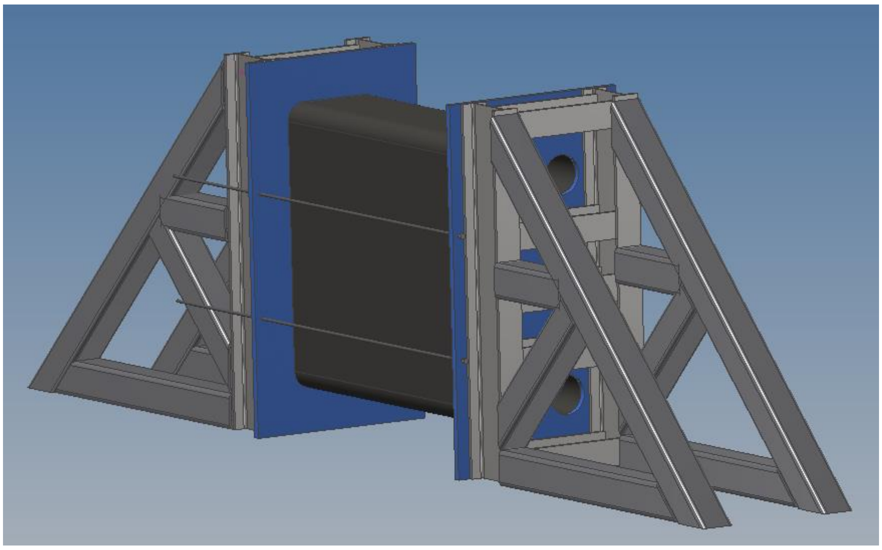

Figure 11.5 Support concept.

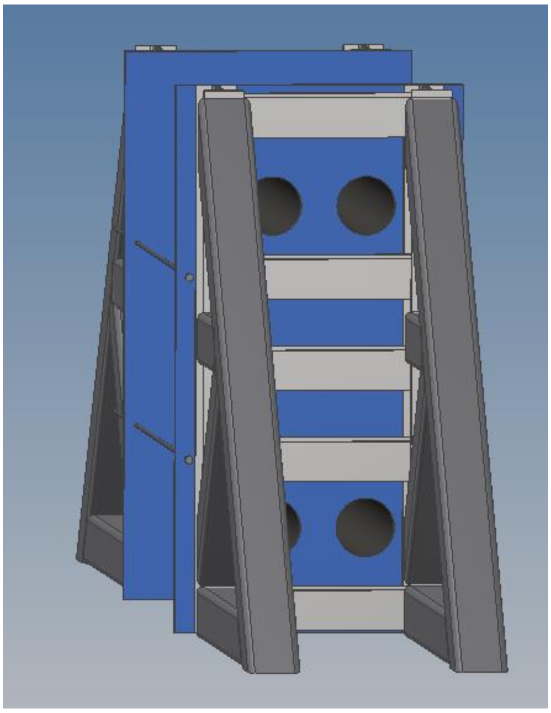

Figure 11.6 Support concept, seen from the front.

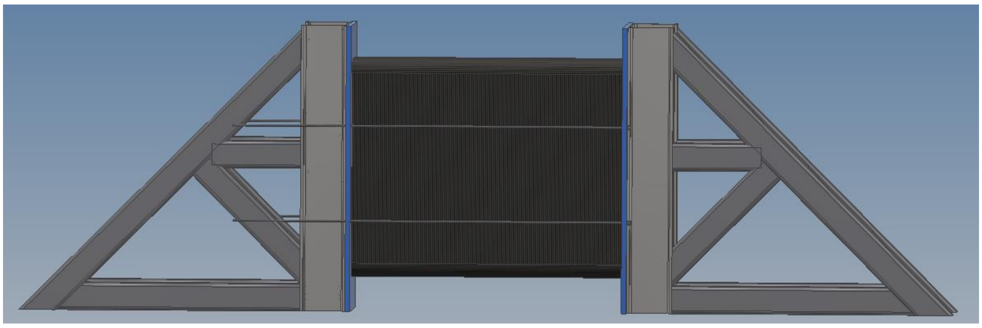

Figure 11.7 Support concept, seen from the side.

11.4 Concept data

The estimated weight, the maximum height, and the required space of the frame concepts were investigated using the CAD tool. The result of the investigation is presented in Table 11.1. The CAD models were not fully defined with all frame components, which likely results in a weight slightly lower than the actual of the complete product. Further, the weight of the plate package was excluded. The plate package length was assumed to be 4,000 mm for all the defined concepts. The operational required space of the concepts was calculated from the rectangular space of the maximum length and width. The height of the GPHE will most likely increase slightly as feet and PP roller were not included in the CAD designs.

Table 11.1 Estimated weight, occupied area, and height of the defined concepts.

Concept	*Weight [kg]*	*Occupied area [m^2]*	*Height [m]*
Thick-wire concept	38 857	10.35 (7241 mm x 1430 mm)	3.54
Modular concept alt 1	32 818	8.91 (5152mm x 1730mm)	3.54
Modular concept alt 2	26 355	16.30 (6996mm x 2330mm)	3.54
Support concept	33 206	30.28 (13763mm x 2200mm)	4.20

12. Concept selection

This chapter presents the concept scoring results and discusses the sensitivity of the concept scoring results.

12.1 Concept scoring

The criteria for the concept screening were based on the needs specified in Section 5.3. The criteria's weighting percentages were set together with Alfa Laval engineers. The scoring of the different concepts was made during the second design review. The rating definition of the scoring criteria is stated in Table 12.1. The current large high-pressure GPHE design was used as a reference when performing the concept scoring.

Table 12.1 Rating definitions.

Relative importance	***Rating***
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

The results of the concept scoring matrix is presented in Table 12.2. The concept scoring rated the "Thick-wire concept" and the "Modular concept alternative 2" as better than the reference, but the remaining two concepts got a lower score than the reference.

Table 12.2 Concept scoring matrix.

	Weights	*Concepts*				
Selection criteria	***%***	***Wire***	***Modular Alt 1***	***Modular Alt 2***	***External support***	***Reference***
Compliance of pressure vessel code	15	2	3	3	2	3
Sustain watertight test pressures	15	4	3	3	4	3
External loads	6	3	2	3	3	3
Tolerance compliance	10	3	2	3	1	3
Environmental corrosion	6	3	3	3	3	3
Easy to service	12	4	2	3	2	3
Sustainable design	4	3	3	3	2	3
Easy to transport	6	4	4	4	4	3
Cost efficient design	4	2	2	2	1	3
High scalability in GPHE range (large, high pressure)	4	4	3	4	4	3
Easy to assemble	10	3	2	2	1	3
Easy to manufacture components	8	3	4	4	3	3
Total score		3.18	2.72	3.04	2.46	3
Rank		1	4	2	5	3

12.2 Sensitivity analysis of scoring

The grading sensitivity was tested by systematically increasing/decreasing the grade by one for the different concepts regarding the different criteria while comparing the concept rankings. A change of the rating in one of the criteria with a low weight percentage does not affect the results of the scoring. However, a criterion with high weight has the potential to change the ranking result between the thick-wire concept (rank 1) and the modular concept alternative 2 (rank 2) if the rating is increased or decreased by one grade.

The weighting sensitivity was tested by increasing/decreasing the weight by 2% for all criteria systematically and comparing the rating of the concepts. The increase/decrease by 2% of any individual criteria did not affect the overall ranking of concepts. Further, sensitivity was also tested by assigning an equal weight to all criteria while keeping the grades the same. However, this did not change the overall ranking order of the concepts.

As a conclusion, the concept scoring was rather stable and did not change with small adjustments. An exception was the thick-wire concept (rank 1) and the module concept alternative 2 (rank 2), where a different grade in the first two criteria would change the ranking order between these two concepts. Taking the sensitivity of the concept scoring in consideration, a concluding ranking of the concept scoring was made and presented in Table 12.3.

Table 12.3 Concluding ranking of the concept scoring.

Rank	***Concept(s)***
1	Thick-wire concept and Modular concept alternative 2
2	Reference (current large high-pressure design)
3	Modular concept alternative 1
4	Support concept
5	-

13. Design review two

This chapter summarizes the content of the second design review and describes the selection process for determining which concepts to move forward with.

13.1 Criteria and weights comments

The engineers considered the defined weight scoring method and most of the chosen criteria relevant for this project. However, they gave a recommendation to remove the criteria “Integrates well with existing production” and “Easy to move in facilities (component)”. They reasoned that these two criteria were giving to much favor to the reference design and that it was obvious that changing the design would lead to some negative short-term consequences. The engineers argued that all changes need to be implemented, which costs money and takes time, especially when a whole new design has been developed. But once the changes are implemented, there will not be any difference in the efficiency of the production system in the long term as the system adapts to the new design.

13.2 Thick-wire concept comments

According to the engineers, the semicircular shelves of the FP and PP provide the plates additional strength which allow a reduction of the thickness of the FP and PP. Furthermore, the wires will support the FP and PP over a larger surface area compared to if tightening bolts were to be used. The engineers considered this a key beneficial aspect of the thick-wire concept.

The thick-wire concept was also considered interesting from a service perspective as the wires might make it easier to access the plate package compared to when using tightening bolts. A suggested aspect to investigate was if the wires can be detached in the middle of the plate package, and still hang in the semicircle shelves of the FP and PP. If the wires can rest on the shelves, the weight needed to be lifted during service would become one fourth of the corresponding weight when using tightening bolts if the weight of the wires and tightening bolts are assumed to be equal.

The engineers mentioned possible concerns about the thick-wire concept regarding the concept's compliance with pressure vessel standards. Unfortunately, there were not any pressure vessel standards experts in attendance during the second design review who could give their input.

13.3 Modular concept alternative 1 comments

The engineers provided insights regarding advantages and disadvantages of the modular concept alternative 1. As the modular concept alternative 1 is modular, it possesses the advantage of being easier to ship compared to the current design; instead of shipping the entire GPHE in one piece, the modular structure allows the different components to be sent individually. Another advantage is that smaller components could enable the use of cheaper production methods compared to when producing big and thick components. However, negative aspects of the modular concept alternative 1 is that more parts must be produced which will most likely increase the total weight of the product. Another concern about this design regard the certification of the GPHE and the required tests. Many certifications need special equipment, making it hard to perform certification tests in customers' facilities. Another concern regarding modular concept alternative 1, put forth by the engineers, is that the plate package must be lifted in and out of the frame. This could potentially be more complicated than expected, for example regarding the tolerances of the FP and PP. However, the engineers suggested that the modular concept alternative 1 would make the service procedure more efficient. During service, the plate package could be removed, and a temporary plate package could be immediately inserted, thus reducing the operational downtime of the GPHE. Once the plate package is serviced, the temporary plate package is removed, and the serviced plate package is re-installed. This led to a discussion among the engineers about possibilities for Alfa Laval to offer GPHEs as a service; the customers own the frame module, but Alfa Laval owns the plate package module, which is then licensed out to customers. This way Alfa Laval can guarantee well-performing GPHEs with regularly serviced channel plates, and at the same time focus on high-quality materials, recycling, and reutilization of components.

13.4 Modular concept alternative 2 comments

Similarly to modular concept alternative 1, the modular concept alternative 2 will, on the one hand, be easier to transport and produce, but on the other hand, problems regarding certification and testing arise. Further, the engineers explained that Alfa Laval already has put many efforts toward investigation of a similar solution a couple of years ago and that Alfa Laval already has good knowledge regarding the strengths and issues with this kind of concept.

13.5 Support concept comments

According to the engineers, many issues remain to be solved to truly be able to evaluate the potential of the support concept. An interesting future avenue of investigation, put forth by the engineers, is to absorb the forces using an external supporting structure. Additionally, for increased scalability in size and design pressure of future large high-pressure GPHEs, the engineers considered the support concept the most promising. However, this concept would alter the GPHE much, both in terms of manufacturing but also in terms of certification due to its new characteristics compared to the current design. Another concern regarding the support concept was how to cast the supporting structures into the ground and how to ensure proper mounting of the plate package in between the supporting structures. Furthermore, each supporting structure is made up of beams which must be welded together, thus introducing high tolerance demands for the beams.

13.6 Design review reflections

The concepts were difficult to evaluate against each other, partly because they were not yet fully defined and partly because they had significant differences in their functions and solutions. Therefore, uncertainty arose about what grade to assign a specific criterion when the concept's function was not yet fully defined. In addition, the differences in the concepts functions and solutions resulted in the criteria having different meanings depending on the concept.

The engineers reacted to the dimensions of the components in the presented concepts as the dimensions were smaller than the engineers were used to for similar solutions. However, no errors were found in the calculations and the analysis approach. One of the engineers that attended the meeting suggested that the reason for the difference in dimensions could be a combination of the safety factor used and the assumptions made during the calculations.

The design review ended in a discussion about which concept that was the most interesting to further research. The engineers found the thick-wire concept the most interesting concept to further analyze in this project. However, they also saw a big potential in the support concept even if it got the lowest grading in the concept scoring. A reason why it got a low grade could be that the support concept was the most different compared to the current design that was used as a reference, thus causing disadvantages for the support concept when being compared to other solutions more similar to today's design. However, the support concept could be a completely new way to build high-pressure frames for large GPHEs. Therefore, the support concept was voted as the second most interesting concept to further develop. Even though there were concerns from before the design review that some of the concepts would have a hard time to satisfy the environmental corrosion requirements, none of the engineers considered this an issue for any of the reviewed concepts.

The engineers' recommendation for the remainder of this project was to focus on the thick-wire and to verify the calculations done with traditional solid mechanics as well as further develop the functions to better understand assembly, service, and transportation activities.

14. FEA

This chapter describes the performed FEA of the thick-wire concept's FP, which aimed to verify the traditional solid mechanics calculations as well as identify any structural design weaknesses.

14.1 Background of analysis

An FEA simulation was made to analyze the stress and deformation that will occur in the FP to verify the earlier calculation as well as to investigate the deformation of the FP and understand the weak spots of the design. An FEA was made because the complexity of the geometry made it hard to assess the stress and deformation accurately with traditional solid mechanics performed by hand. The highest allowed deflection of the FP was set to 1 mm in the product specifications. The material in the FP would be steel S355 and the bolts used are assumed to be made by a material with a yield stress of 730 MPa. The FEA analysis will not analyze the areas where boundary conditions are placed due to singularities. The FEA simulation was made with the tool Ansys Workbench.

Two different load cases were simulated and analyzed:

Simulation 1: Force of tightening the plate package to A-measurement.
Simulation 2: Force of withstanding the test pressure.

14.2 The FEA setup

Firstly, the semicircle shelves were combined with the FP into one part to simulate that the shelves and FP were welded together. In addition, fillets were put on sharp edges to eliminate singularities in the shelves' and port holes' edges. Fillets were added to the edges of the port holes and to the edges of the semicircles which made the result converge in those areas.

The next step was to perform a convergence study. The convergence study was made by dividing the element size until the result converged, i.e., that the stress level differed by less than 5% between the mesh size refinement iterations. The mesh was made finer along the edges of the semicircle shelves than the remaining model. The final mesh used in the simulation is shown in Figure 14.1. The convergence study showed that there were singularities where the M36 bolts were connected.

Figure 14.1 Final mesh.

The boundary conditions were set to “compression only support” on the wire surface, “frictionless support” where the M36 bolts were placed, and a distributed “force” over the whole inside of the FP. To prevent rigid body motion, “displacement” support was assigned to three corners of the model. One of the corners was restricted in three directions, one corner was restricted in two directions, and one corner was restricted in one direction (Figure 14.2).

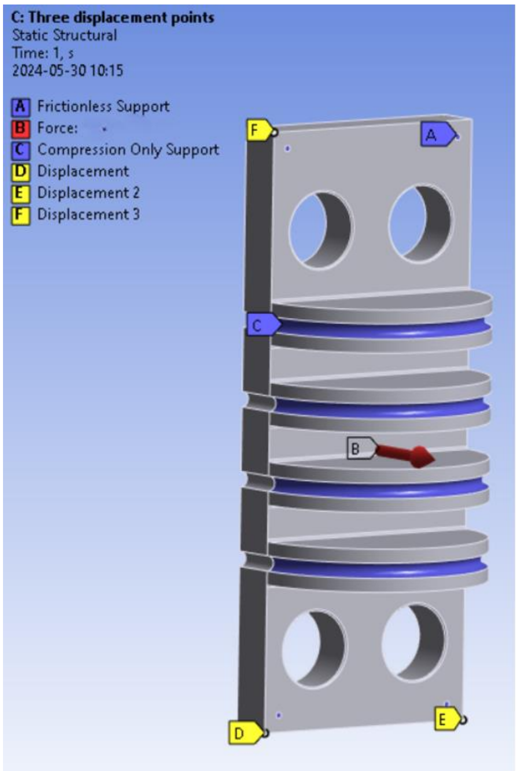

Figure 14.2 Original setup of simulation 2.

However, using the setup seen in Figure 14.2, high stresses arose in the displacement points. Different methods were used try to eliminate rigid body motion while not affecting the stress and deformation result of the simulation. One setup tested was to use a “remote displacement” support, instead of the three “displacement” supports used in the original setup. The “remote displacement” support was fixed in all directions and all rotations (Figure 14.3). Another setup was to set the wire surface as “fixed support” and remove all displacement supports (Figure 14.4). All the setups tested had some flaws, e.g. stress obtained in the hypothetical supports, rigid body motion, or a support type that gave more support than in the real situation. The issue was discussed with engineers at Alfa Laval. Together with the supervisor at Alfa Laval, it was decided OK for this simulation to select the simulation which gave the most conservative results. The setup delivering the most conservative stress and deformation level was the setup using “fixed support” on the wire surfaces (Figure 14.4). The margin of error is assumed to be small as the difference, in both stress and deformation, between the different setups was small. The comparison between the different setups regarding simulation 2 is presented in Appendix G.

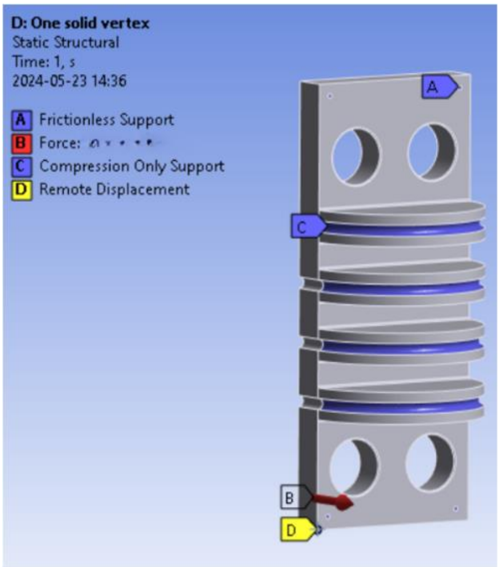

Figure 14.3 Remote displacement support.

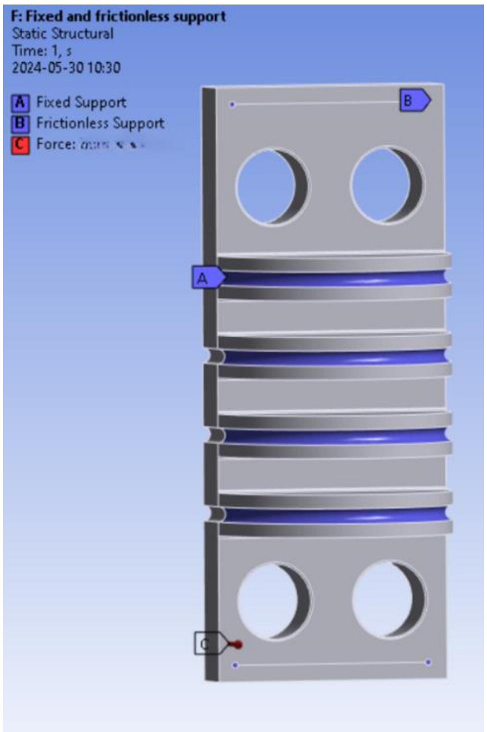

Figure 14.4 Fixed support on wire surface.

14.2.1 **Simulation 1 boundary conditions**

The boundary condition, as seen in Figure 14.5, used in the simulation 1 are:

- M36 attachment points are assigned “fixed support”.
- A distributed “force” load of 1,888,120 N assigned to the inside area of the FP. The force load applied represent the force needed to compress the plate package.

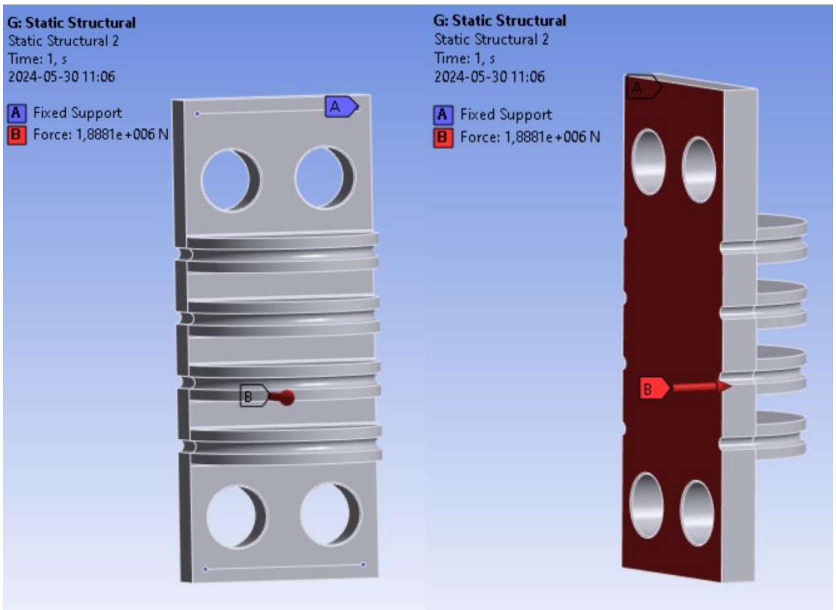

Figure 14.5 Boundary condition in simulation 1.

14.2.2 **Simulation 2 boundary conditions**

The boundary condition, as seen in Figure 14.6, used in simulation 2 are:

- Wire support surfaces are set to “fixed support”.
- M36 attachment points are assigned “frictionless support”.
- A distributed “force” load of 1* N assigned to the inside area of the FP. The force load applied represent the test pressure as well as the force required to maintain the plate package compressed.

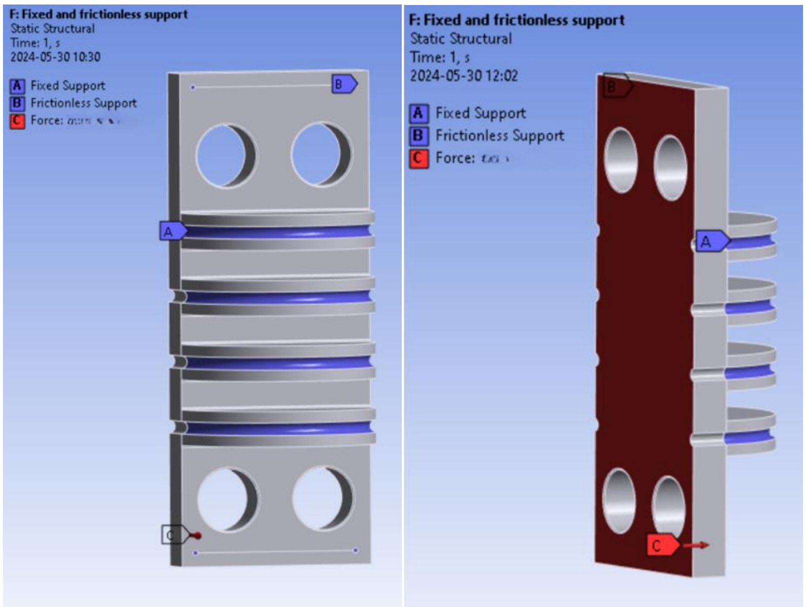

Figure 14.6 Boundary condition in simulation 2.

The applied force load area was a simplification of the real case as the plate package is slightly smaller than the FP and the pressure load is distributed within the gasket. The simplification was made as the geometric shape of the gasket could not be disclosed. The simplification resulted in a more conservative result as more of the force was applied to the top and bottom section of the FP where the wires had less of an impact, thus leading to the tightening bolts placed in the top and bottom sections of the FP experiencing higher loads.

14.3 The FEA results

14.3.1 **Simulation 1: Tightening the plate package to A-measurement**

The first simulation had the highest stress of 605 MPa near the boundary condition for the tightening bolts. The highest stress was a result of a singularity because of the boundary condition added to this surface. The stress level was checked in seven points that were assessed as interesting to investigate (Figure 14.7). All the points investigated had a stress far below the 284 MPa limit (355 MPa reduced by 20%). The second highest stress was 53 MPa located on the fillet of the corner between the top semicircle and the FP. The third highest stress was 27 MPa and was located on the FP in the section between the semicircle shelves. This simulation concluded that that the stress levels were acceptable, and that the material would not start to plasticize in any area.

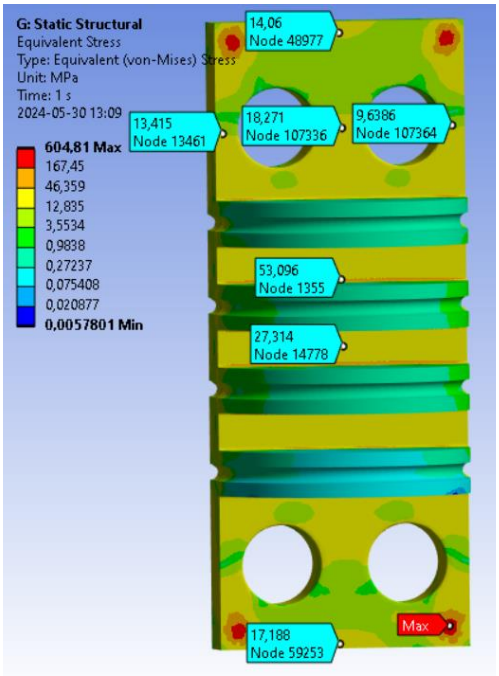

Figure 14.7 Stress distribution in simulation 1.

The deformation of the model was the largest in the middle section (Figure 14.8). The biggest deformation was 1.22 mm. The simulation results were reasonable because the deflection was the highest furthest away from the supports as the wires were not assembled in this step. The requirement set in the project was that the maximum allowed deflection during operation is 1 mm. This configuration will not be used during operation and therefore 1.22 mm is assessed as an accepted value.

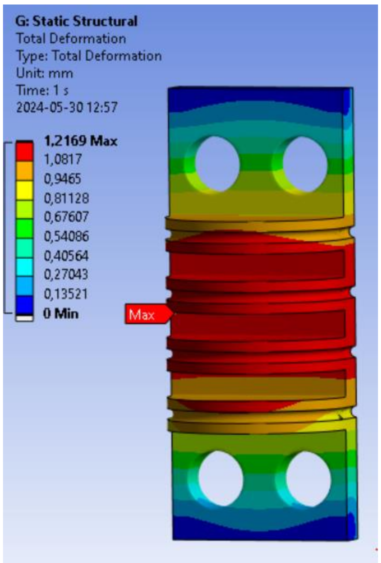

Figure 14.8 Deformation in simulation 1, illustrated in true scale.

The reaction force on the tightening bolts in the FEA simulation was the same as the one derived when traditional solid mechanics were used.

14.3.2 Simulation 2: Withstanding the test pressure

The maximum stress was 751 MPa. However, this stress was the result of a singularity where a boundary condition was placed. Interesting points were selected on the design where the stress was checked. The second highest stress reached 221 MPa and was located in the top section, i.e., in the edge between the semicircle and the FP (Figure 14.9). The location of the stress was reasonable as the semicircles experience the highest amount of force since that is where the wires are connected and carry the largest pressure load. However, this high stress was a result of the chosen radius of the fillet, thus increasing the radius of the corner would reduce the stress level. The level of 221 MPa was below the level of 284 MPa. Therefore, the design is approved; the design will endure the stresses and the material will not begin to plasticize.

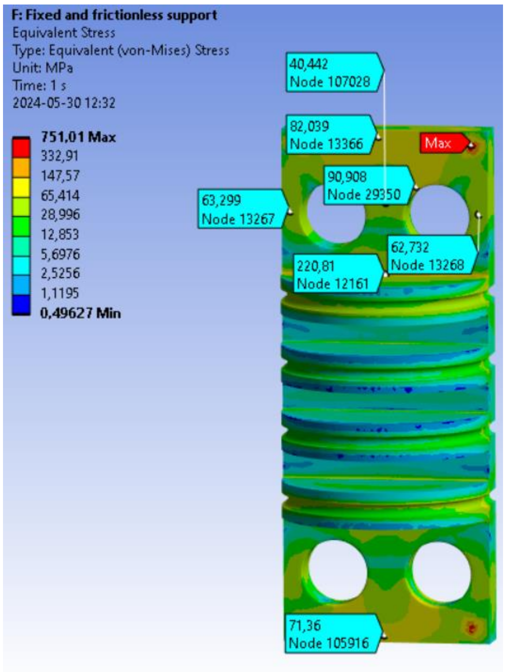

Figure 14.9 Stress distribution in simulation 2.

The semicircles were not analyzed during the traditional solid mechanics calculations and therefore extra attention was given to them during the FEA analysis. The maximum stress in the semicircles was 30 MPa (Figure 14.10).

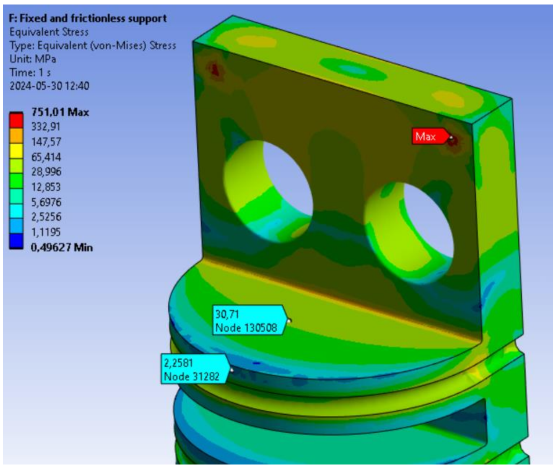

Figure 14.10. Stress distribution of the semicircles in simulation 2.

The biggest deformation of the model was 0.74 mm in the top section of the model between the tightening bolts (Figure 14.11). The result was below the threshold value of 1 mm deformation and was therefore acceptable.

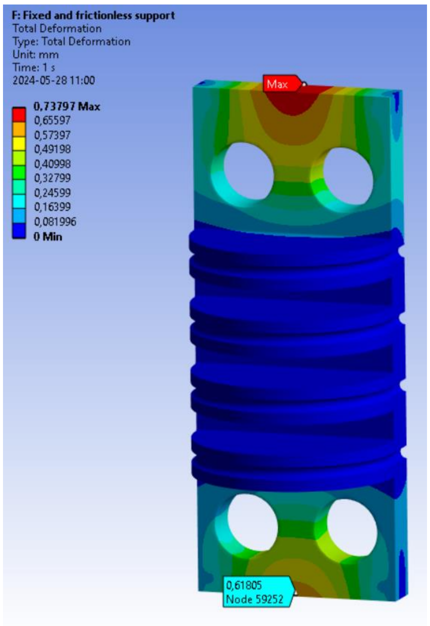

Figure 14.11. Deformation in simulation 2, illustrated in true scale.

The reaction forces for the tightening bolts as well as for the wires were controlled in the FEA simulation (Table 14.1). The comparison of the reaction forces, to the derived forces from the traditional solid mechanics calculations, concluded that the tightening bolt force increased while the wire load decreased.

Table 14.1. Reaction forces in simulation 2.

Component	***Load***
Tightening bolt	Increased compared to calculated F_a in Section 10.3
Wire	Decreased compared to calculated F_p in Section 10.3

The load for one tightening bolt in the FEA was higher than the force derived using the traditional solid mechanics calculations. During the traditional solid mechanics calculations, the tightening bolts were only considered to be involved during the first load case while tightening the plate package. As the stress in the bolt was higher than anticipated, the bolt dimension became too small for the actual load. The necessary bolt dimension to withstand the new force was four M66 tightening bolts.

During the traditional solid mechanics calculations, the wires were considered to withstand a load of 1* N, which was higher than the reaction force found in the FEA simulation. In the traditional solid mechanics calculations, all the forces from the simulation 2 load case would be absorbed by the wires. This means that the wires would be able to carry the load detected in the FEA simulation.

14.4 Discussion of the FEA results

The stresses are in some spots much less than the required 284 MPa. This means that the design is oversized in some areas. To optimize the weight of the design, the material in these regions should be reduced. However, designing the FP and PP as flat sheets of steel would be the easiest and cheapest design to produce and therefore a more optimized design was not investigated.

The detected increase in bolt forces was a result of a stiffness problem in the FP. In the traditional solid mechanics calculations, the wires were assigned all forces from the test pressure. In the FEA analysis, however, the top and bottom sections were attached by bolts, thus causing the bolts to absorb a share of the wires' loads as the FP and PP deflected in the top and bottom section.

In simulation 2, the top section had higher stresses than the bottom section. This was likely due to the height of the top section being larger than the height of the bottom section, which resulted in a bigger distance between the stress zone and the supporting components for the top section.

There were some areas with higher stresses in the design, more specifically around the port holes, in the top section between the tightening bolt attachments, and at the edge between the semicircles and the FP. However, the stresses and deformation around the port holes were assumed to not result in any consequences. Furthermore, the stress in the area between the tightening bolts was well within the acceptable stress limit and the high stress in the edge of the semicircles was assumed to be able to be decreased by slightly increasing the radius of the corners between the semicircles and the FP.

The conclusion of the FEA simulations was that the design is within the acceptable limits regarding the stress level and below the maximum allowed deflection. However, the simulation showed that the original M36 bolt size of the tightening bolts must be increased to M66. The weaker areas of the design were around the port holes, the area between the tightening bolts and in the edges between the semicircular shelves and the FP. However, all areas were within the requirements set in the product specification.

15. BPVC review

This chapter summarizes the content of the interview with a BPVC engineer regarding the strengths and weaknesses of the defined concepts from a regulatory perspective.

15.1 General

Even though the thick wire concept had already been selected as the final concept during design review 2, a meeting was held together with a BPVC engineer at Alfa Laval to hear their input on all the defined concepts, i.e., modular concept alternative 1, modular concept alternative 2, support concept and thick wire concept, as this was of interest for both the evaluation of the selected final concept as well as for Alfa Laval's future evaluation of this project.

The BPVC engineer explained that the foundation to all ASME pressure vessel standards is a cylindrical pressure vessel with a longitudinal weld. Alfa Laval's GPHEs differ a lot from the standard pressure vessel in both geometry and structure. However, it is still possible for Alfa Laval to get ASME approval for their GPHEs if enough information is presented and made available for the ASME organization. The people in the regulatory organizations are specialists within the area.

Further, the BPVC engineer explained that it is possible for Alfa Laval to try to change the BPVC to suit new heat exchanger designs and solutions. However, the process of changing the standards is often long and difficult and takes many years to complete. Implementing changes in BPVC require a lot of information, both empirical data and well-prepared arguments for why the specifical solution or change is needed.

The BPVC engineer provided input on all the defined concepts, which will be described in the following sections.

15.2 Thick-wire concept

The BPVC engineer explained that a wire usually has a low elongation before it breaks. Generally, when the stresses become too high in a pressure vessel, it is desired for the vessel to expand and release the pressure. However, with a wire, the elongation is small, which may result in the wire breaking before the occurrence of a pressure leakage. If a wire breaks under stress, it results in a fast and unpredictable rapture with very high risks. Therefore, wire solutions are often penalized with high safety factors against failure. Additionally, the BPVC engineer comments that it is hard to evaluate the performance of a wire under high and low temperatures, which is something that will be needed to be evaluated to get a regulatory approval.

Further, the BPVC engineer explains that wires are built up by many thin steel threads within the wire rope. Usually, some of the steel threads break when the wire is produced, assembled, and used. For the wire to receive regulatory approval, the threads must be investigated for any thread breakage and its potential extent. A well development method for testing the steel threads is needed.

The BPVC engineer thinks the welded interface between the semicircle and the FP is very important. As the FP and PP want to bend, the semicircles' interface with the FP and PP will experience high forces, which sets high demands for a strong interface. Further, parts that will undergo welding processes must undertake heat treatment to restore the original material properties. One suggested option to avoid welding, as proposed by the BPVC engineer, could be to cast the whole plates and semicircles as one piece. According to the BPVC engineer, casting an FP or a PP cost about the double compared to the current production method of pressing the plates.

In the process of generating and selecting concepts, the belief has been that the wire would provide even support all the way around the semicircle shelves on the FP and PP. However, the BPVC engineer argued that, because the wire is bendable, it would not give support on the outer most part of the semicircle (Figure 15.1). The main force in the wire would be in the direction of the wire. The vertical force component becomes zero at the top of the semicircle because the main force in the cable is 100% orthogonal to the direction of the wire rope. To fully understand how the forces between the wire and semicircles are distributed, the friction between the wire and the semicircles must be considered. However, the BPVC engineer thinks it is hard to take the friction between the plate and the wire into consideration as it is hard to measure. The friction is dependent on many variables and the surfaces can be treated in different ways, such as if the surface is lubricated by the customer.

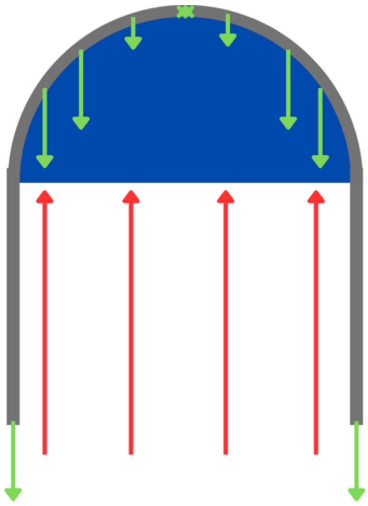

Figure 15.1. Force illustration of the thick-wire concept. Green arrows illustrate the force components in the vertical direction in the wire. The red arrows illustrate the force of the design pressure within the GPHE.

15.3 Modular concept alternative 1

The BPVC engineer considered the crevice corrosion the main problem in this concept. The two painted steel plates would come in contact, causing the paint to scratch off and lead to corrosion of the plates over time. Therefore, the corrosion between these sheets must be controlled. However, according to the BPVC engineer, there currently does not exist any easy way to investigate this corrosion.

15.4 Modular concept alternative 2

The BPVC engineer concluded that the major problem in this concept was crevice corrosion. Similarly to modular concept alternative 1, the beams would be placed on top of the painted FP and PP and the paint will be worn off causing two metal sheets to come in direct contact and corrode over time.

15.5 Support concept

The support concept was based on the supports being cast in the ground. The BPVC engineer explained that this would require the concrete quality and toughness to be tested and evaluated for this specific application.

The BPVC engineer mentioned the fact that the welding processes of the supporting structure would require the supporting structure to undergo heat treatment afterwards to restore the material properties. Performing heat treatment of the supporting structure would be energy demanding and difficult for such a big component. Furthermore, similarly to the modular concepts, the BPVC engineer had crevice corrosion concerns as the support framework would be placed against a painted steel plate.

The support framework would be placed at customers' sites and the GPHE would be assembled outside of Alfa Laval's factories, which would require pressure vessel tests to be performed at customers' facilities. The BPVC engineer considered it possible to certify the GPHE at customers' facilities.

Additionally, the BPVC engineer mentioned a concern not related to the pressure vessel standards. Usually, customers desire the possibility to add more channel plates to the GPHE, thus increasing the size of the plate package by up to 20%. With the current support concept design, it would not be possible to add or remove any channel plates in the GPHE as the supporting structures are fixed.

15.6 Additional information

The current large high-pressure GPHE design has a larger bolt surface area compared to the bolt surface area concluded by this thesis project. The difference in bolt surface area stems from the fact that this thesis project did not follow the approach described in the BPVC standard while the current large high-pressure GPHE did.

According to the BPVC engineer, all external forces should be considered in the process of a BPVC standard approval. An example of such external forces are the forces that arise when lifting the pressure vessel. However, in this master thesis, external forces acting on the GPHE have not been taken into consideration.

16. Final concept

This chapter presents the most promising concept by defining its main functions, suggesting a service procedure, outlining manufacturing methods, and suggesting transportation alternatives.

16.1 Description of the thick-wire concept

The final design will use four M66 tightening bolts to tighten the plate package to A-measurement. The M66 bolts will be placed in the top and bottom corners of the FP and PP. During operation of the GPHE, the design pressure will be withstood by using eight OSS wires with a diameter of D1.1* mm; each wire will be connected to another wire and together reach around the GPHE. The tensioning of the wires will be done using turnbuckles. The FP and PP will have a thickness of 1* mm. Additionally, each of the FP and PP will be equipped with four semicircle supports with a radius of 715 mm. The weight of the frame is approximately 39 tons.

Different turnbuckles were reviewed to investigate if any turnbuckles, that meet the requirements of this application, exist on the market. The company Dawson offers turnbuckles for heavy duty applications within tightening and lashing operations on land and at sea. Their turnbuckles can be used in temperatures between -20 to 200 degrees Celsius. Without customization, they offer turnbuckles with a maximum safe working load of 2,453,000 N. Each wire in the GPHE will experience stresses up to 1* N. The Dawson turnbuckle can tighten the wire approximately 60 cm. (Dawson, n.d) It is possible to buy turnbuckles that meet the large high-pressure GPHE's requirements.

An updated CAD design of the thick-wire concept was created (Figure 16.1). The new changes, compared to the previous thick-wire concept design, are the increased M66 tightening bolts as well as the semicircle shelves that carry the wires when they are not tensioned. The turnbuckle placement is indicated by the bolts' placement on the wires at the sides of the GPHE.

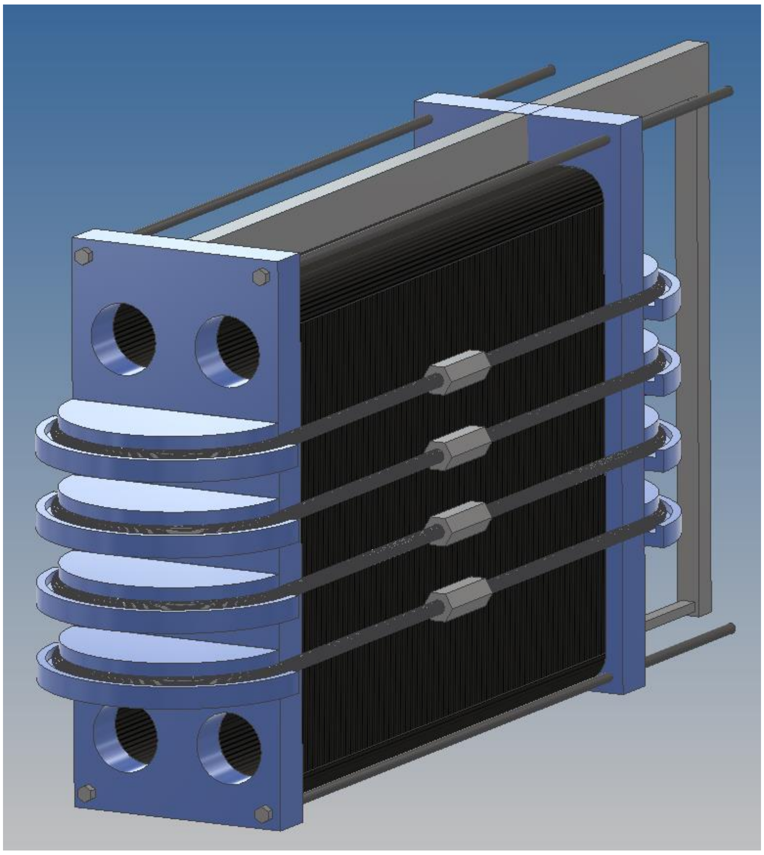

Figure 16.1. CAD model of final thick-wire concept.

16.2 The service procedure

The assembly of the GPHE will be made in the following order:

1. Tightening the plate package to A-measurement with the four M66 tightening bolts.
2. Putting the wires within the semicircle shelves.
3. Lifting and connecting the ends of the wires in the turnbuckles.
4. Tensioning of the wires using the turnbuckles.

The opening of the GPHE will be done in the following order:

1. Releasing the tension in the wires.
2. Detaching the wire ends from the turnbuckles.
3. Letting the wires stay in the semicircle shelves and placing the free wire ends on the ground.
4. Releasing the tightening bolts and opening the GPHE.

16.3 Suggestion of production method

The FP, PP and semicircle shelves are suggested to be casted; the FP and semicircle shelves should be cast as one part and the PP and semicircle shelves should be cast as another part. Casting is preferred to avoid welding processes and their subsequent post-welding treatments to restore the material properties. The casted FP material quality will need to be tested to verify that it meets the regulatory demands. Roughly speaking, casting the plate is about double the cost compared to pressing the plate. However, casting the plate will also save money by reducing the amount of processing of the components.

As this product is a low volume production, and Alfa Laval is not specialized within casting and wires, the production of the casted components and the wires is recommended to be outsourced to companies with special knowledge within the field.

16.4 Transportation of the product

The wire design is recommended to be fully assembled at Alfa Laval production sites and thereafter transported by truck and boat to customers' facilities.

17. Concluding discussion

This chapter includes a discussion of the concepts regarding their potential benefits and limitations. It also covers the sustainability and ethical benefits of this project. Additionally, the chapter comments on project limitations, the project objective and suggested future development.

17.1 Resulting concepts

The project resulted in one final concept. The final concept was the thick-wire concept which would substitute larger tightening bolts with wires and add shelves on the FP and PP in which the wires would be placed. The thick-wire concept would enhance the service procedure as the lifting operations during maintenance is made lighter. Another advantage is that the semicircle shelves, and the fact that the wire is tightened around the FP and PP, would give support in areas where the current design has a high deflection. This would make it possible to reduce the thickness of FP and PP compared to the current frame design. A disadvantage is the more complex structure of the FP and PP, which will require a more expensive production method than for the current frame design. Another disadvantage is that wires are unexplored within the regulatory standards which would require a long process of regulatory approval of the design.

Additionally, two other defined concepts were still considered relevant for future investigation: the modular concept alternative 1 and the support concept. The modular concept alternative 1 offers the possibility of a new business model of the GPHE by letting customers own the frame of the GPHE and Alfa Laval to own the plate package. This would allow Alfa Laval to change their business model by leasing out plate packages to customers, thus providing the customers a more reliable GPHE with regular maintenance and short downtimes, at the same time as Alfa Laval would be able to create better opportunities for business, customer relationship management, and circular material flows. Finally, the support concept has promising design features if there is a desire to further increase the size and design pressures of the GPHE models in the future.

17.2 Sustainability and ethical discussion

GPHEs play a vital role in transforming our societies into more energy efficient ones. In general, GPHE is the heat exchanger to choose for the highest energy efficiency and lowest material use. This project has researched new concepts for large high-pressure GPHE designs to enhance manufacturability, distribution, and maintenance. Possibly, some of the ideas in this project could lay the foundation for a new range of GPHEs that would be more energy efficient to produce and lightweight than the current alternatives.

The maintenance process of large GPHEs is more challenging than that of smaller GPHEs. As GPHEs increase in size, the components' weight and size increase drastically. The equipment in Alfa Laval's facilities can be adapted to the high weight products. However, a concern is that some customers lack the same equipment to perform the maintenance in a safe manner. The suggested concepts in this project have taken the service process into consideration by aiming to make the service procedure simpler and safer to perform for the service operators.

17.3 Limitations

During the concept selection, it was difficult to compare the concepts to each other as well as to the requirements set in the beginning of the project. The concepts that were generated and refined are still not fully developed and there are therefore still some uncertainties about the functions and solutions on a detailed basis.

Some of the concepts generated in this project shared similarities with the current frame solution. These concepts had advantages when graded according to the set requirements and therefore received scores during the grading process that indicated a better performance compared to solutions that are more different compared to today's solution. So, having a concept like today's means that many solutions and issues already are sorted out and adapted to all regulations and laws. However, at the same time, it is very important to consider new solutions that are based on different kinds of technologies to not become outdated and risk losing market shares to competitors. Finding the right balance between setting grades that do not rule out new-thinking concepts but at the same time avoid developing concepts that are too hard to implement is difficult but essential for a conceptual design project of this character.

During the first round of interviews, held with specialists having knowledge of the product and its customers to gather needs for this project, another limitation insight was gained. The specialists were often referring to today's solution and products when explaining the requirements which caused limitations in design freedom. However, according to the engineers at Alfa Laval's development department, all solutions are generally possible to implement and that it is just a matter of time and effort to get the solution developed, accepted, and approved from stakeholders. This led to the learning that a better development approach would be to include product specialists when the concepts are already defined, for example during the design reviews and in the end of the project. This better development approach would increase the design freedom when developing the concepts and instead let the specialists provide input, once the concepts are already defined, regarding how realistic the concepts are to implement. Therefore, the new development approach avoids the trap of generating concepts that aim to improve current solutions instead of redefining the product.

Another limitation of this study was that the calculation method, that investigated the new concepts, differed from the method that was used when developing the current large high-pressure GPHE design. The different calculation methods yielded different component sizes, with this thesis suggesting smaller dimensions compared to those of the current design. Most likely, the difference in dimensions was an effect of different safety factors used in the two projects. This dissimilarity makes it difficult to draw any conclusions about the new designs' weight compared to the current design. The difference also suggests that the dimensions and number of bolts/wires in the new concepts would need to be increased to satisfy an ASME approval.

17.4 Has the project objective been achieved?

The objective of this master thesis was to generate and investigate new frame designs for large high-pressure GPHE frames to give Alfa Laval inspiration for future product concepts. The project resulted in thirteen original frame concepts, of which three were further developed by refining the different concepts' functions and performing calculations of the necessary dimensions to define the frame concepts. All the defined concepts have features that can positively affect manufacturability, maintenance, or distribution of the product. All product specifications, defined in the product specification (Table 6.2), were satisfied by the final thick-wire concept.

The thesis did, however, not result in any concept with clear beneficial advantages compared to the current frame design. Many of the concepts were deemed possible to improve the frame design in some area but that they would also result in disadvantages associated with more complex production and test procedures. How complex it would be to implement the necessary production processes and performing tests was not investigated in this thesis. However, as this is a low volume product, the changes required to implement one of the concepts would likely result in high costs compared to the possible profits of implementation.

17.5 Future development

The first step for future development would be to investigate the different concepts in depth to evaluate if the concepts have some features that can motivate the investment of changing the traditional design. The current frame design is already optimized in many ways, thus making a change in the design will most likely improve some aspects of the GPHE but, at the same time, also impair the GPHE in other aspects.

If Alfa Laval decides to move forward with some of the concepts generated in this thesis, additional calculations of the dimensions, including the praxis of all the latest regulatory standards, should be performed. To improve the calculations in this thesis, an area of improvement would be to more closely follow the calculation procedures outlined in the regulatory standards, for example regarding inclusion of external factors which this thesis did not consider.

Furthermore, the design should be considered on a component level to investigate if current components, such as feet and fluid ports, can be used in combination with the new frame design.

Finally, if Alfa Laval assesses the new design to be able to offer significant benefits, compared to the current frame design, as well as identify a promising market opportunity, the process of having the new frame design regulatory approved should be initiated. The initiation of regulatory approval includes performing tests and convincing the regulatory organizations of the new design’s functionality and advantages.

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Appendix A Project plan

The Gantt chart is a plan for the different project activities deadlines. The preliminary plan (Figure A.1) was developed in the start of this project and the revised plan (Figure A.2) was created when the project report was finished.

A.1 Preliminary plan

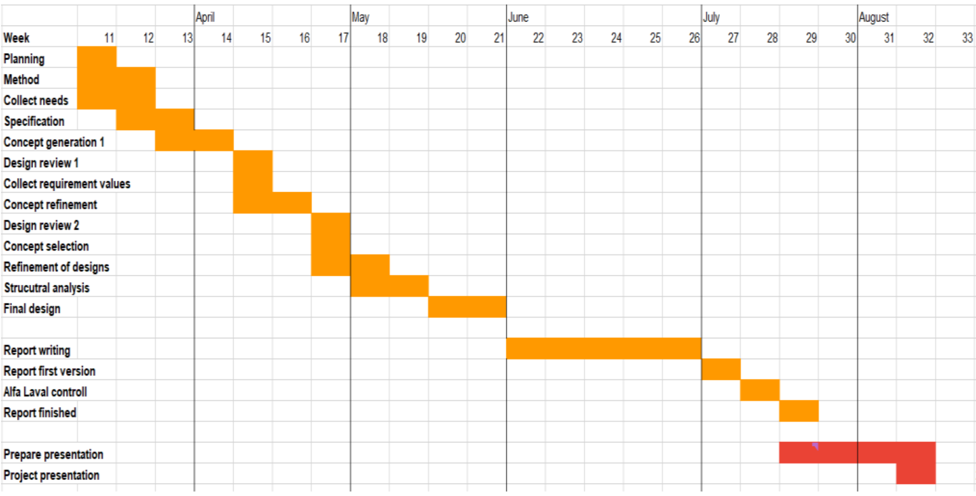

Figure A.1 Preliminary plan for the master thesis project.

A.2 Actual timeline

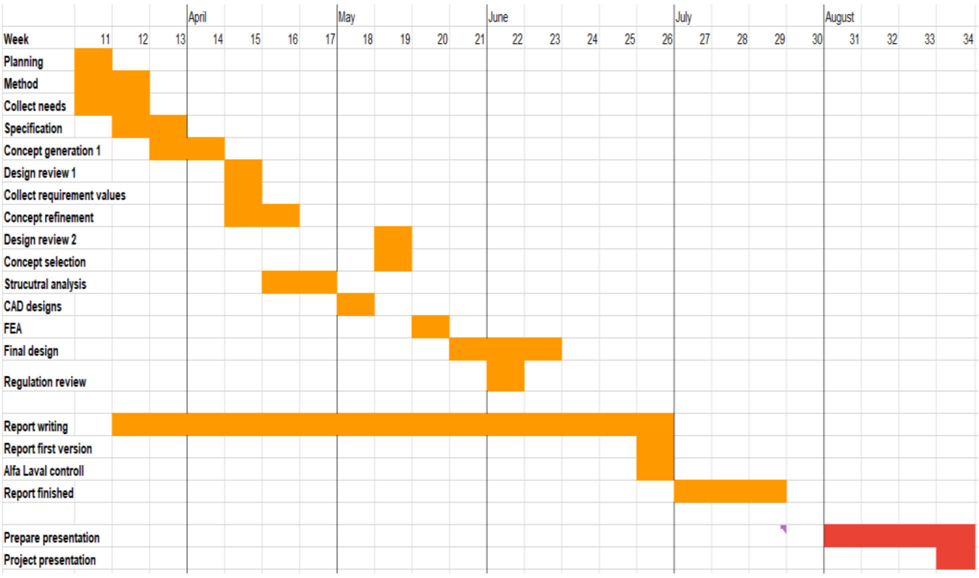

Figure A.2 Revised plan for the thesis project.

Appendix B Interviews

This appendix includes summaries of the conducted interviews with a product manager for large GPHE and a senior development engineer from NPD.

B.1 Product manager, large GPHE

To get a better understanding of customer needs and the product's requirements, the first interview was conducted with a product manager for large GPHEs. The product manager conducted their master thesis at Alfa Laval regarding material properties and started working as an employee at Alfa Laval in 2002 within material science. Since then, the product manager has worked in various positions within Alfa Laval's development departments. The product manager's daily tasks include connecting the stakeholders in development projects, for example, communicating with service, production, development, and the finance department to ensure that projects fulfill all departments' requirements.

The product manager concludes that the two most important desires among customers regarding Alfa Laval's GPHE are:

- Excellent thermal performance
- Excellent mechanical performance

The main goal for customers is to save energy to cut both economic and environmental costs.

The product manager explains that the current large GPHEs are used for many kinds of purposes in all types of industries, for example oil, gas, "heating, ventilation and air conditioning" (HVAC) and petrochemical.

During the interview, the product manager discussed different heat exchanger types. Today, the product manager thinks that the shell-and-tube heat exchanger is the most common heat exchanger type used for this kind of operational demands. The product manager also explained that the welded PHEs are used for high pressure applications. But what makes the GPHE so popular among customers is its ability to be easily serviced and the high efficiency. The product manager also explains that producing a shell-and-tube heat exchanger that is equivalent to a GPHE requires a lot more material and results in a much bigger and heavier heat exchanger with a large environmental impact.

Alfa Laval's GPHEs are either serviced and maintained at customers' facilities or the plate package is removed from the GPHE and transported to an Alfa Laval service center. The most common service needs are to wash off dirt from the channel plates as well as changing old and worn-out gaskets. The service process only considers the plate package, thus leaving the frame of the GPHE untouched. The main problem of the large GPHEs is the size of the components, which makes them harder to serve compared to the smaller GPHEs. To be able to serve the biggest GPHEs, different types of special equipment are needed, such as cranes and forklifts to lift the heavy components. However, according to the product manager, it is common for the customers of large GPHEs to have the required equipment as they usually are large industry companies.

According to the product manager, the operational environment where large GPHEs are used are highly diversified. There are GPHEs placed in, for example, factories, on boats and outside in deserts. There is no standard use case for Alfa Laval's large GPHE. Instead, Alfa Laval offers high customization to customer orders by providing different configurations, special equipment, and materials to suit each customer's specific demands.

The product manager explains that almost all GPHEs today are produced and assembled in Alfa Laval factories. There are regulations and demands that require Alfa Laval to perform pressure tests and other forms of inspections of the GPHEs before delivering them to the end customers. For the large GPHE, Alfa Laval also requires much special equipment to lift the components and ensure proper assembly.

According to the product manager, the most common type of transport, from Alfa Laval facilities to customer facilities, is transportation by either special trucks made for heavy and large cargo or by boat. The biggest problem regarding the transportation of large GPHEs today is the height, since the height makes it difficult to pass under bridges when transporting by truck as well as difficult to fit onto transporting boats.

The product manager explains that the competitors of Alfa Laval’s GPHE are smaller Chinese companies working locally in Asia and a few big companies that work on an international level. The product manager explains that the cost of a GPHE is for many customers vital. Many customers are not familiar with the advantages of a high performing GPHE and therefore tend to buy cheaper and lower performing alternative GPHEs.

Another fact to consider regarding large GPHEs is when the GPHEs become bigger the dimensions increase, thus increasing the demand of customization. For the smaller ranges of GPHEs, there is a higher degree of standardization, for example, standard bolts. In the range of large GPHEs with high demands, the costs increase dramatically because each of the components needs to be produced specifically for Alfa Laval.

B.2 Senior development engineer, NPD

The engineer works as frame development engineer within the group of NPD, focusing on the frame design of GPHE models.

According to the NPD-engineer, the highest loads arrive from the design pressure. The tightening of the plate package to A-measurement requires much less force. The NPD-engineer also explained that going from a medium sized GPHE to one double the size is equal to quadrupling the stresses as the pressure area increases exponentially as both the width and height of the GPHE increase.

The interview continued by discussing the needs and requirements for this master thesis project. As the project has been outlined with a focus on GPHEs, the NPD-engineer considered it necessary to maintain the GPHE’s function at the same time as having as much design freedom as possible.

The following topics were discussed during the interview and were deemed crucial to incorporate in the project in some way.

- Pressure vessel standards.
- External forces on the frame.
- Opening and closing of the frame.

As mentioned in the introduction, Alfa Laval works toward three pressure vessel standards, two of which are PED and ASME. The NPD-engineer specifies that that the verification approach differs between the two standards. While PED assumes that all the material used meets strict material quality standards, ASME anticipates low-quality material. As Alfa Laval only uses high-quality and tested material, PED is easier to satisfy as the material used is already tested. This allows for lower safety factors during structural calculations, which results in lower material usage. For example, the ASME standard results in about twice the amount of required bolts area compared to the PED for the same operational demand.

According to the NPD-engineer, both the ASME and PED frameworks are very comprehensive and complex, often taking many years of experience to fully understand and be able to use correctly. Because this project only will be performed for a couple of months, a specialist in this area will be invited for a design review to evaluate the generated concepts in terms of the pressure vessel standards.

As stated by the NPD-engineer, there are external forces acting on a GPHE. Examples of situations where external forces are present are: lifting of the GPHE, fastening of the GPHE in the foundation, and elevation or movement in the ground (e.g. on a boat) on which the GPHE is placed.

Other central demands in this project mentioned by the NPD-engineer are:

- The GPHE shall be possible and as easy to service as possible.
- The product should be possible to manufacture.
- The channel plate dimensions, and design are not possible to change or adapt. The current design of the channel plate will persist.
- The frame designs must enable connecting pipes to attach to the GPHE.
- The frame should hold up the plate package.
- Compress the plate package.
- Keep the plates in the plate package aligned with each other.
- Consider the price of the solution.

Appendix C Interpreted needs from interviews

This appendix summarizes all the needs for the new large high-pressure GPHE frame, identified from the interview data in Appendix B. The needs were organized into groups of similar needs and the relative importance was set between the needs. A higher number of "" indicates a more important need. Needs without rating were classified as redundant for this master thesis project.*

C.1 Organized list of needs

The GPHE frame design works toward regulations and standards.

*The frame fulfills ASME, PED and/or ALS regulations.

The GPHE frame design can withstand external forces.

**The frame can be lifted.

**The frame can be connected to the ground.

* The frame can withstand lateral loads due to inclined ground.

The frame can withstand fatigue.

The GPHE frame can withstand internal forces.

***The frame can compress the plate package to A-measurement.

***The frame can maintain a watertight test pressure.

The frame can withstand test pressure.

The frame can withstand pressure drops and pressure tops.

The GPHE frame is easy to service.

**The frame allows for easy release of compression of the plate package.

**The frame allows for easy insertion and removal of the channel plates when the GPHE is opened.

The tightening bolts can easily be removed from the GPHE.

*The frame can be serviced with standard customer tools.

The frame can be opened quickly.

The frame allows for easy access to critical components, such as connectors and tightening bolts.

The GPHE frame maintains the plate package position.

**The frame can carry the plate package above the ground.

***The frame can maintain the straight alignment along the orthogonal axis of the plate package.

The GPHE frame is compatible with components not included in the frame.

The frame can connect to different port connections.

**The frame is compatible with the current channel plate design.

The frame is compatible with the current gasket design.

***The frame has acceptable tolerances in its interface with the plate package.

The GPHE frame is economically feasible to produce.

*The frame can be produced with economically feasible methods.

The frame can be produced with economically feasible materials.

*The frame can be produced using Alfa Laval’s and suppliers’ current production capabilities.

The frame can use components that already exist in Alfa Laval’s range of components.

The GPHE frame is easy to manufacture.

**The frame components are easy to handle in Alfa Laval production facilities.

The frame is easy to assemble.

*The frame has a shape that is manageable during production.

The GPHE frame is easy to transport.

**The frame can be transported by road.

The frame can be transported by sea.

The GPHE frame is convenient for the end user.

The frame is efficient in terms of storage area used.

The frame is easy to install in customers' facilities.

***The frame preserves the characteristics of a GPHE.

The frame is sustainable.

The frame only needs maintenance during service.

The GPHE frame can be used in different environments.

The frame can withstand rain.

*The frame can withstand heat.

*The frame can withstand freezing temperatures.

The frame can withstand salt water.

**The frame can withstand a corrosive environment.

The frame can withstand desert winds.

**The frame can withstand corrosive process mediums on its surfaces in contact with the plate package.

*The frame has a lifetime of 40 years.

Appendix D Solution search

This appendix describes the results of internal and external solution searches. The result of the searches acted as inspiration during the concept generation in this master thesis.

D.1 Internal search

In this phase of the project, Alfa Laval chose not to share any information about their ideas of possible solutions. The focus was instead on searching internally in Alfa Laval databases for relevant documentation. Alfa Laval did not want to influence the solution in the early stages of the project. After the preliminary concept generation phase, a design review was conducted with six Alfa Laval engineers to gather input and leverage their expertise in the field to further develop and generate more solutions.

D.1.1 Database search

Alfa Laval offers three main types of PHEs: brazed and fusion bonded PHEs, GPHEs, and welded PHEs. In this section, the high-pressure PHE models of "brazed and fusion bonded" and "welded" are analyzed.

D.1.1.1 Brazed and fusion bonded PHEs

The brazed and fusion bonded PHEs are compact and maintenance free solutions for heating, cooling, evaporation, and condensing. Alfa Laval's most extreme version of this range is the AXP series. Alfa Laval AXP stands for extreme pressure and the maximum PED approved pressure for this series is 167 bar at 90 degrees Celsius. (Alfa Laval, n.d.d) To hold the channel plates together, this type of heat exchanger uses brazing seals between the channel plates. The heat exchangers of the AXP series have thin external frames of carbon steel that allow the AXP heat exchangers to withstand extremely high design pressures. The Alfa Laval AXP112 (Figure D.1) is the biggest heat exchanger in this product series and is capable to work with a pressure of 140 bar at temperatures between -20 to 150 degrees. (Alfa Laval, n.d.e)

Figure D.1 Alfa Laval AXP112 (Alfa Laval, n.d.e).

D.1.1.2 Welded PHEs

Four types of welded PHE designs exist. The most suitable type to investigate, for this thesis, was the welded plate-and-block heat exchanger, also known as Compabloc (Figure D.2). The Compabloc has a different design than the brazed heat exchangers and the GPHEs (Figure D.3). Welded PHEs are used in the most demanding environments and applications. (Alfa Laval, n.d.f), as they can withstand temperatures ranging from -100 degrees to 400 degrees Celsius and design pressures of up to 60 bar. (Alfa Laval, n.d.g)

Figure D.2 Compabloc heat exchanger (Alfa Laval, n.d.h).

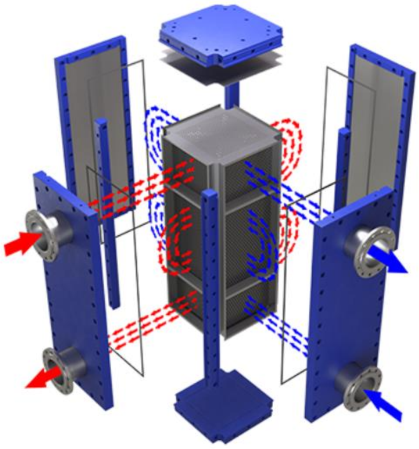

Figure D.3 The fluid flow inside a Compabloc (Alfa Laval, n.d.i).

D.2 External search

The focus of the external search was to investigate competing high pressure frames, compressing solutions and solutions that endure very high tensile forces. Additionally, a patent search for PHE was made.

D.2.1 GPHE

The company Hisaka produces a variety of heat exchangers (Hisaka, n.d.). A notable difference between their large GPHE and Alfa Laval's large GPHE, is Hisaka's inclusion of horizontal supports attached to the FP (Figure D.4).

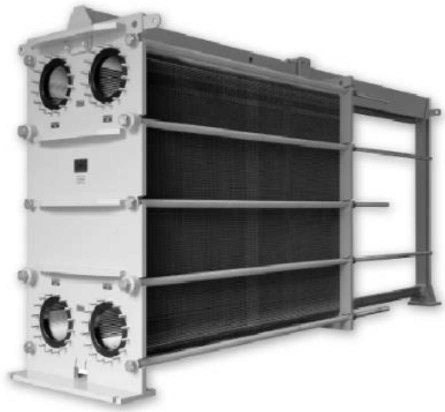

Figure D.4 GPHE Hisaka (Hisaka, n.d.).

Two other companies, within the segment of GPHE, are Tranter and Sondex. However, their GPHEs do not have any additional design features compared to Alfa Laval's GPHEs.

A result of the external search for competing GPHE designs, was the conclusion that all current GPHE designs on the market are very similar in design and functions.

D.2.2 Shell-and-tube heat exchangers

The next step of the external search was to research high-pressure heat exchangers on the market. From an online investigation, the conclusion was made that the heat exchanger type, able to withstand the highest design pressures, was the shell-and-tube heat exchanger. In Figure D.5, three shell-and-tube heat exchangers are shown. The three heat exchangers in Figure D.5 weigh 25 600 kg each and can withstand design pressures of up to 87 bar. (OVS, n.d.a)

Figure D.5 Shell-and-tube heat exchanger (OVS, n.d.a).

In Figure D.6, another shell-and-tube heat exchanger is shown. This heat exchanger can withstand a design pressure of 250 bar. (OVS, n.d.b)

Figure D.6 Shell-and-tube heat exchanger (OVS, n.d.b).

D.2.3 Wires

Wires are generally famous for their high tensile strength. Wires are, for example, used in bridges (Figure D.7) and as road barriers (Figure D.8).

Figure D.7 Bridge cable (Tordis, n.d.).

Figure D.8 Road barrier ropes (SWR, n.d.d).

One way of tensioning wire ropes is by using turnbuckles (Figure D.9). Turnbuckles exist in all sizes and can be used to tension wires in, for example, suspension bridges, large buildings, and road barriers. (Mazzella Companies, 2020)

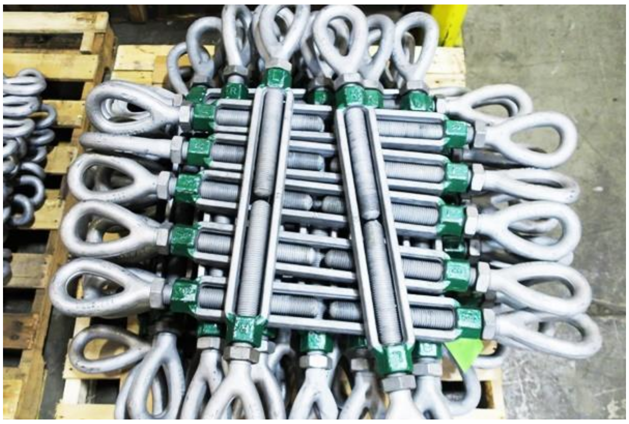

Figure D.9 Turnbuckles (Mazzella Companies, 2020).

D.2.4 Lightweight strength

An interesting solution to make structure lightweight is by using a truss structure (Figure D.10). By using truss structures, it is possible to create stiff structures with relatively low weight.

Figure D.10 Truss bridge (Bridge Masters, 2017).

A material that often is used in high stiffness and low weight applications is carbon fiber reinforced plastic (CFRP). During the online search, a company called Horse was found, who sold CFRP fabric to repair and improve structural strength of concrete structures (Figure D.11). This solution could potentially be combined with steel to reinforce the steel structure in the GPHE without substantially increasing the weight.

Figure D.11 CPRF fabric for reinforcement (Horse, n.d.).

D.2.5 Compressing solutions

As the main function of the GPHE frame is to compress the plate package and to withstand the design pressure during GPHE operations, another interesting avenue of research was pressing tools. From the investigation of pressing tools, two kinds of presses turned out to be of interest: hydraulic presses (Figure D.12) and screw presses (Figure D.13).

Figure D.12 Hydraulic press (Beckwood, n.d.).

Figure D.13 Screw press (HAHN+KOLB, n.d.).

D.2.6 Patent search

A patent search was conducted on Espacenet, which is a free patent database developed by the European Patent Office (Espacenet, n.d.). The search primarily reviewed the drawings of patents to find inspiration for new designs. The detailed descriptions of solutions in the patents were not considered in detail. Two interesting patent classes to review, for this thesis, were F28D and F28F, with a particularly interesting subclass being F28F9/0075. The content in the different classes is stated in Table D.1.

Table D.1 Patent class definitions (Espacenet, n.d.).

Patent class	*Definition*
F28D	“HEAT-EXCHANGE APPARATUS, NOT PROVIDED FOR IN ANOTHER SUBCLASS, IN WHICH THE HEAT-EXCHANGE MEDIA DO NOT COME INTO DIRECT CONTACT“
F28F	“DETAILS OF HEAT-EXCHANGE AND HEAT-TRANSFER APPARATUS, OF GENERAL APPLICATION”
F28F9/007	“Supports for plates or plate assemblies”

Numerous patents related to GPHEs were reviewed. Some of the interesting patents were: KR20230122824A (Hong & Yooin, 2023), CA2877142A1 (Albrecht et al., 2013), GB2127535A (Derry, 1984), CN116518450A (Xu & Dong, 2023), and EP2087306A1 (Hoeglund et al., 2009). However, there were no specific patent regarding large high-pressure GPHE found during the search.

The CA2877142A1 describes a heat exchanger with accessible core (Figure D.14). The patent describes a heat exchanger with a core and a shell, where the shell can be removed to perform maintenance of the core.

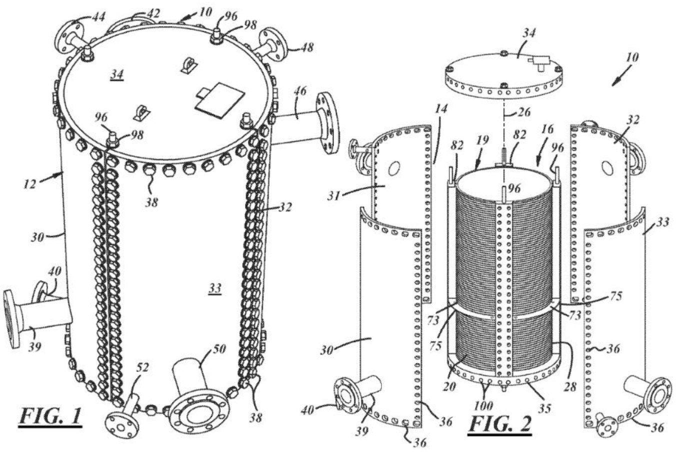

Figure D.14 Heat exchanger with accessible core (Albrecht et al., 2013).

The patent GB2127535A is a heat exchanger solution made for heat recovery (Figure D.15). The heat exchanger uses plate-fin construction cores which are slidably located in a framework.

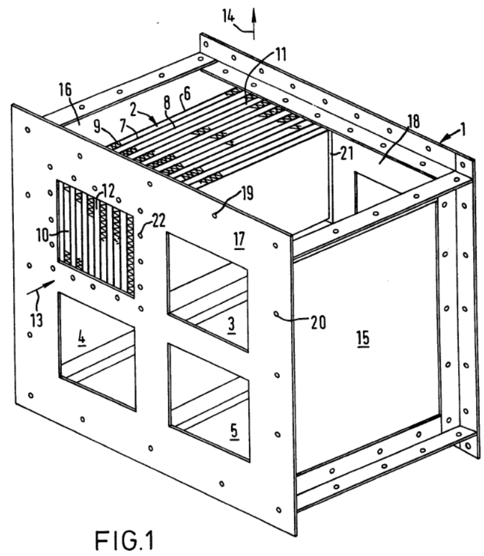

Figure D.15 Heat exchanger patent (Derry, 1984).

The patent CN116518450A provides a plate type heat exchange unit to facilitate cleaning, disassembly and assembly of the heat exchanger plates (Figure D.16).

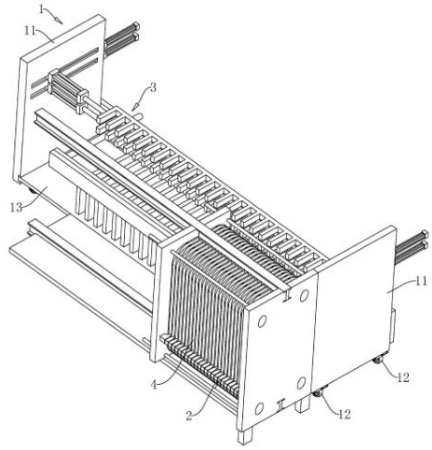

Figure D.16 Plate type heat exchange unit (Xu & Dong, 2023).

The patent EP2087306A1 is an innovation describing a solution to tighten and untighten a plate package (Figure D.17).

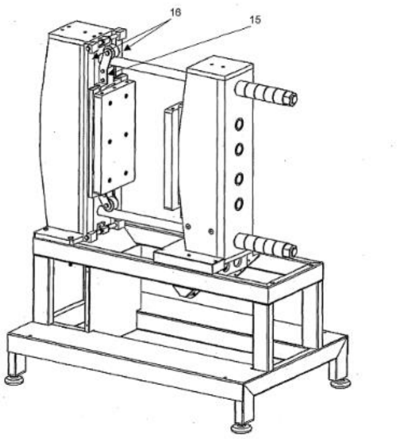

Figure D.17 A clamping device for flow module plates, reactor plates or heat exchanger plates (Hoeglund et al., 2009).

Appendix E Calculations

In this appendix, the traditional solid mechanics calculations, performed during the project, are presented in detail.

E.1 Bolts

Equation E.1 describes the equation of tensile stress, and this equation was used to obtain the required bolt dimensions.

$$\sigma = \frac{F}{A}$$ (Equation E.1)
(Björk, 2017)

Equation E.2 and Equation E.3 were combined with Equation E.1 which resulted in Equation E.4. Equation E.4 describes the number of bolts required to tighten the plate package as a function of the bolt size. "*A*" is the total area of the bolts, "*a*" is the area of one bolt and "*n*" is the number of bolts. A graph of Equation E.5 is presented in Figure E.1.

$$A = a * n$$ (Equation E.2)

$$\sigma \leq \sigma_y * 0.8$$ (Equation E.3)

$$n = \frac{F_a}{a * 0.8 * \sigma_y}$$ (Equation E.4)

$$n = \frac{1{,}888{,}120}{(\frac{Diameter}{2} * \pi)^2 * 0.8 * 730}$$ (Equation E.5)

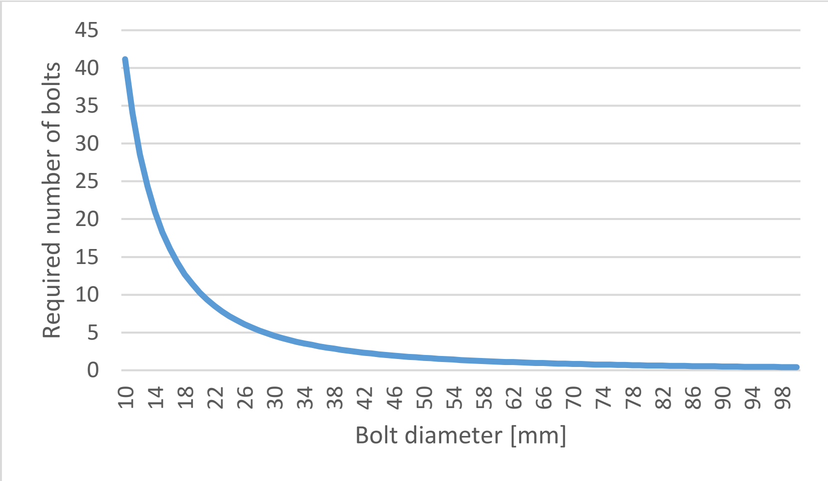

Figure E.1 Required number of bolts for tightening the plate package to A-measurement.

The number of bolts required to tighten the plate package to A-measurement is presented for each bolt size in Table E.1.

Table E.1 Number of bolts to tighten the GPHE plate package to A-measurement.

Bolt size	*Number of bolts required*
M100	0.41
M72	0.79
M64	1.00
M48	1.78
M39	2.70
M36	3.17
M30	4.57
M20	10.29

Equation E.6 describes the number of bolts required to withstand the test pressure as a function of the bolt size.

$$n = \frac{F_p}{(\frac{Diameter}{2} * \pi)^2 * 0.8 * 730} \qquad \text{(Equation E.6)}$$

The number of tightening bolts required to withstand test pressure is presented for each bolt size in Table E.2.

Table E.2 Number of bolts to withstand test pressure.

Bolt size	*Number of bolts required*
M1*	7.59
M1.1*	14.64
M1.2*	84.33

E.2 Thick-wire concept

For the thick-wire concept, the tightening bolt dimensions for compression of the plate package to A-measurement was calculated in Appendix E.1. Furthermore, the wire dimensions, used in this concept, were derived in Section 10.5.2.

E.2.1 FP and PP

In the thick-wire concept, the FP and PP must withstand both compression of the plate package and the test pressure. Eight OSS wires with a diameter of D1.1* mm were needed to withstand the force of the test pressure. The assumption was made to divide the FP and PP into four sections, each section having one pair of wires (Figure E.2). All four sections were assumed to show the same behavior and, therefore, the calculation was only performed once. The sections were simplified as a quadratic solid beam made of 355 MPa steel. The horizontal (Figure E.3) and vertical (Figure E.4) load cases on the beam were assumed to be the elementary case of bending a beam with a point load in the middle of the beam.

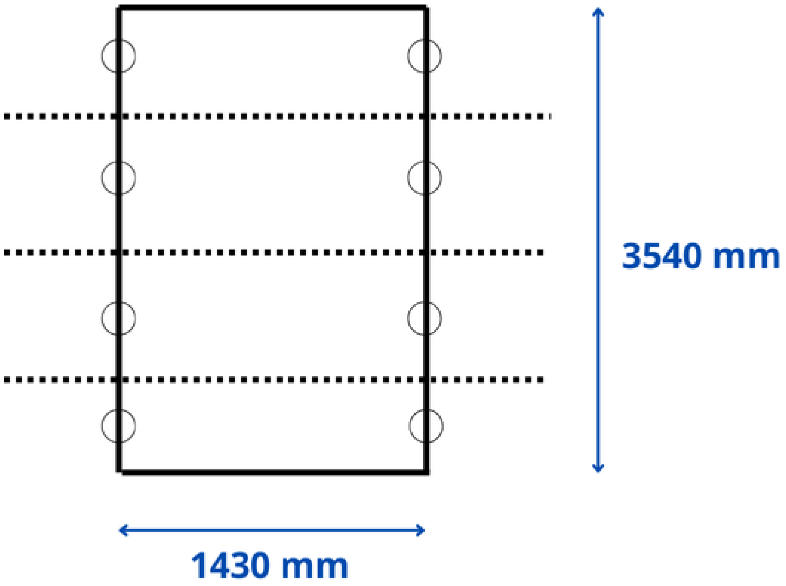

Figure E.2 FP and PP were divided into four sections.

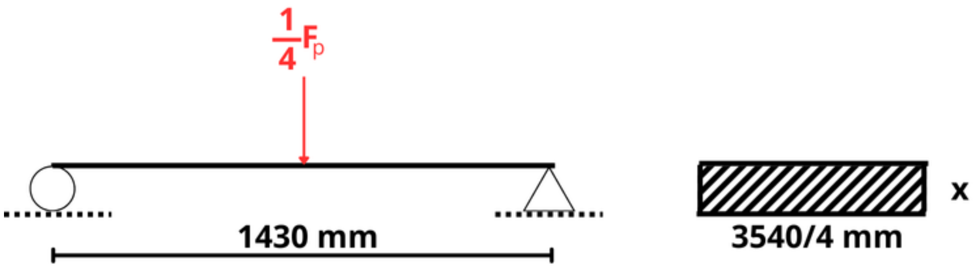

Figure E.3 Horizontal case.

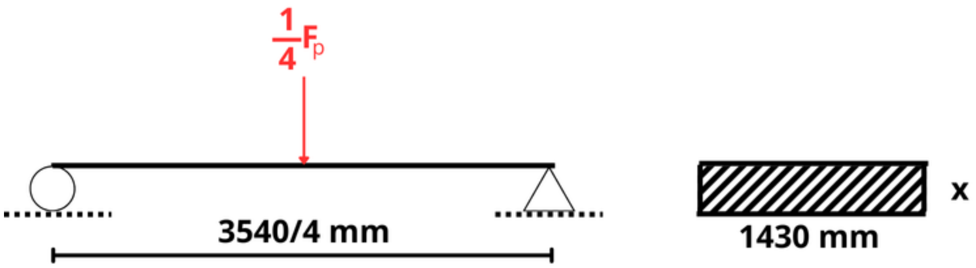

Figure E.4 Vertical case.

The bending stress (Equation E.7) and the shear stress (Equation E.8) were used in the calculations of the required thickness of the FP and PP. Bending moment (M_b)

and bending resistance (W_b) are described in Equation E.9 and Equation E.10. When investigating the required thickness, the von Mises stress (Equation E.11) was compared to 80% of the material's yield stress of 355 MPa (Equation E.12). The von Mises stress, as a function of the FP and PP thickness (x), is seen in Equation E.13 for the horizontal case and in Equation E.14 for the vertical case.

$$\sigma = \frac{M_b}{W_b}$$ (Equation E.7) (Björk, 2017)

$$\tau = \frac{F}{A}$$ (Equation E.8) (Björk, 2017)

$$M_b = \frac{F * L}{4}$$ (Equation E.9) (Björk, 2017)

$$W_b = \frac{b * h^2}{6}$$ (Equation E.10) (Björk, 2017)

$$\sigma_v = \sqrt{\sigma^2 + 3 * \tau^2}$$ (Equation E.11) (Björk, 2017)

$$\sigma_{y.threshold} \leq 0.8 * \sigma_y = 284\ MPa$$ (Equation E.12)

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{4} * 1430}{4}}{\frac{\frac{3{,}540}{4} * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{F_p}{4}}{\frac{3{,}540}{4} * x}\right)^2}$$ (Equation E.13)

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{4} * \frac{3{,}540}{4}}{4}}{\frac{1{,}430 * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{F_p}{4}}{1{,}430 * x}\right)^2}$$ (Equation E.14)

To prevent plasticization of the material, the required thickness of the FP and PP was 1* mm in the horizontal case and 1* mm vertical case. Therefore, for the thick-wire concept, the required thickness of the FP and PP, to withstand the test pressure, was at least 1* mm.

E.3 Modular concept alternative 1

For the modular concept alternative 1, the tightening bolt dimensions for compression of the plate package to A-measurement was calculated in Appendix E.1. The calculations of the FP and PP thicknesses of the frame module in the modular concept alternative 1 were performed in the same way as in Appendix E.2.1.

E.3.1 FP and PP of the plate package module

The thicknesses of the FP and PP of the plate package module in the modular concept alternative 1 were calculated by dividing the plates into two sections (Figure E.5). The sections were simplified as quadratic solid beams made of 355 MPa steel. The horizontal (Figure E.6) load case and the vertical (Figure E.7) load case on the beam were assumed to be the elementary case of bending a beam with a point load in the middle of the beam.

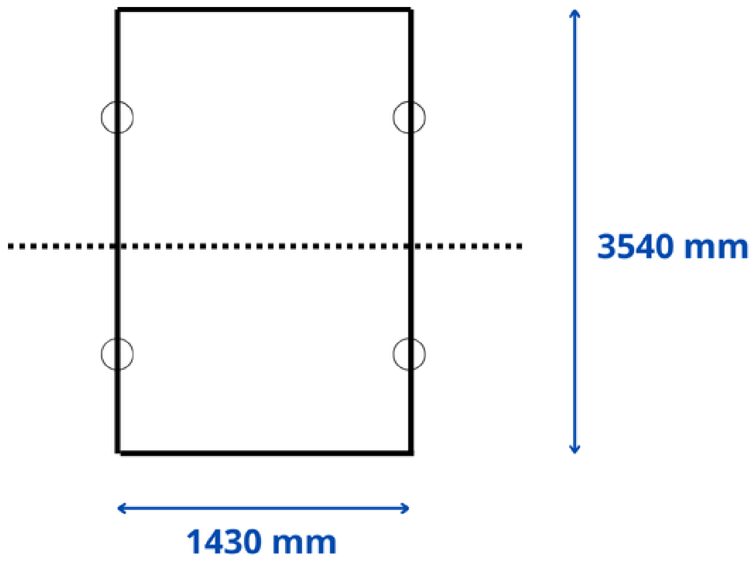

Figure E.5 FP and PP were divided into two sections.

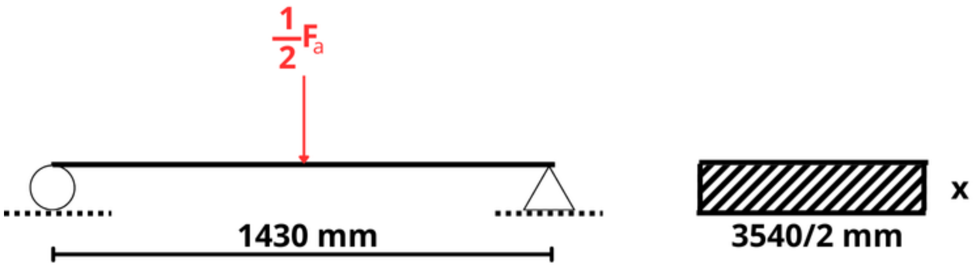

Figure E.6 Horizontal bending.

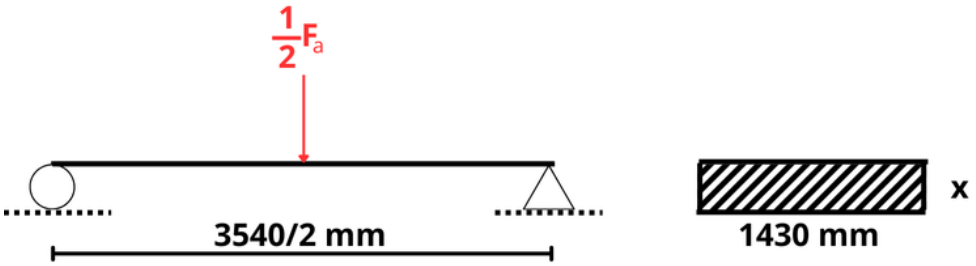

Figure E.7 Vertical bending.

The bending stress (Equation E.7) and the shear stress (Equation E.8) were used in the calculations of the required thickness of the FP and PP. M_b and W_b are described in Equation E.9 and Equation E.10. When investigating the required thickness, the von Mises stress (Equation E.11) was compared to 80% of the material's yield stress of 355 MPa (Equation E.12). The von Mises stress, as a function of the FP and PP thickness (x), is seen in Equation E.15 for the horizontal case and in Equation E.16 for the vertical case.

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{1,888,120}{2} * 1,430}{4}}{\frac{\frac{3,540}{2} * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{1,888,120}{2}}{\frac{3,540}{2} * x}\right)^2} \qquad \text{(Equation E.15)}$$

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{1,888,120}{2} * \frac{3540}{2}}{4}}{\frac{1430 * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{1,888,120}{2}}{1430 * x}\right)^2} \qquad \text{(Equation E.16)}$$

To prevent the material from plasticizing, the minimum required thickness of the FP and PP was 63.5 mm in the horizontal case and 78.6 mm in the vertical case. Since the vertical bending case was harder to satisfy than the horizontal bending case, the required thickness result of the vertical bending case was selected. Therefore, the required thickness of the FP and PP for compression of the plate package was 78.6 mm.

E.4 Modular concept alternative 2

For the modular concept alternative 2, the tightening bolt dimensions for compression of the plate package to A-measurement was calculated in Appendix E.1. The calculations of the FP and PP thicknesses of the plate package module in the modular concept alternative 2 were performed in the same way as for the FP and PP of the frame module in the modular concept alternative 1 in Appendix E.3.1.

E.4.1 Frame module beams

HEM beams were selected for the frame module of the modular concept alternative 2. The HEM beam is a rigid beam type with strong bending toughness. For the modular concept alternative 2, eight horizontal HEM beams, four of which were placed on the FP and four on the PP, were connected using the eight M1* tightening bolts. Each HEM beam had solid pieces of steel at its ends where the tightening bolts would connect (Figure E.8). Data for HEM beams were gathered from “Tibnor konstruktionstabeller” (Tibnor, 2021). The beams were calculated using the elementary case of evenly distributed force (Figure E.9).

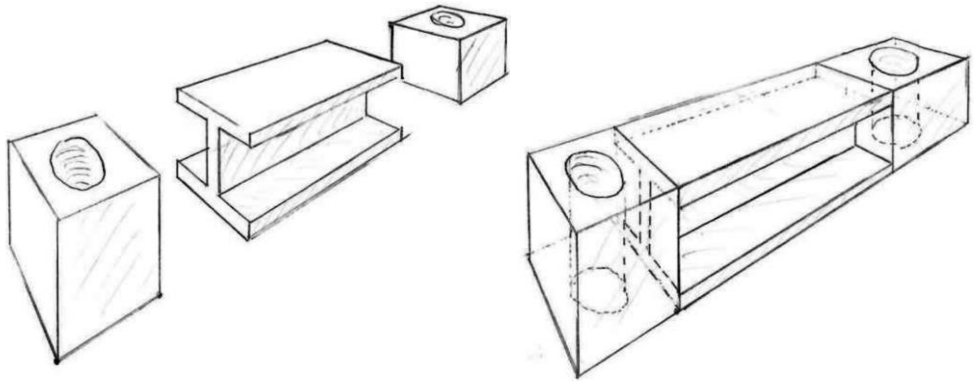

Figure E.8 Structure of the beams.

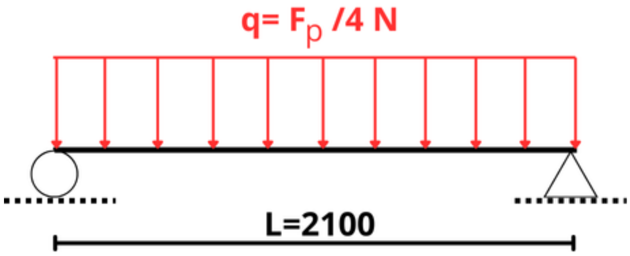

Figure E.9 Load case of the supporting beams.

Since eight horizontal HEM beams, four of which were placed on the FP and four on the PP were used, the bending force was 1/4 F_p and the shear force was 1/8 F_p. To calculate the needed dimensions of the HEM beams, the von Mises stress as a function of the bending resistance (W_b) and cross-section area (A) (Equation E.20) was compared to the threshold yield stress of the material (Equation E.12). To calculate the bending stress in the material, Equation E.18 was used, where M_b was defined in Equation E.19 and W_b was collected from "Tibnor konstruktionstabeller" (Tibnor, 2021). To calculate the shear stress, Equation E.8 was used. The A, needed to calculate the shear stress, was collected from "Tibnor konstruktionstabeller".

$$\sigma = \frac{M_b}{W_b}$$ (Equation E.18) (Björk, 2017)

$$M_b = \frac{Q * L}{8}$$ (Equation E.19) (Björk, 2017)

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{4} * 2100}{8}}{W_b} * 1000\right)^2 + 3 * \left(\frac{\frac{F_p}{8}}{A}\right)^2}$$ (Equation E.20)

The smallest HEM-beam that was able to carry the necessary load was the HEM1*. Results from the investigation of different HEM beam sizes are presented in Table E.3.

Table E.3 Von Mises stresses for different HEM beam dimensions.

Beam	*von Mises stress*	*Approved*
HEM1.1*	361 MPa	NO
HEM1.2*	290 MPa	NO
HEM1*	271 MPa	YES

E.5 Support concept

For the support concept, the tightening bolt dimensions for compression of the plate package to A-measurement was calculated in Appendix E.1.

E.5.1 FP and PP for compressing the plate package

For the support concept, the FP and PP used to compress the plate package had different dimensions than the modular concept alternatives. The dimensions of the FP and PP of the support concept is presented in Figure E.10.

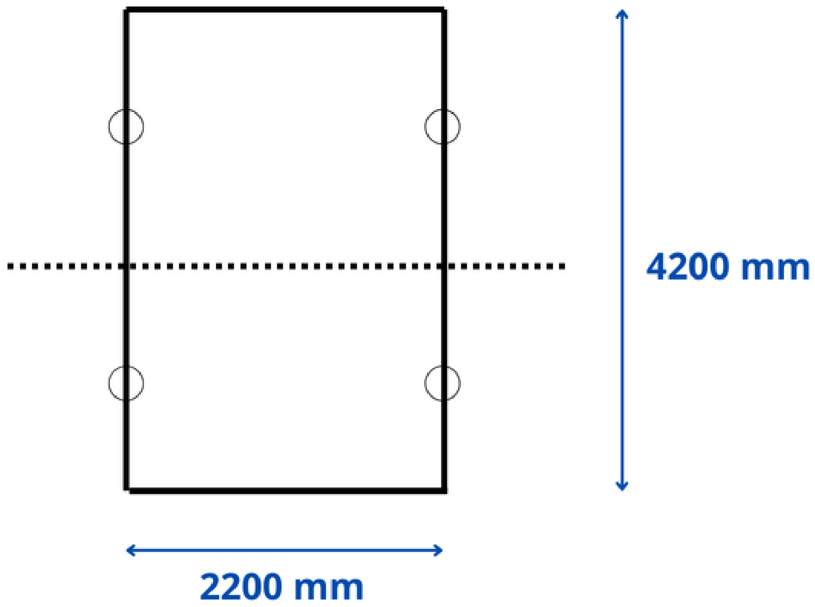

Figure E.10 Thin plate dimensions of the support concept.

The calculations for the thickness of the FP and PP used to compress the plate package in the support concept were performed in a similar way as in Appendix E.3.1, using Equation E.7, Equation E.8 and Equation E.11. The von Mises stress, as a function of FP and PP thickness, is presented in Equation E.21 for the horizontal load case (Figure E.11) and in Equation E.22 for the vertical load case (Figure E.12). To find the minimum required thickness to prevent plasticization of the FP and PP material, the von Mises stress of the two cases were compared to the threshold yield stress in Equation E.12.

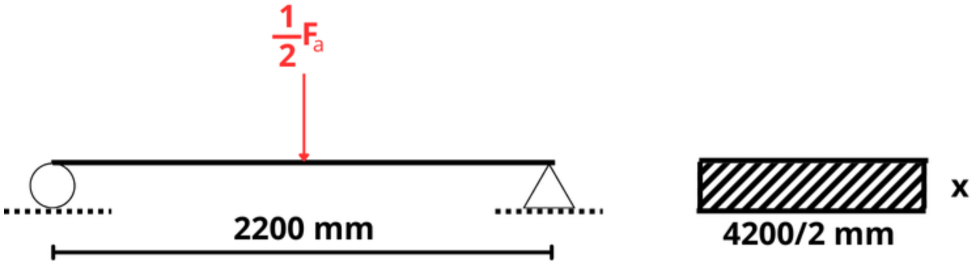

Figure E.11 Horizontal bending case.

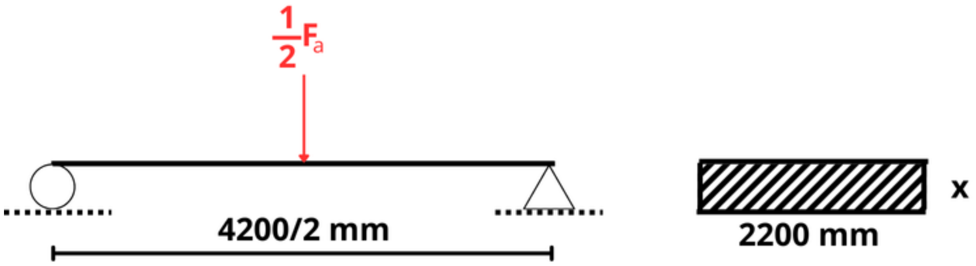

Figure E.12 Vertical bending case.

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{1,888,120}{2} * 2,200}{4}}{\frac{\frac{4,400}{2} * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{1,888,120}{2}}{\frac{2,200}{2} * x}\right)^2} \quad \text{(Equation E.21)}$$

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{1,888,120}{2} * \frac{4,200}{2}}{4}}{\frac{2,200 * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{1,888,120}{2}}{2,200 * x}\right)^2} \quad \text{(Equation E.22)}$$

The required thickness of the FP and PP to prevent plasticization of the material was 71 mm in the horizontal case and 69 mm in the vertical case. Therefore, the FP and PP of the support concept were required to be at least 71 mm thick.

E.5.2 Support structure

The calculations were made for four different structures: Case 1, Case 2, Case 3, and Case 4 (Figure E.13). Two different angles between the top beams were considered: a 45-degree angle and a 60-degree angle (Figure E.14).

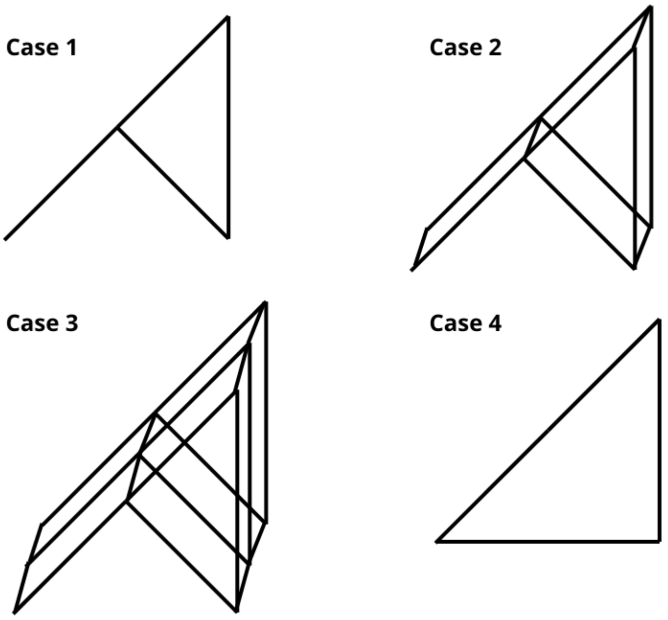

Figure E.13 Structure case 1, 2, 3 and 4.

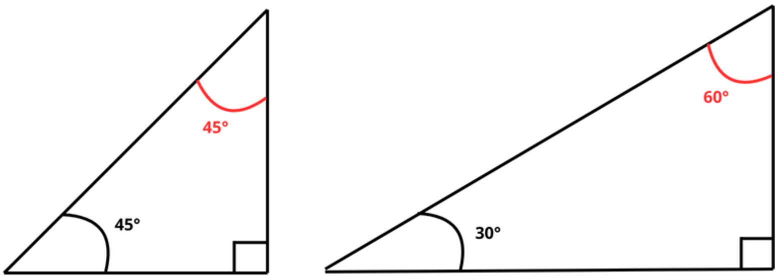

Figure E.14 Top corner angle of 45 degrees and 60 degrees.

Because of the VKR profile's good resistance against buckling, VKR beams were deemed suitable to use in the support structure. Data for the VKR beam were gathered from "Tibnor konstruktionstabeller" (Tibnor, 2021).

To simplify the problem during the calculation, the force in the top and bottom of the FP and PP were assumed to be equal (Figure E.15).

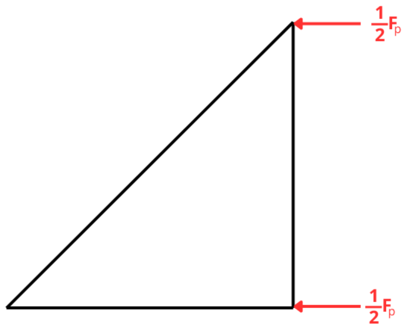

Figure E.15 Assumed load distribution during test pressure.

The equation for buckling is presented in Equation E.23. To avoid buckling, the force in the beams is required to be smaller than P_k.

$$P_k = \frac{4 * \pi^2 * E * I}{l^2}$$ (Equation E.23) (Sundström et al, 2008)

The force F_p was decomposed into two force vectors: F_{beam} in the beam direction and $F_{perpendicular}$ in the direction perpendicular to the beam (Figure E.16). The F_{beam} and $F_{perpendicular}$ for the different top angles are presented in Table E.4.

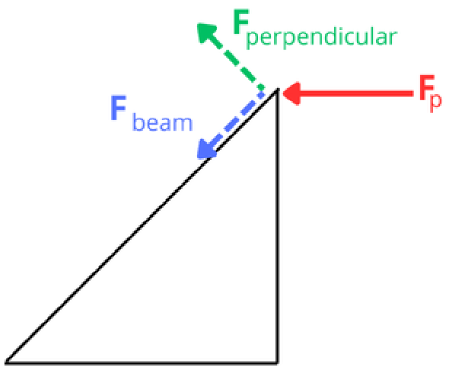

Figure E.16 Decomposed F_p vector into F_{beam} and $F_{perpendicular}$.

Table E.4 F_{beam} and $F_{perpendicular}$ for the different top angles.

Definition	*Top angle*	*Force*
$F_{beam.45}$	45	1* N
$F_{perpendicular.45}$	45	1* N
$F_{beam.60}$	60	1* N
$F_{perpendicular.60}$	60	1* N

The F_b determined the needed I (Equation E.24) and the F_c determined the needed cross-section area (Equation E.25).

$$I = \frac{F_b * L^2}{4 * \pi^2 * E * 0.8} * \frac{1}{1{,}000} \qquad \text{(Equation E.24)}$$

$$A = \frac{F_c}{\frac{0.8 * 355}{\sqrt{3}}} \qquad \text{(Equation E.25)}$$

The needed I and A for each structure are presented in Table E.12. The data used in Equation E.24 and Equation E.25 for each of the cases are presented in the tables Table E.5 through Table E.11.

Table E.5 Parameter values for Case 1 with a 45-degree top angle.

Parameter	*Value*
E	210,000 MPa
F_b	1/2 $F_{beam.45}$
L	2,503 mm
F_c	1/2 $F_{perpendicular.45}$

Table E.6 Parameter values for Case 2 with a 45-degree top angle.

Parameter	***Value***
E	210,000 MPa
F_b	1/4 $F_{beam.45}$
L	2,503 mm
F_c	1/4 $F_{perpendicular.45}$

Table E.7 Parameter values for Case 3 with a 45-degree top angle.

Parameter	***Value***
E	210,000 MPa
F_b	1/6 $F_{beam.45}$
L	2,503 mm
F_c	1/6 $F_{perpendicular.45}$

Table E.8 Parameter values for Case 4 with a 45-degree top angle.

Parameter	***Value***
E	210,000 MPa
F_b	1/4 $F_{beam.45}$
L	5,006 mm
F_c	1/4 $F_{perpendicular.45}$

Table E.9 Parameter values for Case 1 with a 60-degree top angle.

Parameter	***Value***
E	210,000 MPa
F_b	1/2 $F_{beam.60}$
L	2,503 mm
F_c	1/2 $F_{perpendicular.60}$

Table E.10 Parameter values for Case 2 with a 60-degree top angle.

Parameter	***Value***
E	210,000 MPa
F_b	1/4 $F_{beam.60}$
L	2,503 mm
F_c	1/4 $F_{perpendicular.60}$

Table E.11 Parameter values for Case 3 with a 60-degree top angle.

Parameter	***Value***
E	210,000 MPa
F_b	1/6 $F_{beam.60}$
L	2,503 mm
F_c	1/6 $F_{perpendicular.60}$

Table E.12 Required I and A for different angles and structure cases of the support structure.

Structure case	***I [mm4*10^4]***	***A [mm2]***
1 – 45 degrees	1*	1*
2 – 45 degrees	1*	1*
3 – 45 degrees	1*	1*
4 – 45 degrees	1*	1*
1– 60 degrees	1*	1*
2 – 60 degrees	1*	1*
3 – 60 degrees	1*	1*

E.5.3 Interface between support structure and FP/PP

Two alternatives were considered for the interface between the support structure and the FP/PP (dotted line in Figure E.17). The first alternative was to use solid plates and the second alternative was to use a framework of HEM1* beams.

E.5.3.1 Solid plates

Using four support points, two on the bottom and two on the top, on each solid plate resulted in an unreasonably thick solid plate. Therefore, the calculations in this section were performed using six support points, two on the bottom, two in the middle and two on the top, on each plate. In Figure E.17, the structure is illustrated from the side showing the support structure supporting the interface at the three different heights.

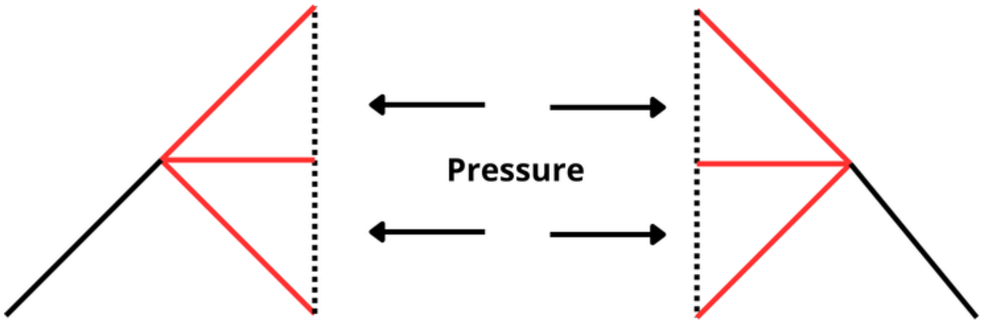

Figure E.17 Pressurized surface in the support structure.

The calculations for the required thickness of the solid plates to withstand the test pressure were performed in a similar way as in Appendix E.2.1, using Equation E.7, Equation E.8 and Equation E.11. The von Mises stress, as a function of the solid plates thickness, is presented in Equation E.26 for the horizontal load case (Figure E.18) and in Equation E.27 for the vertical load case (Figure E.19). To find the minimum required thickness to prevent plasticization of the FP and PP material, the von Mises stress of the two cases were compared to the threshold yield stress in Equation E.12.

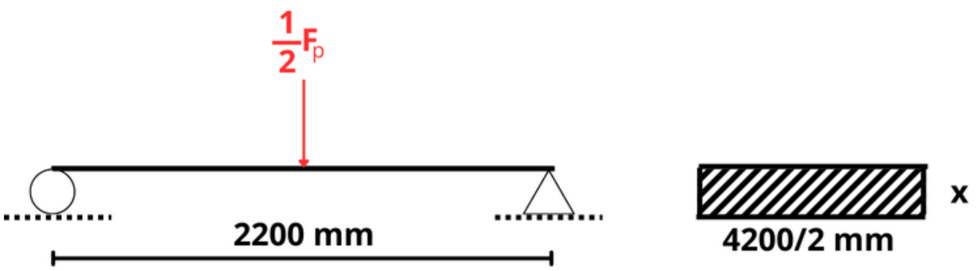

Figure E.18 Horizontal load case.

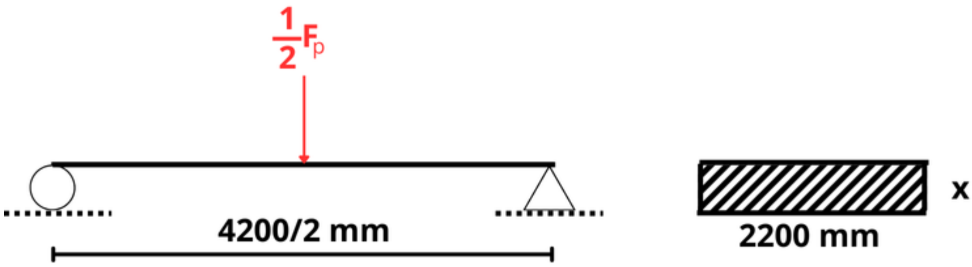

Figure E.19 Vertical load case.

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{2} * 2{,}200}{4}}{\frac{\frac{4{,}400}{2} * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{F_p}{6}}{\frac{2{,}200}{2} * x}\right)^2} \qquad \text{(Equation E.26)}$$

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{2} * \frac{4{,}200}{2}}{4}}{\frac{2{,}200 * x^2}{6}}\right)^2 + 3 * \left(\frac{\frac{F_p}{6}}{2{,}200 * x}\right)^2} \qquad \text{(Equation E.27)}$$

According to the calculations, the horizontal case required a solid plate with a thickness of 1* mm, and the vertical case required a thickness of 1* mm. Therefore, a 1* mm thick solid plate was needed to withstand the test pressure.

E.5.3.2 Using HEM beams

As the HEM1* beam was selected as suitable in Appendix E.4.1, it was also selected as suitable to be used in the HEM beam framework structure. The horizontal bending case is seen in Figure E.20.

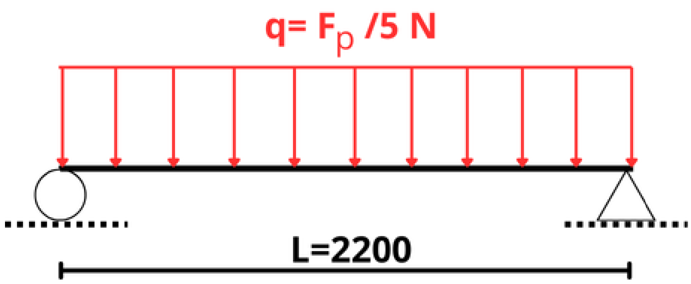

Figure E.20 Load case of horizontal beam bending.

A function of the von Mises stress was derived similarly as in Appendix E.4.1, using Equation E.18, Equation E.19, and Equation E.8. The von Mises stress, as a function of the number of horizontal beams, was compared to the threshold yield stress in Equation E.12. Equation E.28 showed that five horizontal beams were required to get a von Mises stress below 80% of the yield stress.

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{5} * 2100}{8}}{HEM1^*.W_b} * 1000\right)^2 + 3 * \left(\frac{\frac{F_p}{8}}{HEM1^*.A}\right)^2} = 227\ MPa \quad \text{(Equation E.28)}$$

For the vertical bending, two beams were required on both sides of the plate package as more beams would make it impossible to access the fluid ports. The required number of support points on the vertical beams was examined. (Figure E.21).

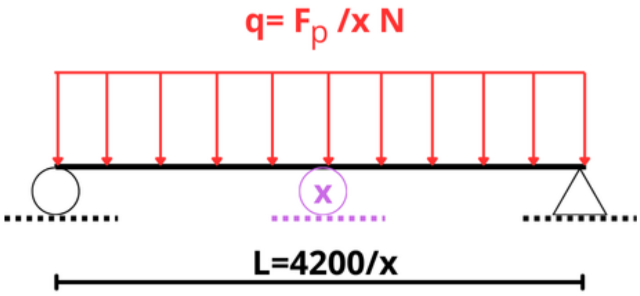

Figure E.21 Load case of vertical beam bending with x supporting points.

The von Mises stress for different number of supports were derived similarly as in Appendix E.4.1, using Equation E.18, Equation E.19, and Equation E.8.

When investigating the required number of support points, the first case to be tested was the case in which no additional support points were added, i.e., x=0. The equation for the von Mises stress with no support is presented in Equation E.29. The von Mises stress was above the threshold yield stress in Equation E.12 and therefore not OK.

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{2} * 4200}{8}}{HEM1^*.W_b} * 1000\right)^2 + 3 * \left(\frac{\frac{F_p}{4}}{HEM1^*.A}\right)^2} = 1083\ MPa \quad \text{(Equation E.29)}$$

Thereafter, one support (x=1) in the middle of the vertical beam was investigated. The equation for the von Mises stress with one support is presented in Equation E.30. The von Mises stress was below the threshold yield stress in Equation E.12 and is therefore OK.

$$\sigma_v = \sqrt{\left(\frac{\frac{\frac{F_p}{4} * \frac{4200}{2}}{8}}{HEM1^{*}.W_b} * 1000\right)^2 + 3 * \left(\frac{\frac{F_p}{6}}{HEM1^{*}.A}\right)^2} = 271\ MPa \quad \text{(Equation E.30)}$$

Five horizontal and two vertical HEM1* beams make up the structure of the framework (Figure E.22). The framework structure requires six support points (red dots in Figure E.22) for the vertical beams: two support points on top, two support points in the middle, and two supports points on the bottom (Figure E.17).

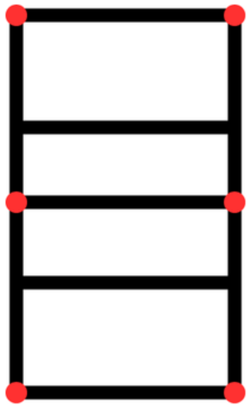

Figure E.22 Framework structure made by HEM beams.

Appendix F Wire rope alternative

An alternative to the selected OSS wire rope from Section 10.5.2, would be the fully locked coil ropes (FLC), which will be described in this appendix.

F.1 Fully Locked Coil Ropes (FLC)

The FLC wire (Figure F.1) has a high structural capability and is used in harsh environments where the “z” pattern protects the inner round cables. (SWR, n.d.c) The FLC properties as well as the calculated required number of wires to withstand the test pressure are presented in Table F.1.

Figure F.1 FLC wire (SWR, n.d.c).

Table F.1 FLC wire.

Wire diameter	*Number of wire ropes required to withstand test pressure*
C1*	6
C1.1*	22
C1.2*	61

Appendix G FEA setup comparison

To prevent rigid body motion of the FEA model, three different setups were considered: three displacement points (Figure G.1), one solid vertex (Figure G.2), and fixed support (Figure G.3).

G.1 Three displacement points

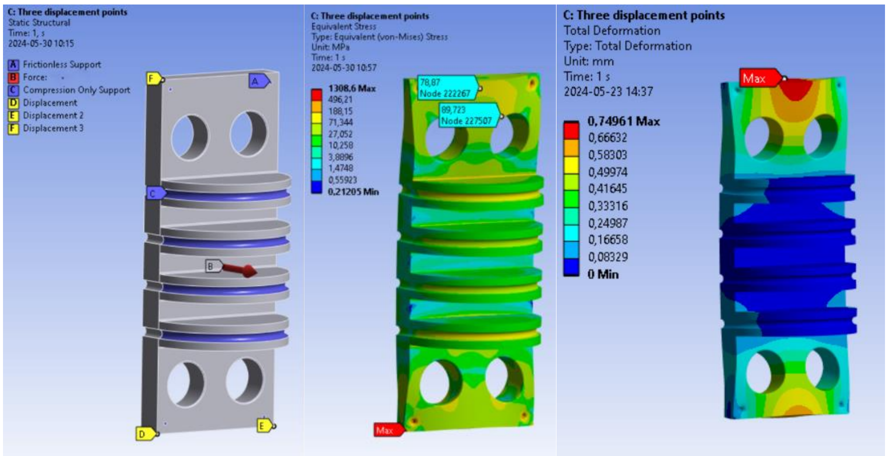

Figure G.1. Equivalent von Mises stress and total deformation of the FEA simulation when three displacement points were used.

G.2 One solid vertex

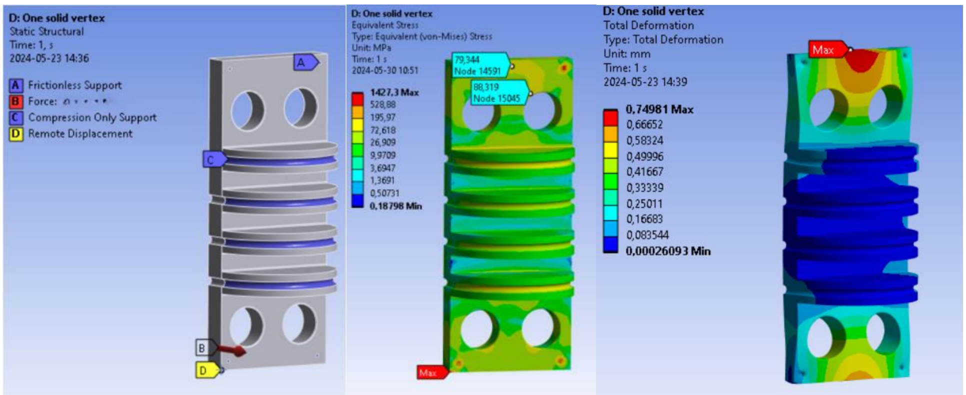

Figure G.2. Equivalent von Mises stress and total deformation of the FEA simulation when one solid vertex was used.

G.3 Fixed support

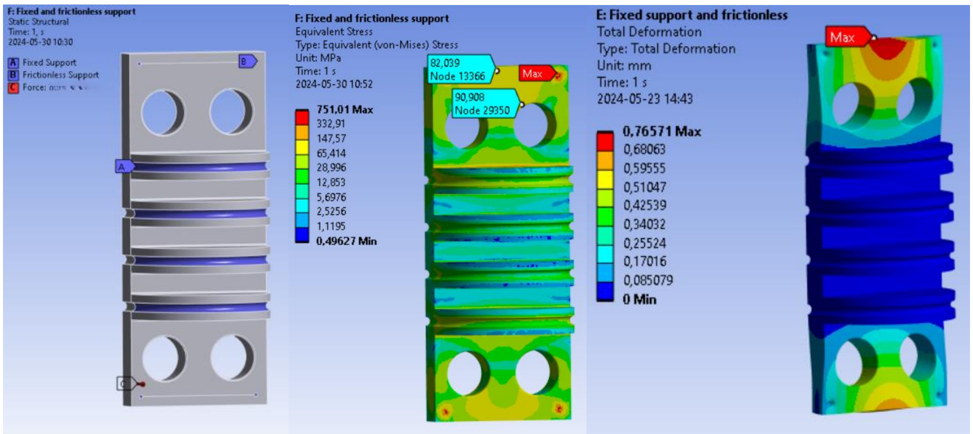

Figure G.3. Equivalent von Mises stress and total deformation of the FEA simulation when fixed supports were used.