MSc Thesis

Design of a foldable 20ft general purpose container

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Abstract

The intermodal transportation transport is used to ship goods from A to B all over the world using different modes of transportation. The intermodal freight relies on the use of standardized containers for this transport. All empty containers need to be shipped back to the areas where there is a demand for empty containers. Since a standard container is the shame shape, independent of whether it is loaded or empty, all nodes in the intermodal system have a significant portion of empty container moves. Holland Container Innovations saw a solution to this problem of empty container repositioning, in the form of a 40ft foldable container, which can save on relocation costs of empty containers. HCI wants to expand its portfolio with a 20ft foldable design as well. Therefore, in this report the design process for the design of a viable 20ft foldable container is described. The end result of this project will be a concept that is adaptable to a full commercial design. The same folding method of the 40ft design is applied to the 20ft design, since it has already been proven to be viable. In addition, this opens up possibilities for synergies between the 20ft and 40ft design, as well as faster acceptation by other stakeholders, due to similarity with the already proven design.

A critical design problem for applying the 4fold design to the 20ft container is the folded container height. The new 20ft design needs to meet a five to one bundle size, meaning that the folded container needs to be one fifth the height of a normal container. The height reduction requirements let to several dimensional design problems in which the design needed to be altered in order to house the parts needed for the folding process. A number of components were redesigned to fulfil the height requirements. After solving the spatial design problems, the 20ft foldable design was evaluated based on the ISO requirements. Initial hand calculations and FEM analysis of critical components have shown that the design fulfils the ISO load cases, as well as the operational requirements outlined by HCI For further development of the 20ft foldable container, the design can be made lighter to reduce the margin of error, and in turn allow for a reduction in material to be used, by performing a full FEM analysis. Although the weight and cost requirements have passed for this design, improvements in these values will always benefit the viability of the design.

Content

Chapter 1 Introduction

1.1 Problem background

1.1.1 Empty container repositioning

The intermodal transport system is an invention from the 1950’s. Initially the goal of this system was to improve the loading and unloading times of ships. This was done by using standardized container loading units instead of smaller units such as crates, barrels and boxes. This system gradually expanded into rail, road, inland and ocean vessels.

With the expanse of the intermodal freight system, the safety of the containerized transport was first standardized by the creation of ISO 668 and ISO 1496 by the International Organization for Standardization in 1968. The general safety for containerized transport was improved by the drafting and implementation of the Convention for Safe Containers (CSC) in 1972 [4] . The CSC formalized testing and inspection methods for containers. The CSC plate on a container, see Figure 1, shows for which ratings and loads the container passed the ISO requirements.

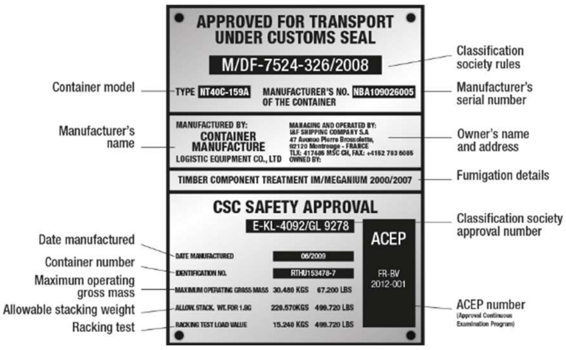


Figure 1 CSC plate (source bic-code.org)

The global container market functions well and is expected to grow. This does not mean that every container that is transported is used for transporting goods. In fact, there is an imbalance in goods for supply and demand between different areas in the world [25]. The problem with this imbalance is that empty containers need to be transported back to the location that has a demand for loading containers. It is estimated that 21% of all containers that are transported are empty containers [25]. This empty container repositioning has considerable costs and is being studied by the global academic community. A Google Scholar search on the keyword phrase: “empty container repositioning cost” shows 11.500 hits since 2015 [5], indicating that it is a relevant subject.

1.1.2 Foldable containers

Improvements in information and communication systems can play a role to streamline the process of empty container repositioning, although it is not expected that it can completely be prevented [25]. Foldable containers have therefore been proposed as a way to reduce the costs associated with empty container repositioning. A number of studies through the years have shown that foldable containers can lead to net benefits in the container transport chain [21, 22, 24] However, this is only the case if the exploitation costs associated with foldable containers can be kept low, such as the costs of folding and unfolding, the higher cost of production, and compatibility with existing containers [2, 22, 23, 25].

The 4FOLD 40ft HC foldable container

Holland Container Innovations saw a way to reduce empty container reposition costs by developing a foldable 40ft HC container. By folding the container and combining several containers into a single bundle, the required space and costs for empty shipping are reduced, as can be seen in Figure 2 .

Figure 2 Bundle of 4fold containers

This system is only viable if the savings that can be generated outweigh 1) the additional costs of folding the container, 2) the increased cost of production of the container and 3) any additional persuasive costs, for all the actors in the chain [2]. It should be noted that break-even in this case is not enough, since that does not create an incentive for more profit.

1.2 Problem formulation

The first container product HCI launched is the 4Fold High Cube (HC) container, see Figure 2. The outside dimensions of the container are similar to that of a normal 40ft HC container. The inside volume of the container lies between that of a normal 40ft container and a 40ft HC container, thus making it viable for the normal 40ft container market as well as a portion of the 40ft HC market. The container market however, does not consist out of only 40ft containers. Another large portion of the container market are 20ft containers, for which the same imbalances can and are occurring. HCI therefore wants to expand its portfolio with a 20ft foldable design as well.

1.2.1 Research questions

The goal of this project is to design a foldable 20ft container for HCI expanding their product line, Figure 3. Therefore, the main research question is formulated as:

What is a viable design for a foldable 20ft container for HCI?

Figure 3 Expand foldable container into the 20ft domain

This question implies the following. There are several aspects to the design of a new container: there are the technical requirements, economic and competitive requirements, and regulatory requirements. If only the technical requirements are taken into account, the end result will be a proof of concept, but this means limiting the design problem. Since HCI has expressed the desire to have a design that is economically viable in the market, this means all other requirements also have to be taken into account. Therefore, a design method was needed that allows for a broader analysis of the design problem. The end result of this project will be a concept that after prototype testing can be improved and adapted to a full commercial design.

In order to create this viable design the following sub questions are researched before the design phase of the project was initiated.

- What makes a foldable container viable?
- What is a viable folding method for the 20ft design?
- What is needed to implement the 4fold folding method to design?
- What are the design limitations for the design?
- How does the design hold up to a normal 20ft container?

1.3 Design approach

A design method was chosen that includes a broad initial approach to find out the key problems for a viable design. The design method used is the method described in Engineering Design: a Systematic Approach, by Pahl (2007)[1], illustrated in Figure 4. The method describes four steps to create a complete design. Its should be noted that out of the four steps only the first three steps are used and not all the substeps are relevant to the assignment.

Task clarification.

In the task clarification step, the design problem is investigated and analysed in all its aspects, in order to come up with a comprehensive requirement list. The requirement list creates a guide that can be used to steer the subsequent design steps. This design step is implemented in chapter 2 and shown in Figure 4 as the yellow section.

Conceptual design.

In the conceptual design step one or more possible principle solutions to the design problem are created. The principle solution can be transformed into preliminary layouts and then be evaluated. The result is that the most promising principle solution can be chosen for further development. This design step is implemented in chapter 3 and shown in Figure 4 as the blue section.

Embodiment design.

In this step the conceptual principle solution and initial layout are evolved into a detailed layout and checked whether it fulfils the requirement list. This design step is implemented in chapter 4. The evaluation of the design in done in chapter 5. These steps are shown in Figure 4 as the orange section.

Detail design.

In this step the detailed layout is prepared for production by defining all parts. This last design step will be kept outside of the scope for this project. This detailed design is not a part of this thesis.

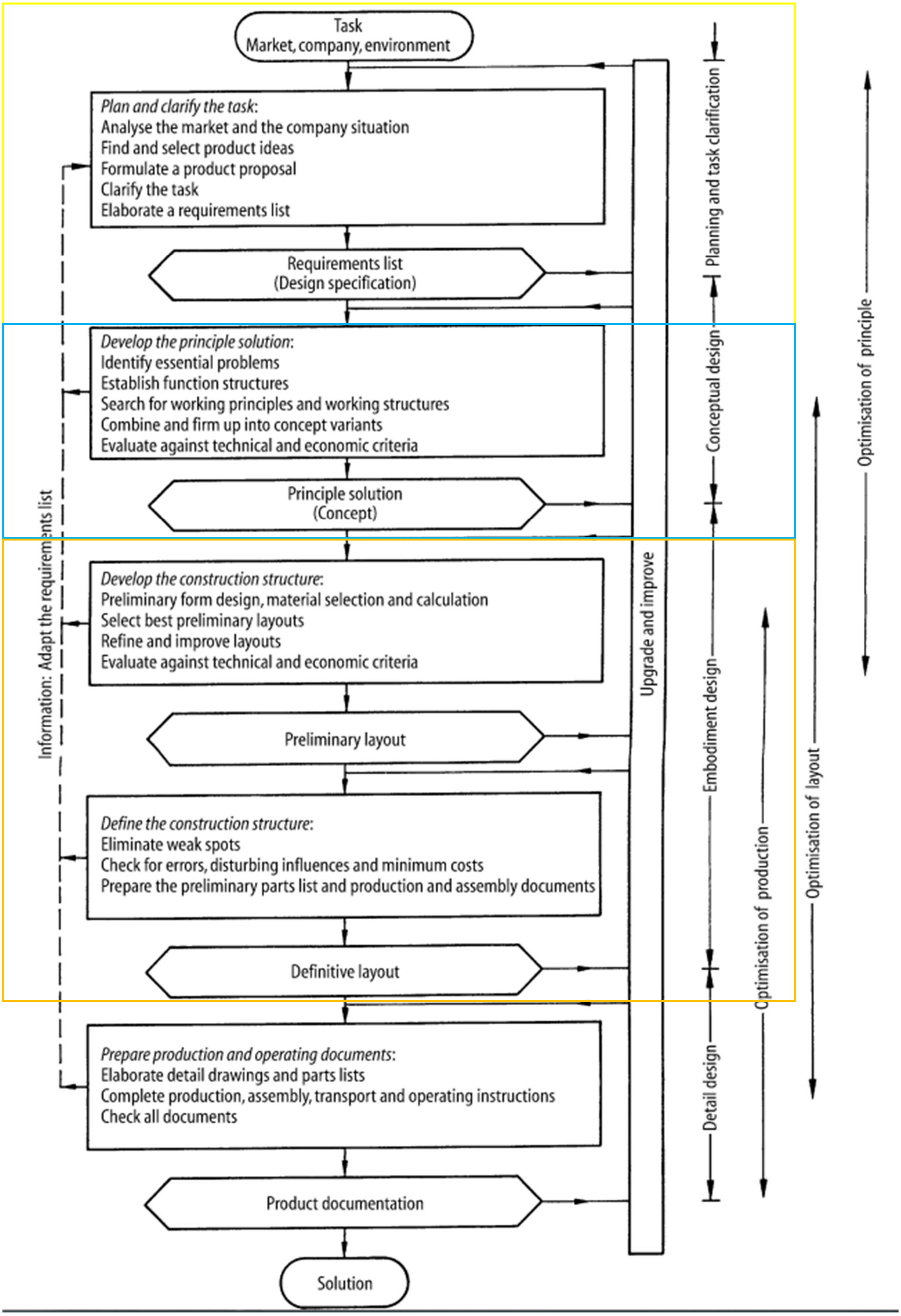


Figure 4. The product design process as described by Pahl (2007) [1].

Chapter 2 Task clarification

2.1 Introduction

The goal of the task clarification is to create the requirement list for the design, as shown in Figure 5. This is done by finding answers to the sub research questions in order to get the problem background. The following questions are relevant for the background investigation:

1. How does the container production process works?
2. What makes a foldable container viable?
    2.1 When is folding a container successful?
    2.2 What are the differences in usage between a 20ft and 40ft container?

This is followed by a technical clarification of a foldable container in the form of a function analysis. For the requirement investigation, the relevant actors are examined. For the foldable container, the following actors are involved:

- ISO
- Competition
- Region specific legislation
- Inhouse experiences

The chapter is concluded by creating the full requirement list, after which some key requirements are highlighted.

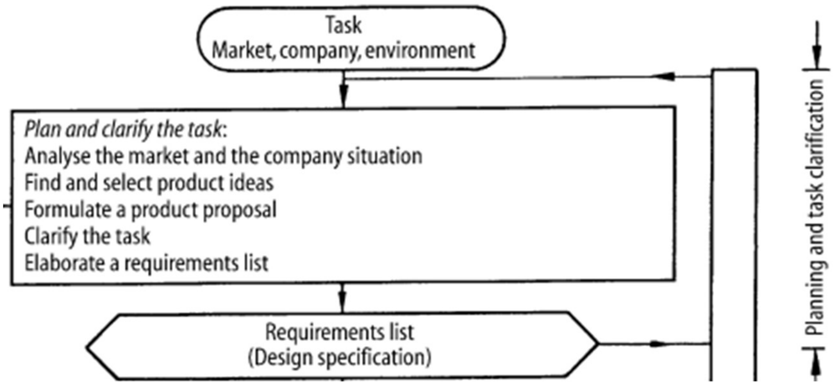


Figure 5 Task clarification detail of the design process described by Pahl (2007)

2.2 Problem background

As a first step, the background of the problem is explored to better understand what steps are needed to design a viable container. First the general container production process is explained, after which a closer look is taken at several aspects of foldable containers.

2.2.1 Container production process

In order to create a good design for a container it is important to understand how the container production process works.

Customers can order containers at container production factories. Customers need to specify the design they want produced for specialty containers, such as foldable containers. For this category, the customer delivers a design to the factory. Before full production starts, several prototypes and small batch series are produced to remove any design flaws and ensure the factory can construct the design to the required ISO specifications. In order to see if the container meets the criteria the ISO code specifies a set of tests and the pass criteria for each of the tests.

The second purpose of the prototype building is to evaluate the construction price. After the production of the prototype the factory usually evaluates its production unit cost.

If a successful prototype is build, the production runs can start. Periodically containers from these production runs are tested to ensure quality. These periodical tests are needed for the certification process.

It should be noted that during the prototype phase small problems are expected to be found after which small redesigns may be needed.

Since the containers need to pass the tests drawn up by the ISO certification before they can be used in practice, all requirements are geared towards passing these tests. This makes it easier to create a design since there is no need to analyse all real-life situations that may occur, these are already covered by the ISO.

2.2.2 Foldable container viability

To start the design the first sub question needs to be answered. What makes a foldable container viable? This question is divided into two separate questions?

- When is a foldable container successful?
- What are the differences in the requirements for a 20ft general purpose container and a 40ft general purpose container?

When is folding a container successful?

Konings and Thijs (2001) [2] describe a number of conditions that are required for a successful container. These conditions can be classified into two fields; product costs and product compatibility.

Product costs

The costs of a foldable container play an important role in the financial feasibility. The product costs can be divided in CAPEX (Capital Expenditures) and OPEX (Operational Expenses). The CAPEX of a foldable container is its construction cost. The OPEX consists of the following: folding costs, unfolding costs, and repair costs. When foldable containers are transported as a bundle there are also savings. The savings are the reduction in transport and handling fees of the additional containers that are bundled. A bundle of four folded containers has a savings of three containers total handling and transport fees.

The foldable container can be financial successful if the CAPEX and OPEX minus savings are lower than the CAPEX and OPEX of a normal container.

Product compatibility

To understand how the foldable container should work in the intermodal system it is valuable to answer the question; are there comparable container types and how do they work?

The most common foldable container that is already on the market is the foldable flat rack container, see Figure 6. This container is used to ship abnormal loads that don't fit inside a normal container, but don't exceed the container length. Since it is used for oddly shaped goods, it is not shaped like a box, but it only consists of a base and two end walls. Since abnormal loads are highly route depended, these containers are foldable so that on the return trip these containers can be shipped more efficiently. The ISO 1496 takes these types of container into account regarding the load cases they need to pass.

Figure 6 Foldable flat rack 40ft container

The only ISO foldable general purpose container on the market is the 4fold HC container from Holland Container Innovations. The foldable container has to be useable as a normal container when unfolded, in order to ensure product compatibility within the chain of operations. When the container is folded and combined as a bundle it once again needs to function as a normal container in the intermodal process.

In the chain of operations of a container, there are a lot of different stakeholders that are involved with the container at one point or another. Since handling a foldable container requires a change in the modus operandi of the stakeholders, it is important that all parties have some kind of benefit in order to minimize the risk. Therefore, it can be concluded that a foldable container needs to benefit all major parties involved in the shipping route. HCI has converted these stakeholder requirements into in-house technical requirements. Therefor the stakeholder list will not be discussed in detail.

Conclusion

A folding container can be described as viable if the following requirements are met:

- The unfolded container is identical in its interactions with the environment to a normal container.
    - Related to this are the ISO 1496-1 requirements for the container, which describe its loads and displacement.
- The folded stack of containers is identical in its interactions with the environment to a normal flatbed container
    - Related to this are the ISO 1496-5 requirements for the loads of a flatbed container.

- Every stakeholder in the transport chain needs something to gain from the use of a foldable container
    - This could be in the form of an efficient folding process such as the 4fold folding method.

This leads to the precondition that a foldable container needs to be the same in its interactions with the environment as a normal standardized container, while the benefits of using a foldable container outweigh the additional costs.

HCI has proven that their folding container design for the 40ft high cube container meets this precondition. This is achieved by the folding method and the robustness of the design. Using the same folding method opens up a lot of possibilities for synergies between the 20ft and 40ft design as well as faster acceptation by other stakeholders, due to similarity with the already proven design.

What are the differences in usage between a 20ft and 40ft container?

The weight rating for both the 20ft and 40ft container are the same in general. This means that the 40ft container in general is used for spacious cargo also resulting in the development of high cube 9ft 6 containers. The 20ft is generally used for heavy cargo using the higher allowable weight per volume compared to the 40ft container.

2.3 Function analysis

In order to understand the working of a foldable container a function analysis is performed. The analysis is split between the functions of a normal container and the additional functions for a foldable container.

2.3.1 Function analysis of a normal general purpose container

The normal container has one mode of operation that can exist in two configurations. It's a box of specific dimensions described by ISO 1191. The structural requirements for the container in this mode are given by ISO 1496-1. These requirements are based on the possible configurations the container can be in. Its two configurations are having the doors open or closed.

With the doors opened the container can be loaded with goods it needs to transport. During the loading processes the container maintains its structural integrity for those loads involved with the loading process. These loads are described by ISO 1496-1 Test No 8.

With the doors closed the container is assumed to be able to maintain its structural integrity while under the influences of the forces involved in the intermodal transport system. These forces are translated in static tests described by ISO 1496-1.

2.3.2 Function analysis of a foldable container

The foldable container has two modes of operation. First there is the unfolded mode. In this mode the foldable container works similar to a normal container described above. In the folded mode the container is unable to perform the functions of a normal container. It is however able to cope with the ISO load cases involving external loads while maintaining structural integrity. An integer number of folded containers is also able to be combined to the exact dimensions of a normal container.

Besides the different state present for a foldable container there are also two processes a foldable container needs to have compared to a normal container, which are the folding and unfolding processes, shown in Figure 7 and Figure 8. These processes allow the container to transform from rigid state to rigid state using a flexible in between state. The detailed folding process for HCI's current foldable 40ft container is shown below. It should be noted that due to the non-reversible effects of gravity the folding and unfolding processes are not their exact opposites.

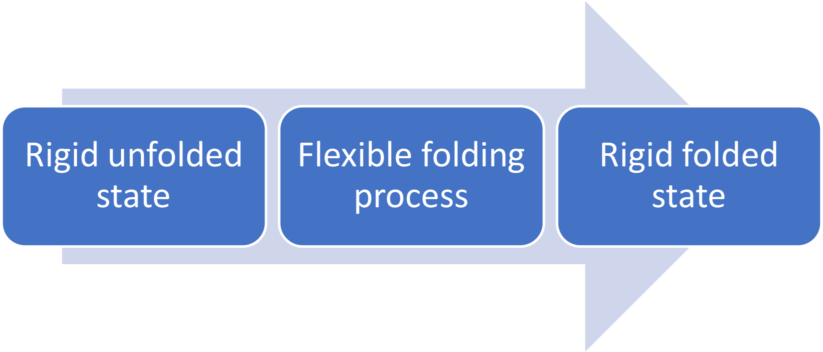


Figure 7 Foldable container folding process

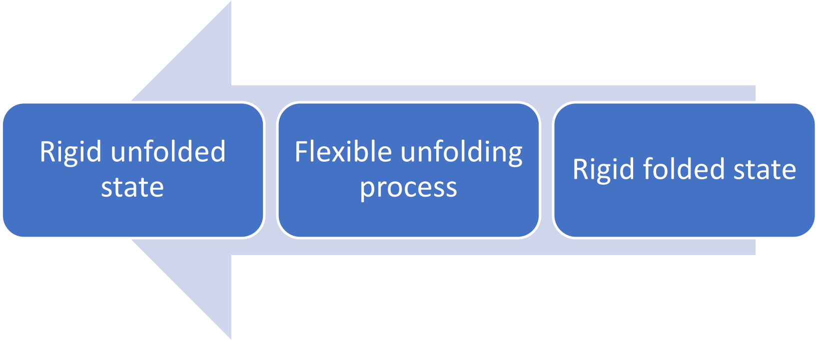


Figure 8 Foldable container unfolding process

The detailed functions of the foldable container can be seen when the folding and unfolding process for the 4fold 40ft container are observed. The same process is schematically shown in Figure 9.

Step 1:

Release all the locks on the sidewall and the end wall. The structure is transformed from rigid to flexible allowing folding operations.

Step 2:

Folding the sidewalls. By folding the sidewalls, space is created for the end walls to be able to fold inward. It should be noted that while the roof is not lifted and the doors of the container are closed the container is safe for workers fold the sidewalls in.

Step 3:

Lifting of the roof and folding of the end walls. In this folding step, the roof is lifted, and the end walls that are connected to the roof with a bar fold inwards. In this step, it is unsafe for workers to be next to the container. The workers are also not required to perform any actions during this step.

Step 4:

Lowering the roof on top of the base. In this final step the container is safe again for workers to be near. When the container is in this configuration the top hammer locks need to be closed in order to create a rigid container again.

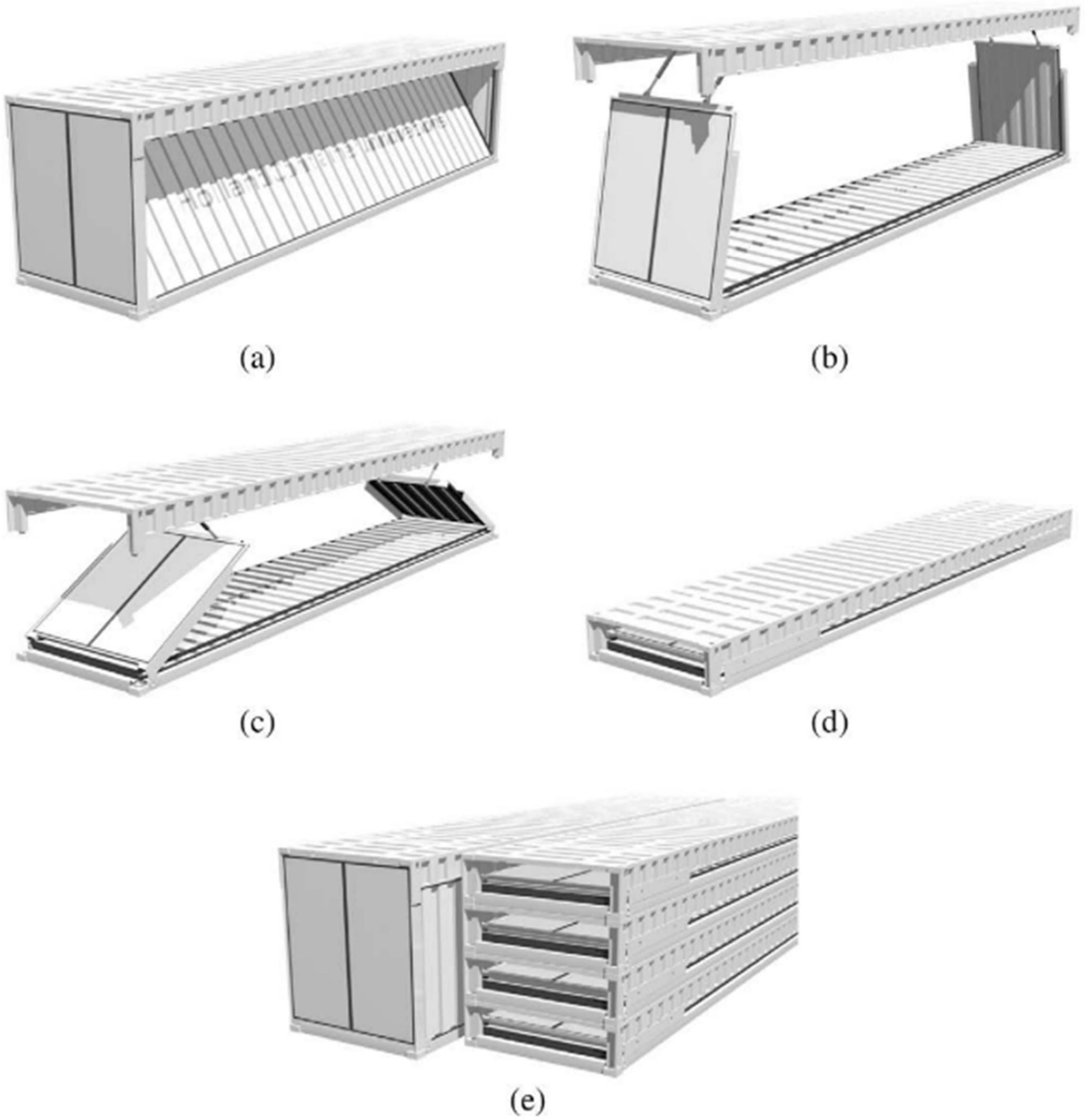


Figure 9 Schematic of the folding and unfolding process of the 4Fold container. A) – e) correspond with steps 1 -4 described above, e) shows the unfolded container compared to four stacked folded containers. (Shintani, Konings and Imai, 2010)[25]

2.4 Requirement analysis

There are 4 areas of interest regarding the requirements for the design. These are the ISO regulations, the assumed competition, relevant legislation and the in-house experience.

2.4.1 ISO requirements

ISO 1496 describes the functional requirements a container needs to pass in order to be ISO certified. These requirements are defined in a number of load cases. These load cases are static load cases derived from the dynamic forces encountered by the container during operations. It also specifies the maximum deflections the container may experience during the load case testing. These maximum deflection limitations ensure that force transmission between the container and its environment are done at the expected place

Besides the functional requirements described in ISO 1496, there are other ISO regulations that need to be taken into account. Those regulations are the following;

ISO 668: Classification, dimensions and rating.

> This ISO regulation describes the classification for the container, the series 1 container designation based on the nominal length of the container. It contains the full list of outer dimensions and accompanying tolerances for the main dimensions, length, width and height. It also describes the rating for the container. These are all required to insure intermodal compatibility.
>
> The ISO 668 also describes the requirements for internal dimensions and the minimum door opening dimensions. These are however not required to insure intermodal compatibility.

ISO 1161 : Series 1 freight containers – Corner fittings -Specifications

> This ISO regulation describes the dimensional and strength requirements for the corner fittings.

The following ISO regulations also are relevant for the container, but they do not influence the main structure of the design:

ISO 3874: Series 1 freight containers- Handling and securing

ISO 6346: Freight containers – Coding, identification and marking

Relevance of ISO standards

The ISO 1496 has created a uniform set of loads and load transfer locations for the container that it needs to meet in order to be ISO certifiable. The standardization provided by the ISO norms means that every link in the intermodal transport chain knows what to expect from the container; whether it be the forces it can withstand, the force transfer areas, or the general geometry. Because of this standardization, every ISO certified container can be used in a similar manner, independent of designer, owner of manufacturer. The ISO requirements also make it simpler for the operators of container transportation and handling equipment. Operators can create stowage plans that take into account the loads every container can handle without the need to test each individual container to see if the container meets the requirements. Additionally, often insurance companies will only accept to insure ISO certified containers. In order to become ISO certified, a new container design must show it can comply with the load cases that are prescribed in ISO/TR 15070. This is done by a number of standardized tests in a specified order. If the container withstands these tests, it will get an ISO certificate. In addition to this, a random sample of all new containers from a factory will be tested periodically by these same tests.

Since the load cases as prescribed in the ISO will determine whether the container becomes certified, this means that there is no need for the designer of the container to reformulate all load cases and situations that affect the container. This will only be the necessary if there is a customer with specific requests that are not specified in the ISO. In all other cases, it suffices to comply with the general cases as prescribed in the ISO. Therefore, since this container design is not commissioned by a customer with certain requirements, the design as described in this report will only need to comply by the load cases from the ISO.

External interactions

The external interactions are described in the ISO 1496-1. The locations were the interactions act on the structure are the corner fittings, forklift pocket and load transfer areas. Since these interaction locations are ISO prescribed their location cannot be changed. A change in location would make the container not ISO certifiable. The relevant areas are described in the following ISO -norms:

1. The corner fittings are located in all eight corners. There are four bottom fittings and four top fittings, the locations are given by ISO 668 Annex A. The detailed dimensions and specifications are prescribed in ISO 1161, see Figure 10.
2. The dimensions for the forklift pocket are described in ISO 1496 (Annex B).
3. The load transfer areas in the floor are described in ISO 668 annex B.

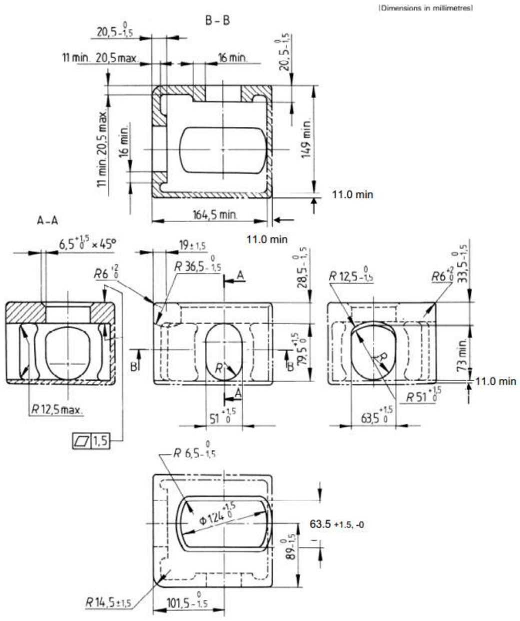


Figure 10 ISO1161 corner specification

2.4.2 Competition analysis

The goal for the competition analysis is to answer the following question: is there direct competition for a foldable 20ft container? The competitor analysis is split into three parts. First, the trends for normal 20ft containers are investigated. The foldable container is its direct competitor and will thus have an influence on the payload requirement for a foldable container. Secondly, there are the companies who are currently developing a foldable container. These direct competitors will influence the bundle size for the foldable container. Finally there are the previous attempts. Analysis of why these attempts have failed can increase the understanding in what requirements are important for the foldable container to be viable.

Trends in normal 20ft general purpose containers

In order to identify requirements for a foldable container in terms of gross weight and payload it is relevant to known the gross weights and payloads for a normal 20ft container. For the largest shippers in the global market these numbers are shown in Table 1. It should be noted that shippers provide this data as reference data. It does show however that the normal tare weight is between 2180 and 2400 kg. It also shows that the higher rating of 32500 kg is also applicable to 20ft containers and that the maximum payload for all shippers is above 28000 kg.

Table 1 Shippers information

Company	**Payload**	**Gross**	**Tare**
Maersk	28300 kg	30480 kg	2180 kg
Evergreen	28080 kg	30480 kg	2400 kg
CMA CGM	28250 kg	30480 kg	2230 kg
Hapag Loyds	30150 kg	32500 kg	2350 kg
Msc	28260 kg	30480 kg	2220 kg
Hamburg Sud	28260 kg	30480 kg	2220 kg
OOCL	28200 kg	30480 kg	2280 kg
APL	28160 kg	30480 kg	2320 kg
One-line	28280 kg	30480 kg	2200 kg

Competitors

Currently there are two companies who are developing a foldable 20ft container. The first company is US- based Staxxon, the second is Navlandis based in Spain.

Staxxon

Staxxon is a company based in the USA. They are developing a folding 20ft container that can be folded sideways into a five to one bundle, as can be seen in Figure 11.

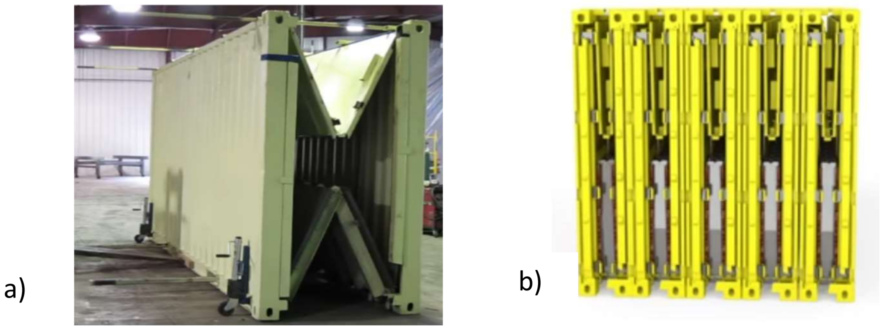


Figure 11a) Staxxon folding [12]; b) Staxxon bundle 5-1.

The working principle for the Staxxon container is an x-folding mechanism[9]. They fold the container by folding the roof and floor as can be seen in Figure 11a. The system is balanced by using horizontal sliding bar on the top and bottom of the container. The container folds 5-1 (Figure 11b). Staxxon has posted their CSC information from their container tested in 2012 [10],**Fout! Verwijzingsbron niet gevonden.**. No newer information is publicly available.

Table 2 Staxxon CSC information

Staxxon CSC	
maximum gross weight	24000 kg
maximum payload	20825 kg
stacking(corner post)	86400 kg
stacking capacity	192000 kg
transverse racking	15286 kg
floor strength	7257 kg

From the CSC information the own weight of 3175 kg for the container can be derived. It also should be noted that the maximum allowed gross weight is an older standard and that the current standard for a 20ft container is 30480 kg. No trial information is currently publicly available, however there is a public video partially showing a working folding mechanism, see Figure 11[11]. The video that is available is uploaded by Staxxon LLC on 24 January 2011, this is their only upload of a real world test of their solution. Other videos they have online include two fully digital rendered videos. The first video shows the working principle of the container. The second video shows how the container could work in the intermodal container environment. Staxxon does not have any patents on their folding mechanism, since it is based on an expired patent from the 70s. However, they do have a patent on the sliding bars that are used for the 5-1 stacking.

Navlandis

Navlandis, a company based in Spain, is also developing a 20ft foldable container, called Zbox [13]. The working principle of the Zbox is shown in Figure 12. Their container has doors on both endwalls (Figure 13a), which can be rotated onto the sidewalls. The sidewalls with endwalls can then slide in a Z configuration (Figure 13b). The folded Zbox stacks 5-1.

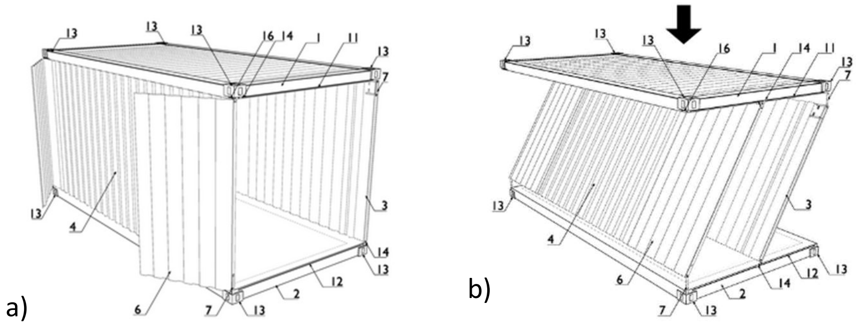


Figure 12 a) Navlandis container with opened doors on endwalls; b)Navlandis container folding in Z-configuration

As of 20-10-2018 there is no public CSC information on the Z-box capabilities, and there is no public information on trials being undertaken, active or otherwise. No videos are posted directly by the company, but one video showing the process is posted by Startupxplore[14]. This is a credible source since Startupexplore has run a crowdfunding campaign for Navlandis. Navlandis has patented their folding method and mechanism under patent US9802754B2 (granted), EP3061707A4 (pending), CN105307956B (granted), ES2421059B1 (granted) and WO2014202802A1 (application). The patent was filed in 2014[15]. It describes in detail how the folding mechanism is constructed and works.

Previous attempts at folding containers

Besides the current two companies working on a foldable 20ft container there are also three previous attempts worth noting.

Cargoshell

In 2009 Cargoshell [16] came into the news as a company trying to develop a folding container based on composite materials. When looking at their website it shows that they are currently focusing their designs on fixed normal and reefer containers with a weight reduction and improved reefer efficiency. They seem to have dropped their ambitions of a foldable container.

Since Cargoshell managed to get a CSC certificate for the normal and reefer container the assumption is made that they did not manage to get a foldable construction able to withstand the requirements for the CSC certificate.

Fallpac and SIO

A study done in [1] identifies the SIO and the Fallpac container as two previous attempts. Both of these containers started appearing in the 1980s. The SIO container was a container that could be disassembled into multiple parts and shipped compressed Six-Into-One, hence the name SIO. The main drawbacks of the SIO container are that it has long folding and unfolding times, a 3.5 times higher unit cost, and a vulnerability to damage.

The Fallpac container has a detachable roof and walls that fold on top of the floor. In this way four folded containers can be stacked in a fifth container. According to Konings, no technical problems or serious disadvantages have been reported, except for its high tare weight, which is 4000 kg and a max gross of 24000 kg.

Conclusion

It should be noted that none of the competitors have achieved ISO and CSC certification. This is a crucial step to allow the products to be used globally. It is unclear what the progress is of these companies, since no new information is being released. However, it is clear that the competitors plan on using 5-1 stacking or 6-1 stacking, with is an important consideration for the competitive advantage for the new HCI container.

Based on the competition analysis the following requirements are derived:

- The container should be able to have a payload of 28000 kg. Since the rating of a container is increased stepwise the rating for the design should be 32500 kg in order to fulfil the payload requirement. This is assuming that the design will weigh more than a standard container.
- The container must be foldable to one fifth its normal volume and five folded container should be stackable to form a bundle the same size as a normal container.

2.4.3 Region specific regulatory requirements

There are two areas of legislation relevant to the requirements of the design. First there is the worker safety regulations when looking at the folding process. Secondly the effectiveness of the folded bundle depends on the maximum number of folded containers a single truck is able to move.

Safety legislation

Besides the ISO regulations, the safety legislation is also important to take into account for the design requirements. There are two governing bodies that have a leading role in worker safety, these are the

European Agency for Safety and Health at Work in the European Union and the Department of Labor in the United States of America.

The EU legislation says that no workers are allowed under a suspended load unless this hampers the work [17]. The US legislation on this point is much stricter and clearer. From standard number 1926.1425 (e)(1): “No employee must be directly under the load”. Furthermore 1926.1425(b) states: “While the operator is not moving a suspended load, no employee must be within the fall zone”. And although there are exceptions to the latter, there are no exceptions for 1926.1425 (e). Since the container needs to be designed for a global market the legislation for the United States is leading, since it is stricter than the EU legislation. This means that while parts of the container are suspended, no workers are allowed to be near the container.

Maximum number of folded containers

In Europe, for intermodal container transport, a truck including container can have a maximum weight of 44 ton. One truck is able to carry two regular 20ft containers, which means it should be able to carry two stacks of five folded 20ft containers, corresponding to 10 containers total. The own weight of the truck and the trailer is 14 ton [19],[20], which means that there is only 30 ton left for the containers. Therefore, in order to transport 10 folded 20ft containers, each container cannot weigh more than 3000 kg. In comparison, a normal 20ft container weighs around 2300 kg. Therefore, it is desirable that the new HCI folding container would weigh less than 3000 kg. This is not a hard requirement, since a truck transporting even one stack of folded containers is already transporting 2,5 times as many containers as in the normal situation.

2.4.4 Inhouse experience

HCI has operated several versions of their 40ft HC design and have found and solved problems in the use of the foldable container. This resolves into the following requirements.

- Usage requirements:
  - All parts need to stay connected: if one of the parts is lost somewhere along the operations chain, the entire container is no longer usable, which could lead to long delays and additional costs.
  - (Mis)handling of the container: this consist of two parts. First, the process should be as easy as possible so that no mistakes are made along the way. Second, the folding process should allow for relatively large movements without damaging the container. Because the equipment that is being used for the handling of the container is relatively large and inaccurate, it is difficult to make tiny and precise movements in the folding of the container. Guides can be used to slide parts into the right place without damaging other parts.
  - Lightproof: clients often desire a lightproof container, in order to make sure no rodents or insects are able to enter the container. This is not the same as the waterproofing requirements, because the latter is only required under normal position of the container.
- Cost and production requirements:
  As mentioned before, the OPEX and CAPEX need to be economically viable.
- Folding method requirements:
  The 4fold folding mechanism is already known and used by multiple parties, therefore they already understand the time and effort it takes to fold the container. Using a similar folding

method for the 20ft container would ease the adaptation of the new container. In addition, HCI already has a patent on this folding mechanism, which means the design would be protected against no additional costs. Although it would be possible to design a new patentable folding system, the current folding system has already proven itself to be successful and usable in the chain of operations.

2.4.5 Environmental interactions

Unintentional external interactions

Unintentional interactions are rough and misplaced movements of the containers. These happen in the real world and damage from these interactions should be minimized.

Misalignment of the containers

In order to secure a container during transport it is placed onto twist locks with can rotate and keep the container in place. An example of a twist lock is shown in Figure 13. The twist lock itself is a cone-like steel cast. If a container is misplaced on the twist lock, damage needs to be prevented.

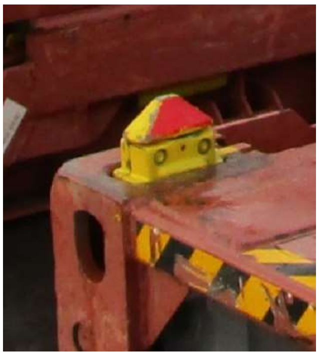
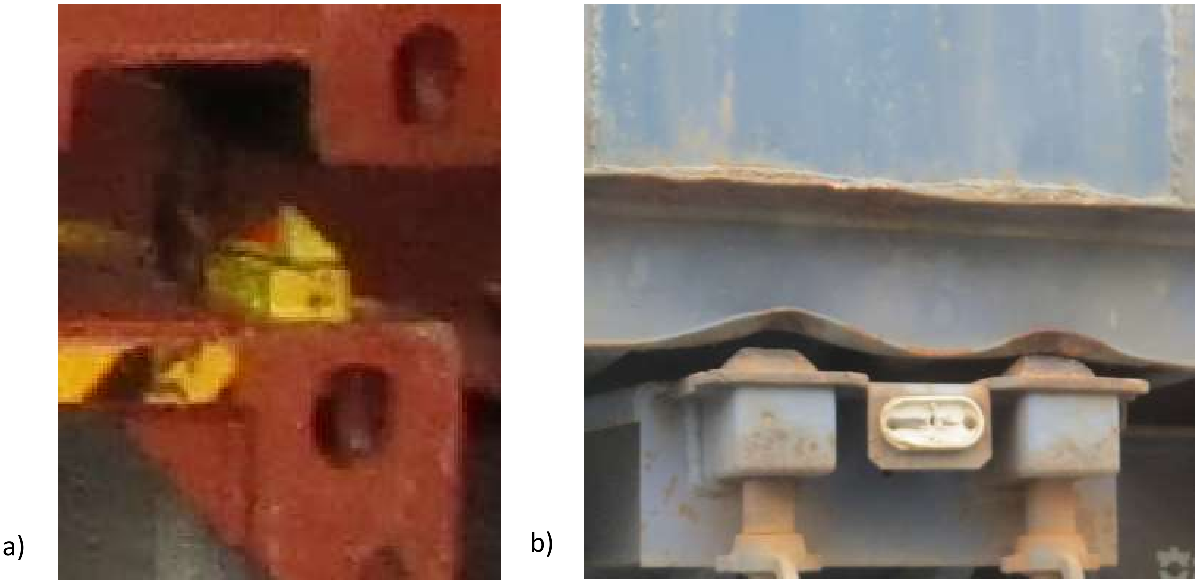


Figure 13 Twistlock on the topcorner

Damage from operations

The risk of damage from operations, for instance when transferring the container from one location to another, as can be seen in Figure 14, needs to be minimized. Since most of the container consists of thin steel material, an outer edge can be added to the outside of the container, of which the main goal is to absorb impact. This will prevent damage to other parts of the container.



a) b)

Figure 14 a) and b) are two examples of container misalignment during operations.

Internal interactions

The internal interactions are the interactions that occur when the container is in the process of being folded or unfolded, and when in folded or unfolded state.

Endwall base interactions

The endwall needs to rotate on a hinge point, see Figure 15, in the base to the unfolded vertical position and a horizontal folded position on top of the sidewall. The movement is achieved using the folding system located on the roof, as discussed in Chapter 2. This means the endwall needs to move over the folded sidewalls and needs to stay connected to the roof in order to function.

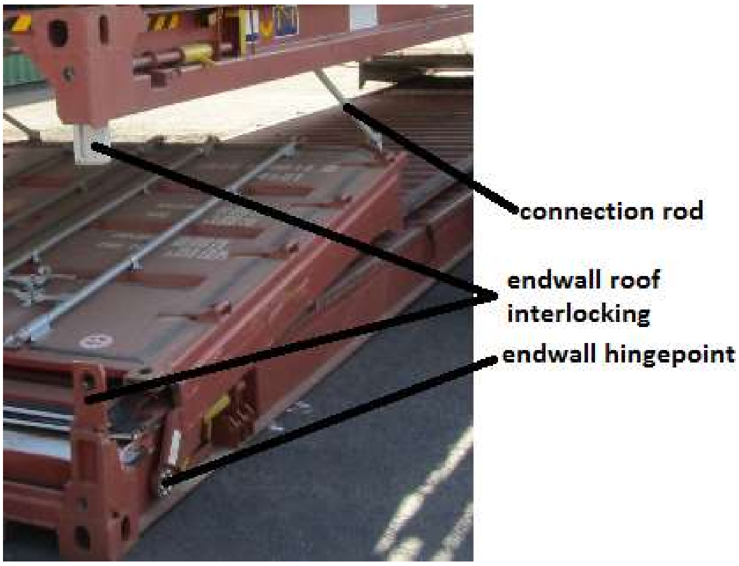


Figure 15 Endwall interactions

Endwall roof interactions

The endwall in unfolded position needs to interlock with the roof when the roof is lowered on the sidewall, in order to make the structure rigid. Also the folding mechanism is connected between the top of the endwall and the roof. With this mechanism the endwalls can be folded and unfolded using the roof, see Figure 15.

Endwall sidewall interaction

Between the endwall and the sidewall, one or more locks are needed to compress the rubber seal between the two components and create a watertight seal, see Figure 16. Additionally, these locks function as a securing to keep the sidewalls in an upright position.

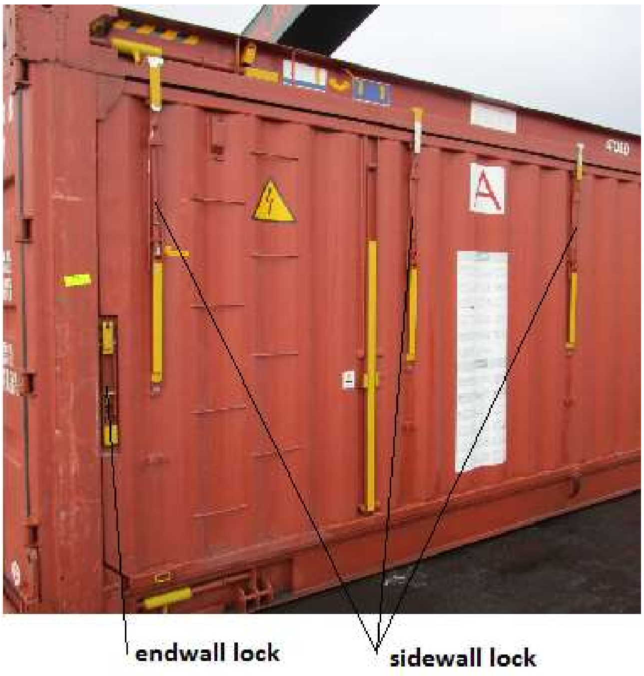


Figure 16 Endwall and sidewall lock details

Sidewall roof interactions

The sidewall is connected to the roof with several sidewall locks, see Figure 16 . The functions of these locks are threefold: first, they need to secure the sidewall in the vertical position; second, they ensure that the seal between the sidewall and the roof is compressed and create a watertight seal; third, the locks create a rigid structure and allow the transfer of forces between the main members. This is achieved in conjunction with the seals.

Sidewall base interaction

The sidewall is connected to the base using a piano hinge. This allows for the inward folding of the sidewalls, and allows the even transfer of load forces between the sidewall and the base. Additionally there is an energy capturing device placed in the middle of the base to limit the impact of the folding sidewall and as a protection measure in case the container is not empty while being folded.

2.5 Requirement list

2.5.1 Complete requirement list

There are three types or requirements:

Critical (C) – These are requirements that must be satisfied
Preferred (P) – These are goals that should lead to a good design
Wish (W) – These are requirements that improve the design

General

- Comply with ISO 1496-1, ISO 1496-5, ISO 1161, ISO 668 where applicable [C]
- Lifespan of 10 years [C]
- Door opening 2200 mm [P]
- Internal width minimal 2324 mm [P]

Production

- Unit cost max USD 10,000 [C]
- Minimize construction failure risk [W]

Usage

- The unfolded container can be used as normal container [C]
- Maximum own weight of 3000 kg [P]
- Container rating:
    - 32500 kg [P]
    - 30480 kg [C]
- Minimize critical damage risk [P]
- The container will be designed for minimum maintenance and repair costs [P]
- A single folded container should be moveable by standard handling equipment [C]
- All parts of the container must stay connected [C]

Folding operations

- The folded container can be bundled into the height of a normal container in a stack of:
    - Four containers [C]
    - Five containers [P]
- Can be folded with the same equipment as the 4fold container [P]
- Interlocking mechanism should be integrated in the design [C]
- Folding operations should be done in a maximum of 5 minutes using two persons [C]
- Folding should be done in a safe and controlled manner [C]
- The status of the locks (open/close) are clearly visually identifiable [C]

- All locks and raisers have a second securing [C]

- A safety (securing) is present on energy storing parts [C]

Intellectual property

- The design should be:
    - IP free [C]
    - Patentable [W]
    - using current HCI patents [P]

2.5.2 Key requirements

Based on the complete requirement list above, there are three requirements that will have the most influence on the design.

ISO compliance

The container should be ISO compliant and all load cases should be passed.

5-1 folding

Because the new design should conform to standard sizing for 20ft containers, 5-1 folding means there is a restriction on the height the folded container can have in order to maintain the desired height. This will have significant impact on the folding options.

32500 rating

This is a weight requirement, and inherently a folding mechanism will bring additional weight to the design as compared to a non-foldable container. The rating is stepped up one step compared to normal containers to offset the increased tare and have a competitive payload.

4fold folding mechanism

As described before, there are a number of advantages over the use of the 4fold folding mechanism. If this turns out to be feasible, no other design need to be considered since this will already be preferred.

2.6 Conclusions for the next design step

This chapter has shown the requirements that should be fulfilled in order to design a 20ft foldable container. From the exploration of the actors that influence the requirement list, it was found that if the 4fold folding mechanism can be applied to the new design, this would be preferred over other designs. The next step according to the design process of Pahl (2007) is conceptual design, in which a number of concepts are generated. However, since from the requirement list it was found that one mechanism would be the best solution, this will be treated as the only concept. It is important to first explore whether this is feasible, if not, other designs could be generated. Therefore, in the next chapter a preliminary concept is drawn up in order to determine the possibility of using this mechanism.

Chapter 3 Principal solution selection

Normally in the design process the first step after the creation of the requirement list is the concept generation phase, see Figure 17. However, due to the preference of using the HCI current patents, no new concepts will be developed if the patent protected principle solution that is used for the 40ft design can be used for the 20ft design. So this chapter will focus on the question:

What are the essential problems that need be addressed to make the 40ft design meet the requirements of the 20ft container?

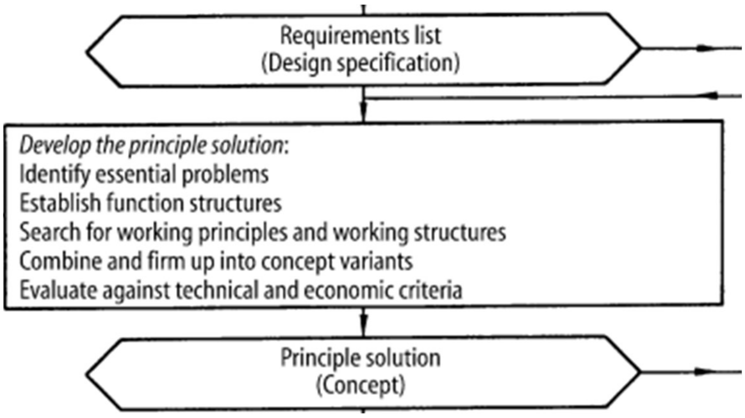


Figure 17 Principle solution detail of the design process described by Pahl (2007)[1]

Since preferred principal solution is centred around the 4fold folding mechanism used on the 40ft 4fold container, the steps described in Figure 17 are done in a different order. The first step is to evaluate if the folding mechanism would work for the 20ft foldable container with a scaled version of the 40ft container. After this evaluation it is possible to identify the essential problems and focus on one concept.

3.1 Evaluation of the 4fold folding concept for the 20ft design

The folding mechanism depends on the ability to change the position of the bars that connect the end walls to the roof. When the container needs to be folded, the position of the bars is limited such that the end walls' centre of mass is pulled beyond the hinge point in the base, forcing the end walls to fold inward. When unfolding the connection, the bars are allowed to move to a position where the roof is fully raised. The end walls can be raised such that their centres of mass pass the hinge points again and the end walls fold outward.

3.1.1 4Fold adaptation for the 20ft container

What needs changing?

The outside dimensions of the 4fold and 20ft container are given in Table 3. These dimensions are converted from imperial units into SI-units. Besides the outside dimensions, the folded height also needs to change. For the first evaluation this is not taken into account yet, since it is expected that this would involve the redesign of various parts.

Table 3 dimension comparison

Dimension	**4fold**	**20ft**	**Difference**
Length	12192 mm	6058 mm	6134 mm
Width	2438 mm	2438 mm	0 mm
Height	2896 mm	2591 mm	305 mm

How can the design be scaled?

The side view of the 4fold design is show in Figure 18. The first step in finding out if scaling is possible, is to identify how scaling can be applied in a simple way that does not require much engineering. The main criteria that a container needs to withstand are deformation (deflection) of the geometry and buckling of the main members.

Figure 18 4fold 40ft HC container

No adjusting of the profile cross section is allowed with scaling, to ensure that the folding mechanism still fits. Additionally the container is not allowed to buckle and the deformation of the container under load is limited to a given value. This buckling resistance comes mainly from the profiles, since the main arears of the container consist out of corrugated plate. In general there are two equations that are important for the container design. The first is the deflection under load formula given by (1) and second there is the Euler buckling formula given by (2).

(1) $$\delta = \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I}$$

(2) $$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{L^2}$$

From the formula's (1,2) it shows that changes in length or load have an easily predictable effect. Changing the width and height of a hollow profile has an unpredictable effect, since the area moment of inertia (I) does not scale in a predictable way. *I* is dependent on width and height, but also on the profile thickness.

The CSC rating for a 20ft and a 40ft container is set the same at 32500 kg gross weight. The worst case effect of the same rating results in a doubled load per unit length. This assumes that the own weight of the container is also uniformly distributed across the container length. This is not the case, but uniformly distributed loads result in a higher deflection. The weight distribution of the own weight is more toward the front and end wall, since these walls have a substantial weight.

The scaled model

The new required dimensions are obtained by cutting out the highlighted areas shown in Figure 19. The height reduction is accomplished by removing one foot of material from the middle of the design. This reduces the length of the corner post and the height of the sidewall. The reduction of the length is accomplished by removing two sections of 10ft between the forklift pockets and the end walls.

Figure 19 Scaling of the 4fold design, by removing the two highlighted areas from the design.

3.1.2 Adaptation effects

The following changes result from the adaptation proposed above:

- Overall height: If the top side rail and bottom side rail height are not adjusted, the overall internal height will be lower than the normal container. The 4fold container has an internal space between a normal and a HC container.
- Overall weight: By chopping the design the weight of the container will be lower. It will not be half of the weight of the 40ft container, since the end walls and corners of the container are relatively heavy and these remain intact.
- Door dimensions: By scaling the corner post to reduce the height from 9.6ft to 8.6ft, the door height is reduced from 2508 to 2203 mm. This is 58 mm lower than the minimum door height from the 2261 mm given by the ISO. Current container trends show doors that are even larger than stated in the ISO norm: a common door is 2280 mm; this gives a difference of 87 mm.
- Bundle height: The bundle height is unaffected by the scaling effects on the container, see Figure 20. This means that the bundle of four containers is too high. Reducing the bundle to three containers does not result into a standard container height either.

Figure 20 4fold modified bundle

3.1.3 Comparison with requirements

The effect of scaling on the ability of the design to withstand the ISO load cases is shown in Table 4. The effects are classified as *improvement*, *unknown*, *no change*, or *worse effect*. The best result possible is a *no change*. This means that the right amount of material is used to withstand the load case. An improvement in the result means that too much material is used to withstand the load case. In that case there is more headroom available and thus a weight reduction is possible. A worse effect means that the design in all likelihood will not pass the ISO requirement. The assumption here is that the design of the 4fold is engineered in such a way that there is minimum headroom in the design to pass the requirement.

Table 4 Scaling effects on the ISO loadcases

ISO case	**Name**	**Effect**	**Reason**
1	Stacking	improvement	Lower length gives more margin on buckling
2	Top lift	no change	Half unit length of BSR gives lower moment in bottom but double load per unit length
3	Bottom lift	improvement	Lower BSR length gives higher margin on buckling
4	Restraining	no change	Acceleration forces are unaffected by unit length
5	Strength of end wall	improvement	Decrease in height gives lower span
6	Strength of sidewall	worsened effect	Decrease in height gives lower span but load per unit length is doubled
7	Roof load	no change	Roof is not affected
8	Floor load	no change	Local wheel load is similar
9	Racking (longitudinal)	improvement	Lower height of corner posts gives lower moments
10	Racking (transverse)	improvement	Lower height of corner posts gives lower moments
11	Forklift lifting	improvement	Lower BSR length gives lower moments , space between fork pockets is relatively higher

In Figure 21, the 4fold folding mechanism is applied to a 20ft container. It can be seen that when the end walls are rotated on the hingepoint to the folded position they do not reach other. This means that the base has enough length to facilitate this folding process, and therefore the 4fold mechanism is viable in essence.

Figure 21 4fold folding projected on a 20ft container..

3.1.4 40ft design evaluation summery

Simply scaling the design will result in a container that can incorporate the folding mechanism, but with three disadvantages:

- it has a reduced internal height compared to the ISO requirement, which means less transport volume;
- it can withstand the load cases better than required, this means the container is essentially over dimensioned and uses too much material;
- the bundle height does not result in a height similar to that of a normal 20ft container.

Therefore, it can be concluded that some changes to the design are necessary to develop a satisfactory foldable container. It is necessary to make a more detailed redesign, in order to solve the problems mentioned above. However, the mechanism itself should be viable, as shown in Figure 21, and therefore it is not necessary to develop an alternative folding concept. A detailed execution based on the current folding concept will be the preferred design, since this will fulfil most of the requirements.

3.2 Essential problem extraction

As mentioned in 3.1 the three problems with scaling the current design are the following:

- an incompatible stacked container height;
- too little internal height, leading to reduced volume;
- over dimensioning of the design regarding the loadcases, leading to an excess of material and thus too high weight.

These problems should be solved in order to apply the 4fold folding concept to the 20ft design. Therefore, in the next chapter, the initial design is drawn up, which starts with an adjustment of the height of the folded container. This is important in order to make a competitive design, since it was seen that a number of competitors are developing a 5-1 stack. In addition, by adjusting the stacked height, it is possible to remove material and adjust the internal height, but solving the problems the other way around would not result in a compatible stacked height. Therefore, the folded container height is the first problem that needs to be solved.

The internal height problem and the over dimensioning of the parts can be solved by redesigning the following parts: bottom side rail, floor, top side rail, front wall, and back wall. For the roof and sidewall it is possible to do a simple check to see if they meet all the requirements. However this is not possible if it is not known how much space is available in the overall design to fit all these parts. Since the available space and the incompatible stacked height of the container are both linked the essential problem can be defined as:

The essential problem is that the height of the 4fold folded container needs to be changed in order to fit in the allowed height for the folded containers in a 5-1 bundle.

To solve the problem two steps need to be taken.

- Define the allowed height of the folded container.
- Break down the design into main components so a high level distribution of the allowed height can be done.

3.2.1 Height allocation

There are two types of 40 ft containers: standard and high-cube (HC). The height of a standard container is 2591 mm, which is the same as the standard height of a 20 ft container. The height of a HC container is 2898 mm, however this height does not exist for 20 ft containers. Therefore, for the 4fold 20 ft container the total height of the stack should be 2591 mm. The height of the 40ft 4fold container is based on the 40 ft HC height in a 4-1 stack: 724 mm in folded condition. Since it was determined in Chapter 2 that the 4fold 20 ft container should be stacked 5-1, the total height available for one folded container is 2591 mm divided by 5, which equals 518 mm. The above mentioned heights are summarized in Table 5. Compared to the 4fold 40 ft design, this means that the 4fold 20 ft design needs to have a height reduction of 29%.

Table 5 Container height overview

	Standard height (mm)	High cube height (mm)	Folded height (mm)
40 ft	2591	2896	-
20 ft	2591	-	-
4fold 40 ft HC	-	2896	724
4fold 20 ft	2591	-	518

3.2.2 Simplifying the main components of the 4fold concept

A container can be seen as a rectangular box with six components: five walls and one door. It is possible to design a container with two doors, for instance on the front and rear end side, but this is undesirable because of a) the added costs and b) the fact that it then becomes necessary to check and lock both doors before transport. Therefore, only one door is usually implemented on the rear end side.

The first step in the design of the 20ft container is determining the amount of space that is available for each component, in order to fulfil the requirements listed in Chapter2. In order to do this, the design of the 4fold container concept is divided into the six main components listed below, see Figure 22, only in this case these components can move relative to each other when the folding or unfolding process is performed. The six components are: Roof, Sidewall (L), Sidewall (R), Front end wall, Rear end wall with doors, and Base.

In addition, there are a number of auxiliary components that exist in between the six components, see Figure 23a. Since these influence and interact between multiple components, they are given a separate category. For the mock up design the auxiliary parts will be omitted.

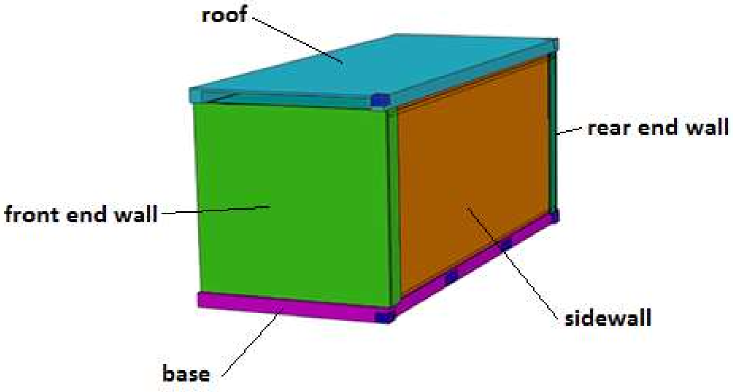
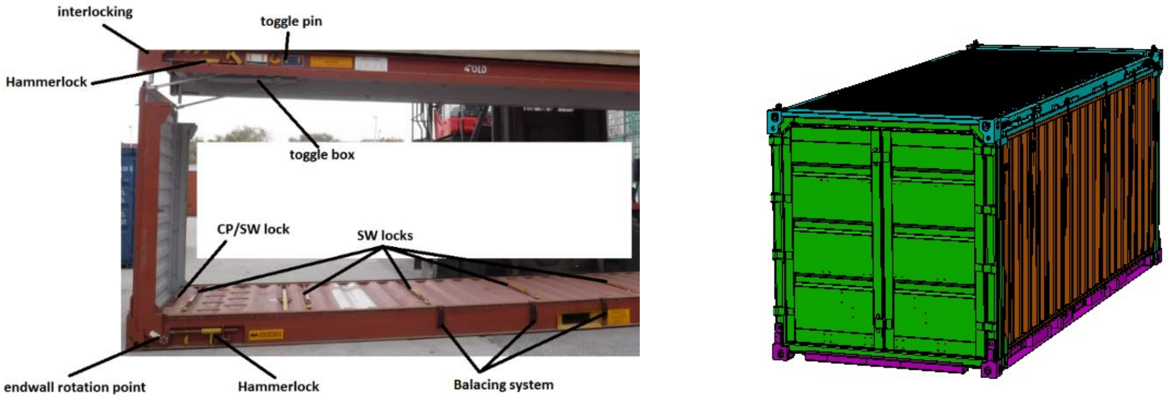


Figure 22 Main components of the 4fold concept

The components consist of a number of sub-assemblies each, but in order to first allocate the main dimensions and clarify the design problem, these parts will be treated as a single part with simplified dimensions. After the available space is allotted to each component, the design will be expanded into more details. The full list of main components and their sub-assemblies is shown in Table 6. A graphical overview showing the differences in detail are shown in Figure 22 and 5b.



a) b)

Figure 23 a) The auxiliary components for folding; b) detailed design showing the sub-assemblies and auxiliary parts

Table 6 component overview

Main component	**Sub-assemblies**
Roof	Corners
	Top side rail
	Top header
	Roof plating
Endwall rear	Corner post
	Corner flap
	Doors
	Top frame
	Door sill
Endwall front	Front end flap
	Front end frame
	Front end wall
Sidewalls (L+R)	Lower beam
	Top beam
	Side
	Mid-section
Base	End transverse members
	Lower corner fittings
	Bottom side rails
	Floor board
	Forklift pocket
	Transverse members
Auxiliary parts	Side wall locks
	End wall lock
	Top hammer lock
	Bottom hammer lock
	Folding mechanism

3.3 Mock up model

With all the information on the main dimensions and the component interactions known, a mock up design for the main components can be created. This mock-up model is used to evaluate the effect of the hinge location and additionally ensure the reserved ISO spaces are according to the norms.

3.3.4 Mock-up model overview

The two states of the mock-up model are shown in Figure 24. The goal of the mock-up model was to evaluate whether folding of the container was still possible while the design kept evolving. In addition, this provides an easy way to evaluate where any possible free space would be available, if it turned out that more space was needed for the six main components.

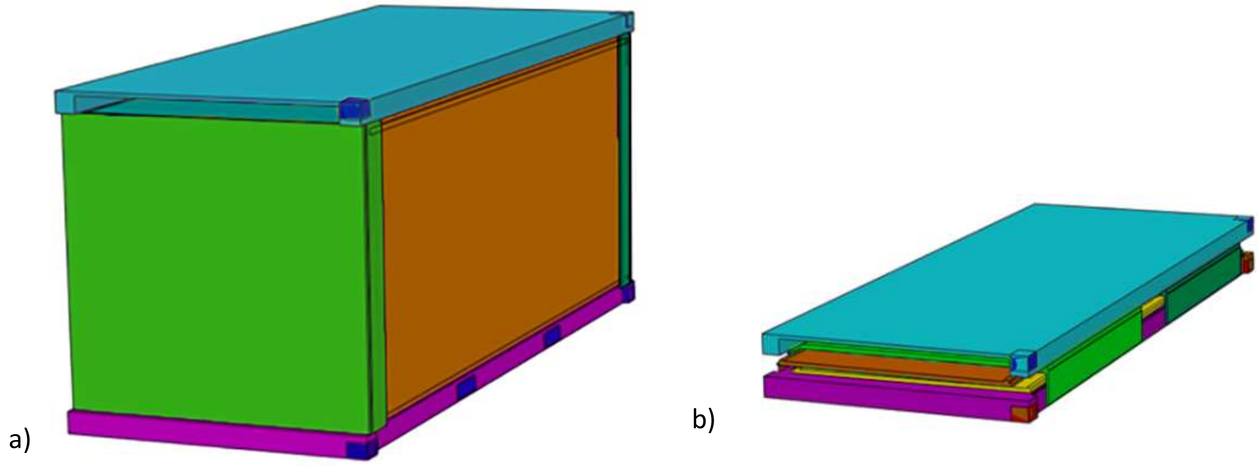


Figure 24 a) Mock-up model in unfolded state; b) mock-up model in folded state

3.3.1 End wall hinge location

The known parameters for the location of the end wall hinge are the following:

- The angle between the vertical and horizontal position is 90 degrees.
- The inward location of the unfolded end wall is known (both x- and z-coordinates).
- The z-coordinate of the folded end wall is also known.

Both x- and z-coordinates are located on a circle with the hinge centreline at its centre location.

The hinge point centreline needs to be placed inward as much as possible to allow for a smooth unfolding of the end wall. For the unfolding to be successful the centre of mass of the end wall needs to be outside of the x-coordinate of the hinge centreline. The result is that the hinge centre line needs to be located on the most inward point on the curve where the hinge still has a clearance with the bottom side rail flange.

3.3.2 Reserved ISO location

As described in Chapter 2, there are a few components needed for interactions with the environment and the container. These components are described in detail in the ISO code: they are the corner fittings and the forklift pockets. The location and area needed for these components are shown in dark blue in Figure 25.

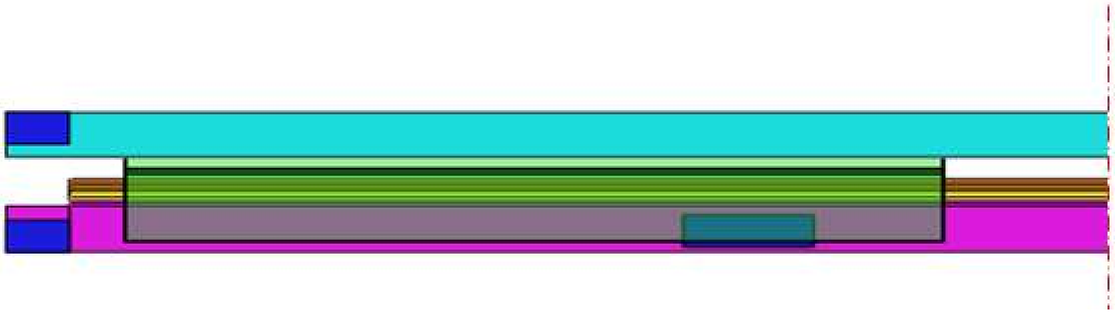


Figure 25 Mock-up model showing the corner fittings and fork lift pocket in dark blue.

3.3.3 Other preferred part considerations

The overall height reduction might seem like a simple problem, but there are complicating factors. First, it is desirable to use as many standard parts as possible, in order to reduce costs, but also to facilitate easy repairs and exchange of parts. In the case of the 4fold container, the standard parts are the doors, sidewall corrugated plating and the transfer members in the base. These parts should ideally not be redesigned, which means their height is known. Following this, based on the height of the standard parts, the folded height of the sidewalls and the endwall in the 4fold design is already optimized to the minimum height needed to incorporate these. Second, since the structure of the container is flexible, there is a minimum amount of clearance needed between all the components to ensure components only interact with each other at the designed points and not somewhere else. This is to ensure that force transfers follow the designed path and not in unexpected locations where damage to the structure might occur. These clearances are especially crucial for the interactions of the endwall with the sidewalls. In the folding sequence, the side walls fold in first, after which the endwall is folded on top. If the clearances are too small or in the wrong location, the forces transferred through the endwall may end up damaging the side walls, since they are made of thin corrugated steel. It is assumed that the necessary clearances can be similar to the clearances in the 4fold 40 ft design.

3.4 Height allocation

With the container reduced to a simplified model of the six main components and the essential problem identified as reducing the overall height of the folded container, the preliminary height allocation should be defined for all six main components. This preliminary allocation should allow for the design to fulfil its derived requirement of having a folded height of 518 mm, based on the key requirement of 5-1 folding.

The end and sidewalls are already optimized in the 40ft design based on the standard parts available to construct a container. The standard parts of the walls are the most common parts in need of repair. Changing these parts into custom parts and possibly reducing the packet height is seen as a last resort.

This leave the base and roof height as parameters to design with. The 4fold 40ft container has a higher floor height but also has a heightened container height. The main reason the base of the 40ft was higher was due to the midpoint deflection under load. The 20ft container is half the length and thus 0.5^4 lower deflection according to formula (1) in 3.1. The 20ft cannot be heighted and so the initial design will have the standard floor height. If the standard floor height is not sufficient a design iteration needs to be made resulting in less space for the roof section.

Since the total container height is a fixed value the height of the roof section is given by the remaining height available.

1. *Sidewalls (L+R)*

The sidewalls are standard parts, their height is allotted first. The minimal folded sidewall package, consisting of both sidewalls plus hinge clearances from the floor and towards the folded endwalls, is 112 mm. This is also shown in the red outline in Figure 26.

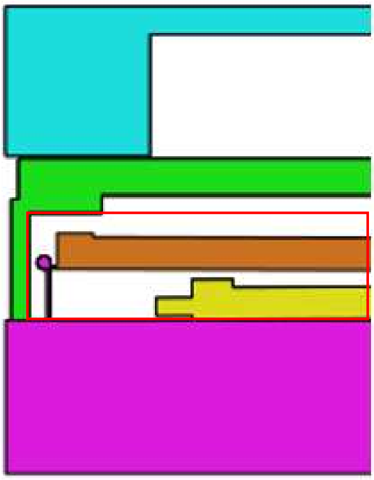


Figure 26 Height allocation of the folded sidewalls

The sidewall folded packet consists out of the following elements:

- Lower Sidewall Bottom beam
- Lower sidewall corrugation
- Sidewall interaction space
- Upper sidewall corrugation start
- Upper sidewall bottom beam

2. End wall

The folded endwall height is set at 60 mm. This is the minimum folded height if the doors of the endwall are constructed out of standard parts. Additionally, this is also the height of the main member of the endwall cornerpost in the 40ft container. Since the loadcase for the corner post is similar for the 40ft and 20ft container, changing this height as a first step is considered undesirable and the height is kept the same.

3. Base

The height of the base was allotted secondly and was set at 170mm since it is preferred that this will be the same height as in a standard container.

The base should not be lower due to the following reasons: it would reduce the option of using standardized parts within the base design; it would be difficult to add required forklift pockets for transport; and the fitting of the doors would be problematic. Increasing the floor height of the container is not preferred, since it would reduce the height allowance of the other components, and it would decrease the available volume in the unfolded container.

4. Roof

The rest of the available height is allocated to the height of the roof. Since the roof panels are standardized, this means that this height allowance defines the space between the top of the top flange of the top side rail and the bottom of the lower flange.

3.5 Principal solution summary

The preferred principle solution for the folding mechanism is the mechanism used on the 40ft 4fold container. The mechanism has enough space to function on a 20ft design. The folded height of a simple modified 4fold 40ft design however does not meet the height limitations set by the 5-1 folding key criteria.

The required height reduction needed to fulfil the 5-1 folding height criterion was identified as the essential problem. In order to provide an initial solution to this problem the container was simplified to a mock-up model consisting out of the six main components of the container. For each of the main components the allotted space is defined and will be used as a basis to perform the redesign off all the components.

Chapter 4 Embodiment

In this chapter the design adaptation of the 4fold design to a viable 20ft foldable container is realized. The design is realised based on the initial solution presented in Chapter 3. The details of the embodiment design phase are shown in Figure 27. First the material for the design needs to be selected, this is due to the requirement that the new container will work in the current construction and repair facilities. With the material selection known , the mock-up model needs to be expanded into subassemblies again and every sub assembly needs to be evaluated against the height limitations to see if a redesign is needed.

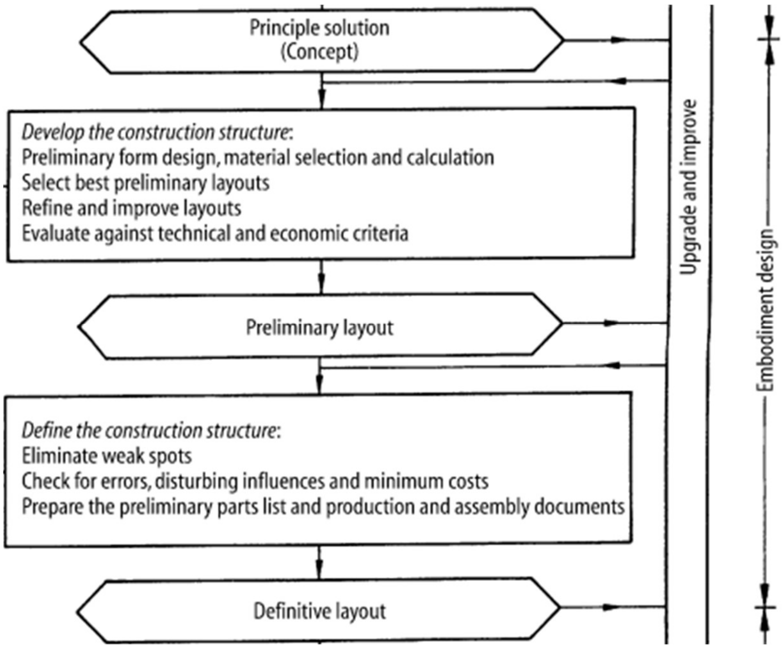


Figure 27 Embodiment design phase according to Pahl (2007)

When the subassemblies and the materials are known a preliminary layout can be created. It is expected that the preliminary layout will reveal design challenges that need to be solved in order to create a definitive layout.

4.1 Material selection

The design limitations for the material selection are investigated based on the following criteria:

- Minimize maintenance and repair costs;
- Minimize critical damage risk.

To minimize the repair costs the choice was made to use standard container materials as much as possible. This limits the possibilities in the design, but resolving these requirements first is a more efficient route to creating an overall viable design.

4.1.1 Material type selection

Three different materials are specified for the container. The material requirements for the corner castings are specified in ISO1161, with the following requirements:

- Yield strength: 275 MPa
- Tensile strength: 480 MPa

The walls and roof of the container are made of corrugated sheet metal supported by profiles made out of open or closed sections. All steel is SPH-A steel which is the standard material for containers and has the following properties:

- Yield strength: 345 MPa
- Tensile strength: 480 MPa
- E modulus: 210.000 MPa

The standard available thicknesses are: 1.6 mm, 2 mm, 3 mm, 4 mm, 4.5 mm, 6 mm, 8 mm or 10 mm. For the floor the material needs to be 19-layer 28 mm thick plywood, supported by a steel frame. This is also standard for container design.

4.1.2 Minimal material thickness

Containers are used in a rough environment and as such are envisioned to be able to handle some damage in the form of minor bending and dents and still function. It is customary that these damages are repaired periodically.

Besides these “normal” damages, there are also damages that impair the safe functioning of the container. The most important of these critical damages is the post buckling of (parts of) the container. When buckling occurs the whole buckled section needs to be replaced before the container will be approved again. The costs involved in replacing whole sections are usually higher than the value of the container. Therefore, damage is critical if the repair costs outweigh the value of the container.

In order to minimize the risk of critical damage, the chance buckling needs to be minimized. This can be achieved by ensuring the buckling failure mode is not the critical failure mode. This can be assured by making sure the allowed buckling stress is larger than the yield stress of the material. There are two types of buckling that can occur. There is the possibility of sections buckling under the load cases. These sections will be checked against the buckling criteria when evaluating the load cases in Chapter 5, since they are dependent on the final designs. Secondly, there is the possibility of local plate buckling, since the container is made from thin plate sections. Local plate buckling depends on the geometry and boundary conditions of the plate. The critical stress for which buckling occurs is given by Equation 3:

$$(3)\quad \sigma\mathrm{cr} = k \cdot \frac{\pi^2 \cdot E}{12(1-v)^2 \cdot (\frac{b}{t})^2}$$

The stress depends on the plate buckling coefficient *k*, which is a factor depending on the boundary conditions of the plate. The different values for *k* are shown in Figure 28a. The value of *k* goes to its minimum value if *a*/*b*>10, with *a* being the length of the plate and *b* the width of the plate. [Ziemian, 2009] The critical buckling stress is highly dependent on the boundary conditions of each plate used. These boundary conditions are shown in Figure 28b. For the container design there are two relevant cases. First there are the closed boxed sections. These have fixed-fixed boundary conditions resulting in a k-factor that has a minimum of 7. This is not the critical type of case for the container.

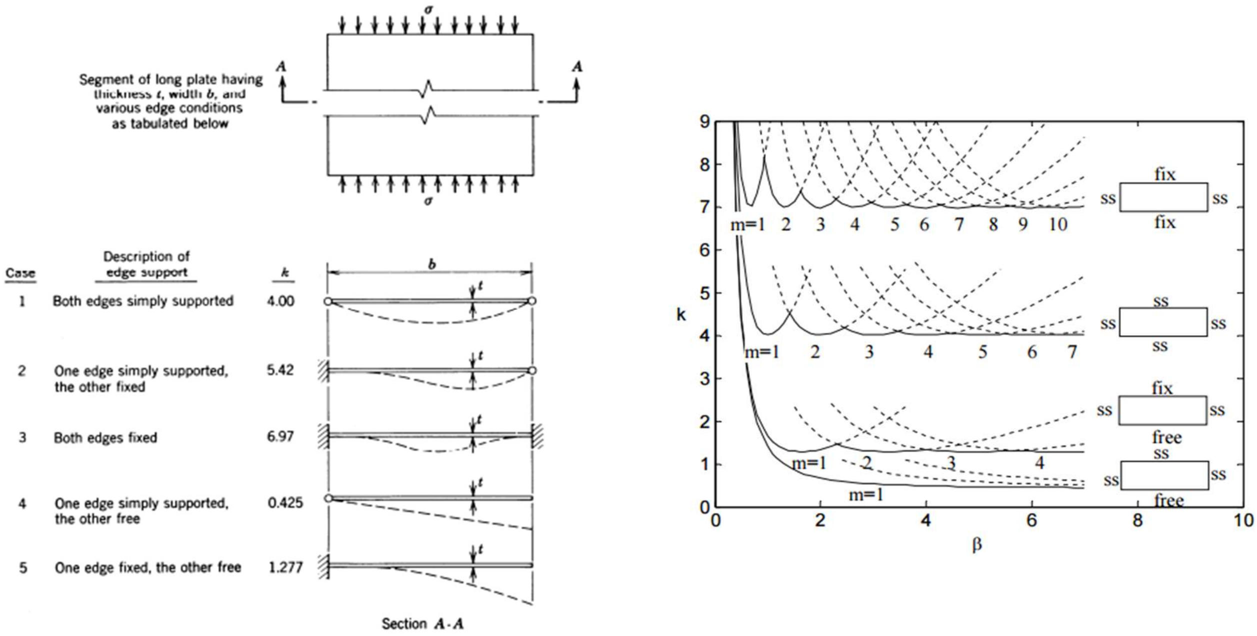


Figure 28 a) Plate buckling coefficient k as function of the normalized plate length β=a/b, m= number of buckled half waves; b) Plate buckling coefficients k from Ziemian (2009)

The second case are the open C sections present in a container design. For open sections of plate there is also the risk of flanges failing due to local plate buckling. The open flanges are on the side rails of the container, see the highlighted section in Figure 29. Local plate buckling would result in the need of complete replacement of the affected section. For these open plate sections the boundary conditions are fixed-free due to the section being made by folding sheet metal. The k-factor has a minimum of 1.27 and this is identified as a critical case. The width of these open C sections are based on the design for the 40ft container and the required ISO dimensions for the corner castings of the container.

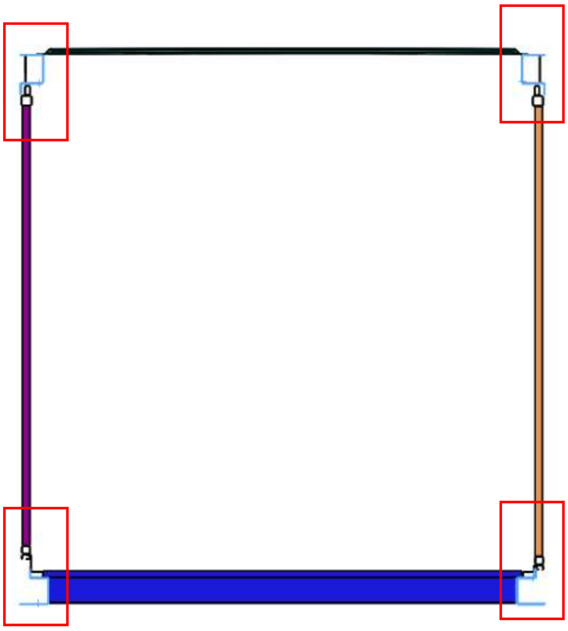


Figure 29 Main open C sections in the design

For the design of the container, the top flange of the top side rail and the bottom flange of the bottom side rail are at risk of buckling, since these are open sections The critical stress is dependent on the thickness of the flange for both cases, a minimal plate thickness is selected in such a way that the risk of plate buckling is minimized. The maximum width of the flanges (*b*) are 116 mm for the top side rail and 128 mm for the bottom side rail. This width is needed to protect the rest of the structure of the container, as shown in Chapter 3. The free length *a* depends on the section, but is always larger than 1500 mm for both rails, which results in the minimum *k* factor for both rails of 1.277. When entered in the critical stress formula, this results in the critical stresses shown in Table 7.

Table 7 Critical plate stress, the fields in green indicate safe plate thicknesses

t **(mm)**	**Yield (MPA)**	**σ_{cr} (top) (MPa)**	**σ_{cr} (bottom) (MPa)**
2	345	134	110
3	345	301	247
4	345	535	439
4,5	345	677	556
5	345	835	686
6	345	1203	988

The yield strength for SPH-A is 345 MPa. Because of the above described importance of minimizing the risk of buckling, in order to eliminate this risk, a safety factor of $\sigma cr > \sigma yield$ is introduced. This would result in a minimum thickness of 4 mm for both the top and bottom side rails. This will ensure the flanges will not fail due to local plate buckling. The plate buckling formula will also be used to check the other open sections of the container design. It should be noted that this does not mean that the open sections are loaded up to this stress level, but if this stress level is encountered the failure mode is not buckling but yield.

The thinnest material currently used on the 40ft design is 1.6mm thick. As a check on the assumption that boxed sections will not have a limitation due to plate buckling the minimum thickness for boxed sections is also calculated. To evaluate all boxed sections the conservative approach is taken assuming the minimal k factor of 7 for all boxed sections. With the results for the bottom open section the minimum required value for b/t is calculated. For closed sections the result is that b/t < 75 or for the smallest thicknesses of 1.6, 2 and 3 mm. a maximal width of 120, 140 and 225 mm respectively. These box dimensions are assumed to not be a problem and will be taken into account for evaluation thin box sections.

4.2 Defining the sub-assemblies

The next step in the design process is to identify which sub-assemblies need to be redesigned in order to fit in the new height allowance, and which can stay identical in their height compared to the 4fold design. By comparing the heights of the sub-assemblies to the above allotted heights of the components, the ones that exceed these heights will have to be redesigned. This is also shown in Table 8.

- Roof: the corners, the top side rail need to change; the top headers and roof plating can stay the same.
- Endwall rear: the corner post and corner flap need to change; the doors, top of the endwall frame and door sill can stay the same.
- Endwall front: the front end wall can stay the same, the front end flap and front end frame need a redesign.
- Sidewalls (L+R): the initial design of the sub-assemblies can stay the same.
- Base: the end transverse members, the corner fittings, and the bottom side rail have to be redesigned. The fork lift pockets do not exist in the 40 ft model and therefore need to be added.

Table 8 Sub assembly overview

Main component	**Sub-assemblies**	**Height adjustment**
Roof	Corners	Yes
	Top side rail	Yes
	Top header	No
	Roof plating	No
Endwall rear	Corner post	Yes
	Corner flap	Yes
	Doors	No
	Top frame	No
	Door sill	No
Endwall front	Front end flap	Yes
	Front end frame	Yes
	Front end wall	No
Sidewalls (L+R)	Lower beam	No
	Top beam	No
	Side	No
	Mid-section	No
Base	End transverse members	Yes
	Lower corner fittings	Yes
	Bottom side rails	Yes
	Floor board	No

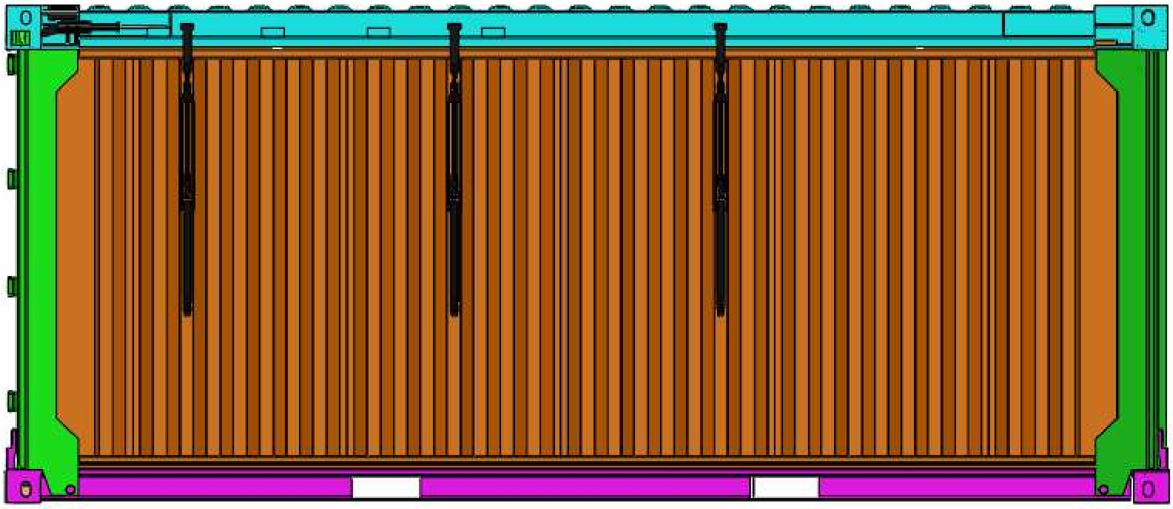
	Forklift pocket	Yes
	Transverse members	No
Auxiliary parts	Side wall locks	No
	End wall lock	No
	Top hammer lock	No
	Bottom hammer lock	No
	Folding mechanism	No

4.3 Preliminary layout

The initial design is created based on the new height allocations The goal of the initial design is to see if there are any spatial conflicts when all subassemblies are assembled, both within the subassemblies themselves and between the components. The initial design is created based on the following guidelines:

- Parts that do not need to be redesigned due to the new height restrictions will be kept the same as in the 4fold design.
- Parts that do need a redesign will have their shape altered to fit the new design.
- The goal is to keep the cross section area similar to the 4fold 40 ft design, since this will increase the chances of fulfilling the load cases. Therefore, the thickness of the material will not be altered if the cross area stays roughly the same.
- When the cross section area would be significantly less, the thickness of the material is increased.

The initial design is shown in Figure 30. The design table is updated in order to give an overview of which subassemblies are resolved, and which need more adjustments. This will be elaborated on in the following sections. In some cases, even though no height adjustment was necessary, it is still necessary to redesign the part based on their interactions with other parts.



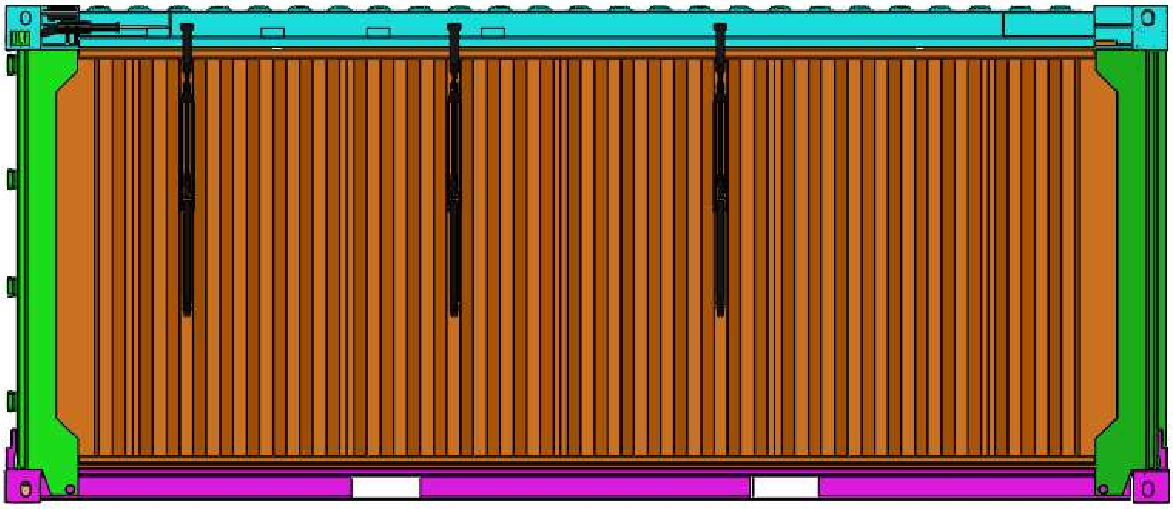


Figure 30 Initial design

After the initial design is drawn up it is evaluated to find out if the height adjustment was sufficient to meet all the spatial requirements on a subassembly level or if a more detailed solution is needed. The results of this evaluation is summarized in Table 9 and described in detail below.

Table 9 Preliminary layout evaluation

Main component	**Sub-assemblies**	**Height adjustment**	**Total redesign**
Roof	Corners	Yes	Yes
	Top side rail	Yes	Yes
	Top corner pocket	No	Yes
Endwall rear	Corner post	Yes	No
	Corner flap	Yes	Yes
Endwall front	Front end flap	Yes	No
	Front end frame	Yes	No
Sidewalls (L+R)	Side	No	Yes
Base	End transverse members	Yes	Yes
	Lower corner fittings	Yes	Yes
	Bottom side rails	Yes	Yes
	Forklift pocket	Yes	Yes
Auxiliary parts	Top hammer lock	No	Yes

4.3.1 Initial roof design evaluation

The height of the roof has changed from 341 mm to 176 mm. The length of the roof has changed from 12,192 to 6,058 mm. The width is the same. Subassemblies that run into problems in the roof are the following.

Near the corner casting:

- The endwall hammerlock shape and location: The endwall hammerlock has no room to fit below the reserved space for the corner fitting, if it needs to stay above the lower flange of the top side rail.
- The container coupler location and stowage method: There is no room in the available space for the top side rail to fit both the hammerlock and the coupler in the same configuration as is used for the 40ft 4fold container

The top side rail:

- The top side rail lower flange location: When the top side rail flange is placed above the protrusions into the top side rail, coming from both the folded endwall and the sidewall locks, the profile would look like that in Figure 31. This would mean that the profile is wider than it is high, and for a profile under bending stress this is a suboptimal shape. It should also be noted that there is no room for the endwall hammerlock to slide in and out.

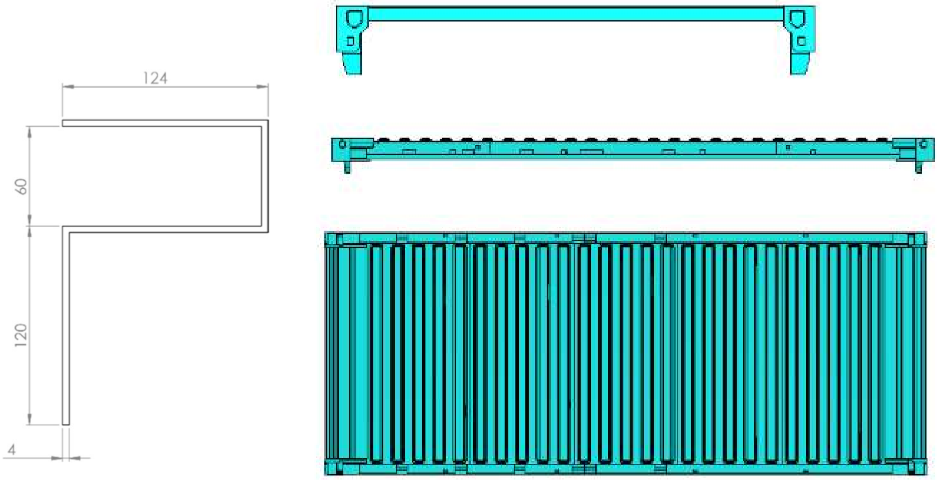


Figure 31 unsatisfactory top side rail section

This means that there are two design challenges in the roof:

- The top corner casting and the adjacent pocket.
- The top side rail.

4.3.2 Initial base design evaluation

The design of the base has changed as follows:

- Height from 241 to 170 mm;
- Length from 12192 mm to 6058 mm;
- Width still is the same.

The design challenge encountered in the base is that there is no room to fit both the endwall hinge point and the lower sidewall hammerlock.

The rear end transverse member could be adapted into a different shape to fit in the reduced height. To compensate for the reduced height the lower flange has been increased in thickness. This lowers the section center distance compared to the bottom and it increases the second moment of inertia.

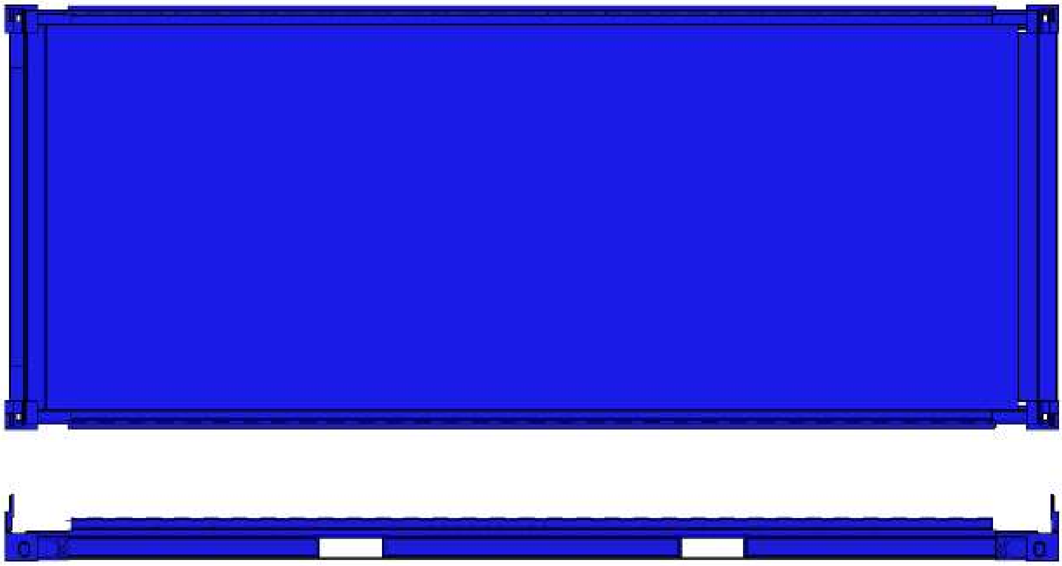


Figure 32 overview of the base

4.3.3 Initial rear end wall design evaluation

When the cornerpost flap has the identical shape as in the 40ft container, it overlaps the entrance points to the forklift pockets. Since the required height reductions for the front of the base were realized by reducing the height of the rear end transverse member, the door sill in the rear end wall frame can stay the same.

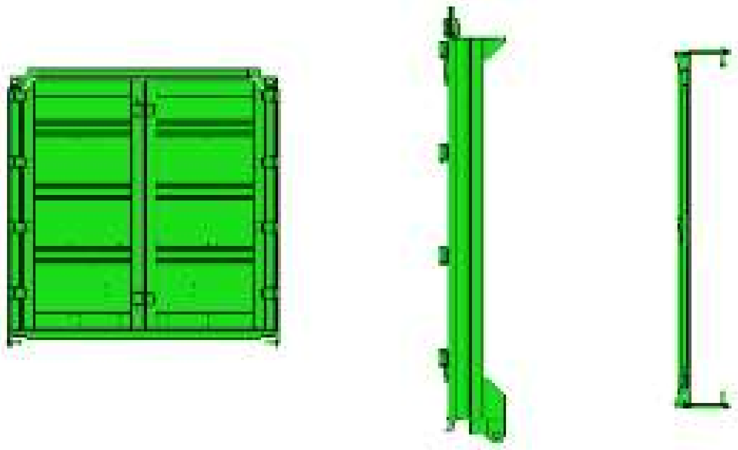


Figure 33 overview of the rear end wall

4.3.4 Initial sidewall design evaluation

There are no problems with the adaptation of the sidewall shown in Figure 34. The sidewalls get lowered in height, which allows for easier fitting in the folding scheme. The length reduction of the sidewalls also poses no problems since the check to see if the folded endwalls have enough space is already done in Chapter 2.

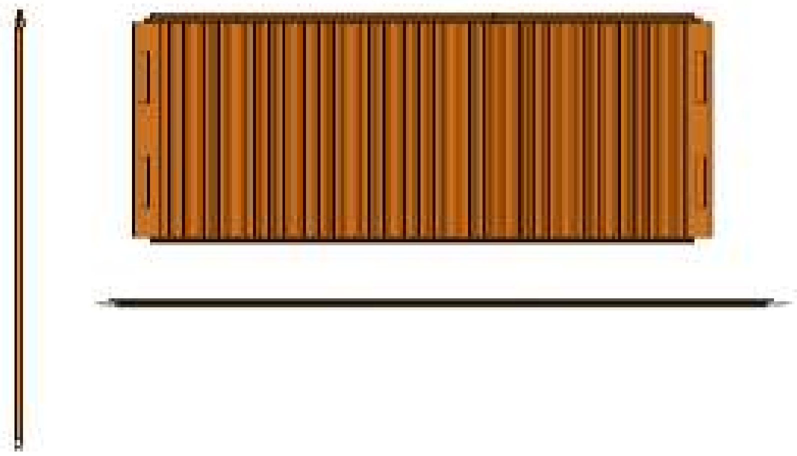


Figure 34 overview of the side wall

4.4 Main design challenges

Based on the initial design evaluation there are four areas in the design that give design challenges that need to be solved for a viable concept, see Figure 35. Those four areas are:

1. Corner area: The lower base corner;
2. Corner area: The roof pocket that houses the top hammerlock and the coupler;
3. Connecting section: The top side rail stiffener;
4. Connecting section: The end wall corner post.

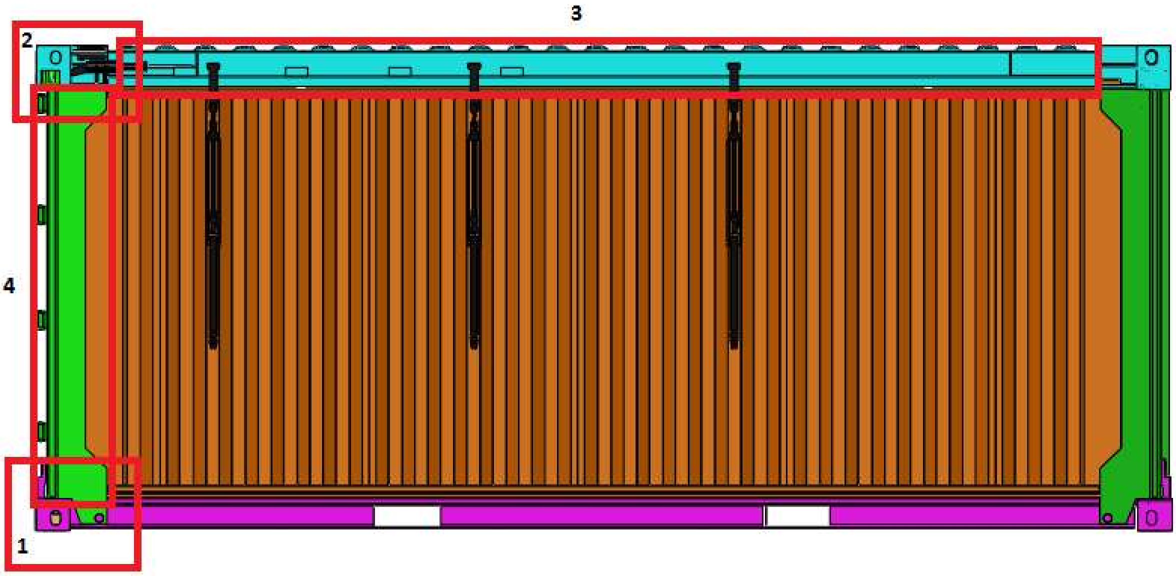


Figure 35 Areas where still design challenges remain in the initial design, indicated by a red border. 1) lower base corner; 2) roof pocket; 3) top side rail stiffener; 4) end wall cornerpost .

They need to be solved in a particular order. First the corner areas need to be resolved, since solutions for those challenges can have effects on both the corner areas (1,2) and the connecting sections (3 and 4). However, changes in the corner piece (2) will not affect the lower base corner (1). Similarly, the design of the roof pocket might influence the cornerposts (4) and top side rail (3). Below the problem areas are described in more detail and a design solution is presented.

4.4.1 The base corner

The 40ft design had a hammer lock in place to lock the endwall to the base, see Figure 36. The lock prevented movement between the upper structure and the base. It also transferred the forces involved in the racking and top lift load cases.

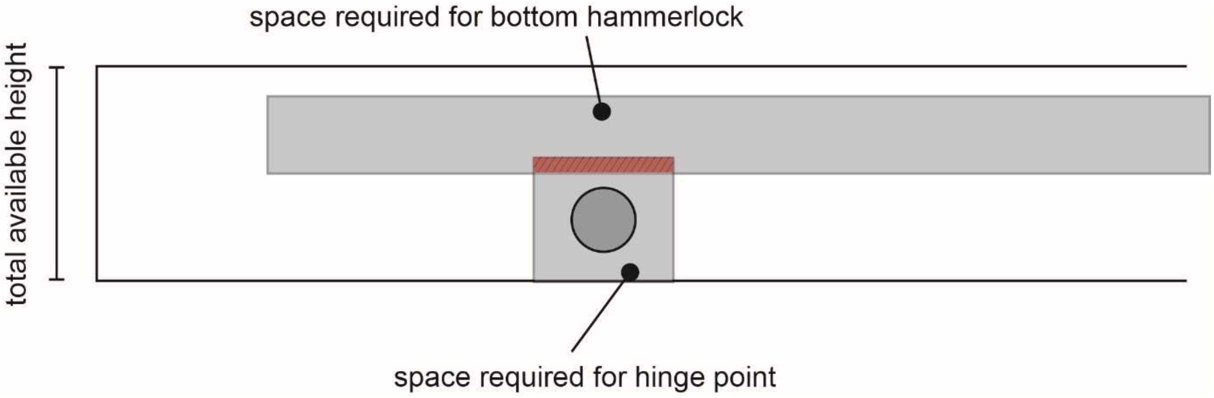


Figure 36 Detail of the 40ft basecorner design, showing the bottom hammerlock and the hingepoint.

Due to the reduced height of the base, from 240 to 170 mm, there is no room to fit both a hammerlock and an endwall hinge. The hinge is critical for the folding mechanism and needs to stay in place. The first solution to be considered is to remove the hammerlock and replace its function. To replace the functions of the lower hammerlock the following alternatives are considered:

1. A thicker endwall hinge with a block in place for the longitudinal racking load case: the hinge is increased in thickness to incorporate the full load cases that are placed on the hinge. The only load case that is not covered is the longitudinal racking case, since the forces involved work in the same direction as the rotation of the hinge. In order to cope with this load case a blocking mechanism is envisioned on the side wall, preventing movement of the end wall.
2. A thicker endwall hinge with a ballpoint-pen-style lock in the corner post: This is similar to the previous solution, but instead of a blocking mechanism on the side wall, a ballpoint-pen style lock is envisioned, that is placed in the corner post and protrudes in the base.
3. A hammerlock placed in the end transverse member instead of the base: Since there is no room in the bottom side rail, the previous solution of HCI was to place the hammerlock in the end transverse member. This solution worked for the older versions of the 40ft design.

In order to choose between these alternative concepts, the advantages and disadvantages are evaluated. For the third solution, the advantage is that it is certain that the load case will be fulfilled, since it is the same technology in a different location. A disadvantage is that the hammerlock needs to be placed in the end transverse members, where there is little space. In effect this would mean that the problem of too little space in the bottom side rail is merely shifted to the end transverse members.

The advantage of the second concept is that there is a ‘hard’ lock between the corner post and the base. The disadvantage is that it could be a complex solution. Besides, in this case parts need to be placed in the corner post, which is already at risk of buckling, Therefore, this is not an ideal location for creating additional stress points.

The first concept has as advantage that it simplifies the design by eliminating the bottom hammerlock and it is also the simplest in construction, since there is no lock, effectively reducing the number of parts. This does mean that the lower corner does not add rigidity in all degrees of freedom, however the rigidity is already determined by the interactions between the end walls and the roof. The disadvantage is that its transversal racking load case is a risk, since the corner post is no longer directly connected to the base. This might lead to additional deformation. In addition, the hinge would need to be executed larger and more sturdy, which means that the available area where the hinge can be placed is reduced. The effect of this could be that the unfolding process can be hindered. Despite this, it is the simplest solution, and therefore most likely the cheapest. Compared to the drawbacks of the other solution, the drawbacks of this solution are considered the least risky. This will need to be reevaluated once the full design is ready. The solution is shown in Figure 37.

Figure 37 Chosen base corner solution where the hammerlock is removed

.

Due to the removal of the hammerlock, the hinge will need to carry the full load cases, that were previously carried by the bottom hammerlock. Therefore, the following requirements, A, B and C, are added for the hinge itself:

- A) Tightening of the tolerances. This is due to the risk of damage to the seals due to the top lift case, since the top case lift is the most occurring load case.
- B) The hinge needs to be able to transfer the full load of the transverse racking and top lift load case.
- C) A blocking element is needed for the longitudinal racking case.

To meet criteria A and limit the effect of tolerances, the following solutions are implemented. Instead of consisting of multiple parts, the casing for the hinge in the base is cast as a single part with the lower corner casting. Since there are no separate parts, the tolerances can be tight, and quality control on these tolerances is easier. The corner post flange and base of the main corner post should be a separate subassembly. Combined with a hinge pin and the bushing, this set will have to meet the tolerances described and prevent endwall base separation.

The new designs for the hinge are not proven to work a minimum safety factor of 1.5 is introduced. This safety factor allows for a uncertainty in the design while keeping the size of the components to a minimum.

The loadcases for the hinge are the following.

1. Off centric loaded container top lifted.
2. Transverse racking away from the hinge with a shear force of 150 kN.

3. Longitudinal lock. Loads on the lock need to come from modelling and calculations in Ansys, but are estimated to be similar to the load on the hammerlock in the 40ft design in the same case.

Based on initial calculations, the first case is the critical case for the hinge. The load on the hinge is assumed to be 159 kN based on the top lift loadcase. Since the working environment is marine, there is a risk of galvanic corrosion if non-corrosive resistant materials are used. Therefore, the bushing in the hinge needs to be of a different material than the hinge pin and the housing to prevent the parts from corroding shut. There is the option of using a plastic bushing, however these are limited in the stress that can be transferred. The strongest non-metal bushing found has a load limit of 150 MPa. With a dimension of 28 x 69 mm this results in a load limit of 290 kN . This results in a safety factor of 1.81 on the bushing.

The next step is selecting a hinge pin that will meet the requirements. Standard stainless steel 316 has a yield of 205 MPa. With a cross section of 615 mm^2, this would result in a maximum shear force of 126 kN. This does not meet the requirements for the pin. The pin needs to have a circular cross-section to allow rotation and the cross-section needs to handle the load as a shear force. An alternative is Duplex steel S31803 2205, this has a lower limit on its yield strength of 480 MPa, resulting in a maximum force of 295 kN. This means a safety factor of 1.85.

The endwall flap that is connected to the hinge pin needs to meet no yield criteria on the hole location. This is given by the stress concentration factors described by the Kirsch equations. With the plate width of 90 mm and a hole size of 30 mm, this results in a concentration factor of 2.3. The maximum global stress in the plate is 345/2.3 = 150 MPa. With a plate thickness of 20 mm, this results in a maximum force of 270 kN and a resulting safety factor of 1.69.

4.4.2 Roof corner pocket

The roof corner pocket needs to change for the following reasons:

- There needs to be space for the top hammerlock to fit underneath the top corner fitting;
- There needs to be space for the coupler mechanism where it can be stowed away when not in use.

In the current design, the following requirements for the pocket are not yet fulfilled and need to be solved:

- house the top hammer pin both in open and closed position;
- house the coupler when it is not in use;
- maintain water tightness when the container is unfolded.

The following requirements are already fulfilled, but these restrict the possible design solutions:

- free movement of the toggle system placed just inside the corner of the roof; this means that the pocket cannot be placed more inwards.
- a sufficiently strong header connecting the left and right corners of the roof; this means there is little space available in the y-direction.

The top hammerpin lock needs to be placed below the space for the top fitting. This means that the hammerpin needs to be lower than the allowed space for the roof. When the endwalls are folded, they are rotated inwards and thus create some available space for the pocket to expand into, therefore the decision was made to design the pocket into this available space, see Figure 38a. Similar to that is that both of the sidewalls fold inward also creating some space that can be taken up by the roof. This available space was used to house the top hammer pin without modifying that design too much. It is assumed that that part will function as intended, because the hammerpin creates a lock with a lug inside the endwall, and its system boundaries remain the same. In addition, the pocket needs to house the coupler when it is not used for coupling the folded container stack. The integration of the coupler is mandated by the requirement list and can be achieved by creating a 'cup' behind the header section in the roof. This cup does not interfere with the toggle folding mechanism placed on the inside corners of the roof.

Although the pin and its workings do not change, the complete lock does need to be changed since it needs to move back and forth in the available space of the top side rail, which was also reduced in height. This means that the connecting piece between the hammer pin and the main part of the hammerlock needs to be elongated to be able to cope with the increased height difference. This is shown in Figure 38b.

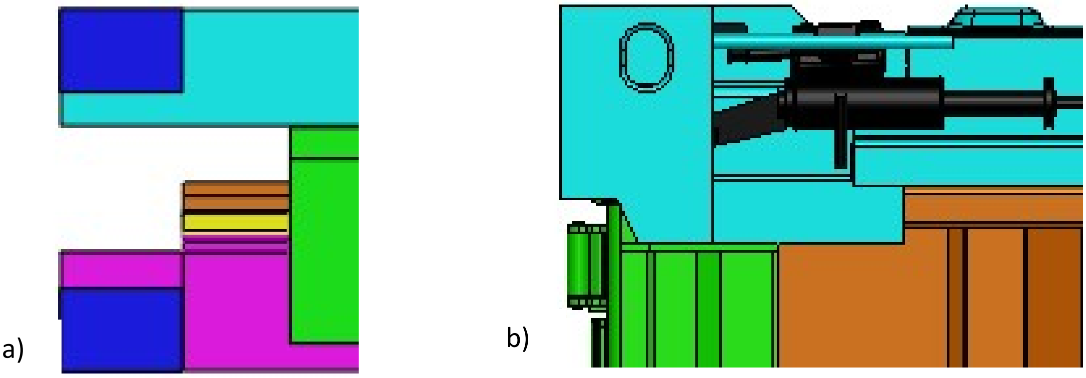


Figure 38 a) Folded mock-up side view detail; b) Top fitting side detail

4.4.3 Top side rail

The top side rail needs to have torsional stiffness. It needs a box shaped profile with a larger height than width in order to function properly. Since there are protrusions from the folded endwall and the sidewall, the top side rail needs to have holes in the corresponding positions. In order to keep the container watertight when unfolded, these need to be closed off by welded covers above the top side rail lower flange.

Due to the side wall load case, the top side rail is experiencing a torsional moment. To minimize the torsional rotation the torsional stiffness is increased where possible. This can be done by welding in an additional web plate in the section.

There are 2 possibilities for placing the stiffener plate, shown in Figure 39:

1: on the plane of the side wall pin lock.

2: on the plane next to the side wall clamp

The advantages of the first option are that it is easier to repair and a simpler construction. However, it will be less effective and harder to align. The advantages of the second option are that the alignment is less critical and it has a greater effect on the stiffness; however if damaged the repair will be more complex. Since the risk of complex repairs is outweighed by the fact that the stiffener is much more effective, and since the initial construction will be easier, the second solution is chosen.

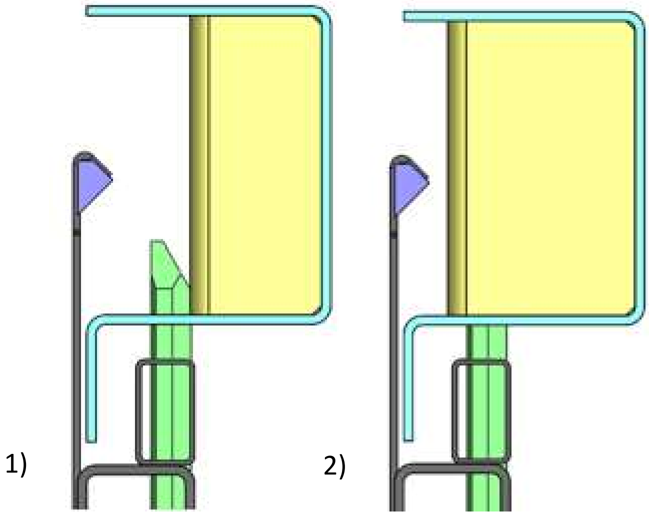


Figure 39 Top side rail stiffener options. 1) On the plane of the side wall pin lock (green); 2) on the plane next to the side wall clamp (purple)

4.4.4 End wall corner post flap

The endwall cornerpost needs to be adapted so that it has sufficient overlap with the sidewall in the unfolded state. The sidewall cannot be extended outward without entering the path of travel of the endwall when it is being folded. The endwall needs to stay clear of the forklift pocket entrance in the folded position. Therefore, on the lower side a flap needs to be created that has enough overlap with the sidewall, in order for the seals to work.

4.4.5 Forklift pockets

The forklift pockets have to be added to the design since they are not required for the 40 ft design. They are a fairly standard part. The main difference with a normal container is that the forklift pockets combined with the endwall flap need to prevent damage to the folding hinge and seals of the sidewall. This is done by a tubular profile that is welded in front of the forklift pocket. In this way the first object that the sidewall flap connects to is this tubular profile and not the folded sidewall.

A standard design for the forklift pockets was evaluated using the ISO loadcases. This means that only the base frame is used for forklift calculations. For the loadcase of the forklift pocket the initial design failed and a design adaptation was needed. An initial calculation showed that if the base did not get any bending stiffness support from the enwalls and the roof of the container the base would fail if the folded container stack was lifted.

A redesign was needed to ensure that the base, endwall and roof all contributed to the folded forklift load case. The redesign is shown in Figure 40. A connection plate is added to the right of the forklift pocket, in order to ensure that the endwall transfers load to the base. At the same time, a similar plate is added between the roof and the endwall, in order to make sure the roof rests on the endwall. These changes are highlighted by the red squares in Figure 40.

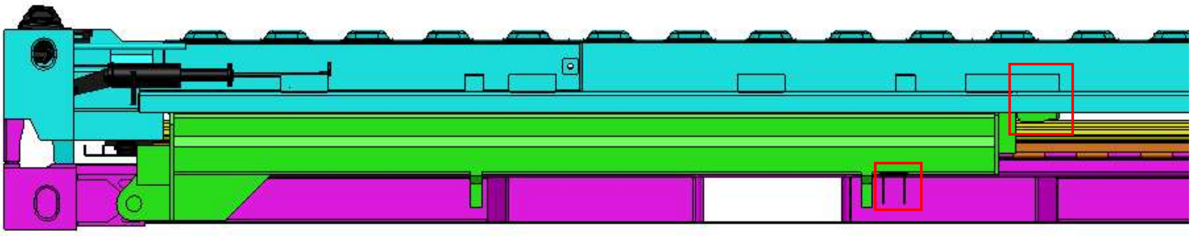


Figure 40 Forklift redesign. The red outlines indicate the changes in the design.

In combination with closing the hammerlock, this creates a rigid structure in which all three components share the load of the load case for the folded forklift. A complicating factor for this design was the fact that the achievable tolerance between the main components has been shown to be very loose in practice. It is estimated that this tolerance gap was between 0 mm and 12 mm. In order to solve this, fitting plates have been added to the design in the two areas highlighted in Figure 40. These fitting plates can be fitted on a container-to-container basis in order to compensate for these tolerances during construction. This will bring the tolerances back to a range of 0 mm to 2 mm, which is deemed acceptable. The reduced gap allows for less bending of the base before the enwall and the roof take up part of the load as well.

4.6 Conclusion

In the Table 10 below, it can be seen that all components have now been redesigned taking into account the design limitations investigated in chapter 4.2. By solving the design challenges, the height reduction is fully implemented. In this stage, the space that is available for each component has been solved, all the required components fit. However, it is still necessary to calculate whether all load cases can be fulfilled by the new container design. Therefore, in the next chapter calculations are done for all the load cases to determine the viability of the design.

Table 10 final initial design check

Main component	Sub-assemblies	Height adjustment	Meets height requirement
Roof	Corners	Yes	Yes
	Top side rail	Yes	Yes
	Top header	No	Yes
	Roof plating	No	Yes
	Top corner pocket	Yes	Yes
Endwall rear	Corner post	Yes	Yes
	Corner flap	Yes	Yes
	Doors	No	Yes
	Top frame	No	Yes
	Door sill	No	Yes
Endwall front	Front end flap	Yes	Yes
	Front end frame	Yes	Yes
	Front end wall	No	Yes
Sidewalls (L+R)	Lower beam	No	Yes
	Top beam	No	Yes
	Side	No	Yes
	Mid-section	No	Yes
Base	End transverse members	Yes	Yes
	Lower corner fittings	Yes	Yes
	Bottom side rails	Yes	Yes
	Floor board	No	Yes
	Forklift pocket	Yes	Yes
	Transverse members	No	Yes

Auxiliary parts	Side wall locks	No	Yes
	End wall lock	No	Yes
	Top hammer lock	No	Yes
	Bottom hammer lock	No	Yes
	Folding mechanism	No	Yes

Chapter 5 Design validation

In order to validate the design, it needs to be checked against the requirements set up in the requirements list. For the ISO requirements, there are 11 loadcases that need to be met. In this chapter the design will be checked to ensure it meets the requirements. The following requirements need to be checked:

- Meeting maximum allowed stress criteria
- Meeting maximum allowed deflection criteria
- Meeting weight limit
- Meeting construction cost limit

The 40ft 4fold container will function as a reference design. Although the load cases are not the same for the 40ft container, they are similar and the 4fold is already proven in practice. This allows for hand calculations for parts of the design that are similar to the 40ft design. The numbers needed for the calculation can thus be adapted and used for the 20ft design to verify whether it is meeting the requirements.

Basic hand calculations were used when possible to create the design. To allow for some room for error the design limits for the hand calculations are as follows:

- Stress limitation to yield stress
- Conservative boundary conditions
- Conservative load bearing areas

This way a basic but complete design could be created, which allows for design iterations when calculations show that stress or displacement criteria are not met. The exception to the FEM model is the load case involving the load on the sidewall. The top side rail is an open profile under torsional load and its displacement is needed. Calculating the torsional moment of inertia for an open profile is complex, therefore a simplified FEM model is used for this calculation.

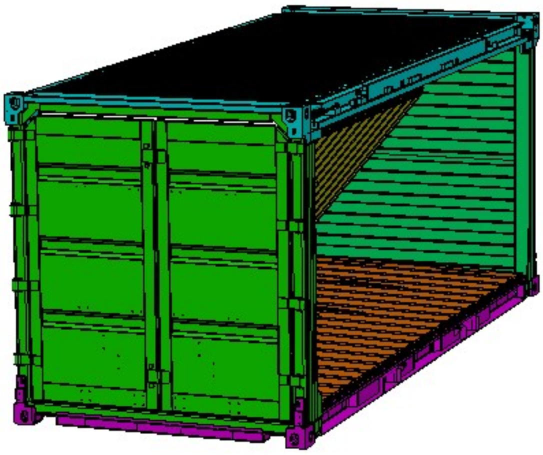


Figure 41 The 20ft design with folded sidewalls

5.1 ISO relevant design information

The load case validation calculations are split into the cases relevant to the unfolded and the folded container state. The unfolded cases are described in ISO 1496-1:2013 and the folded container cases are based on ISO 1496-5:2013. Unless otherwise stated the material involved is SPA-H steel and has the following properties.

Yield strength	345	MPa
Ultimate tensile strength	481	MPa

5.1.1 Critical locations

Figure 42 shows the 20ft container with circled in red the locations where the different load cases act. Letters are assigned to the areas to clarify which load case affects which areas, as shown in Table 11.

Table 11 Critical locations

Location	Name
A	forklift plate
B	container mid-section
C	bottom side rail mid-section
D	sidewall midsection
E	Front endwall hinge
F	Front endwall section
G	top side rail section
H	roof section
I	Door sides
J	Rear end corner midsection

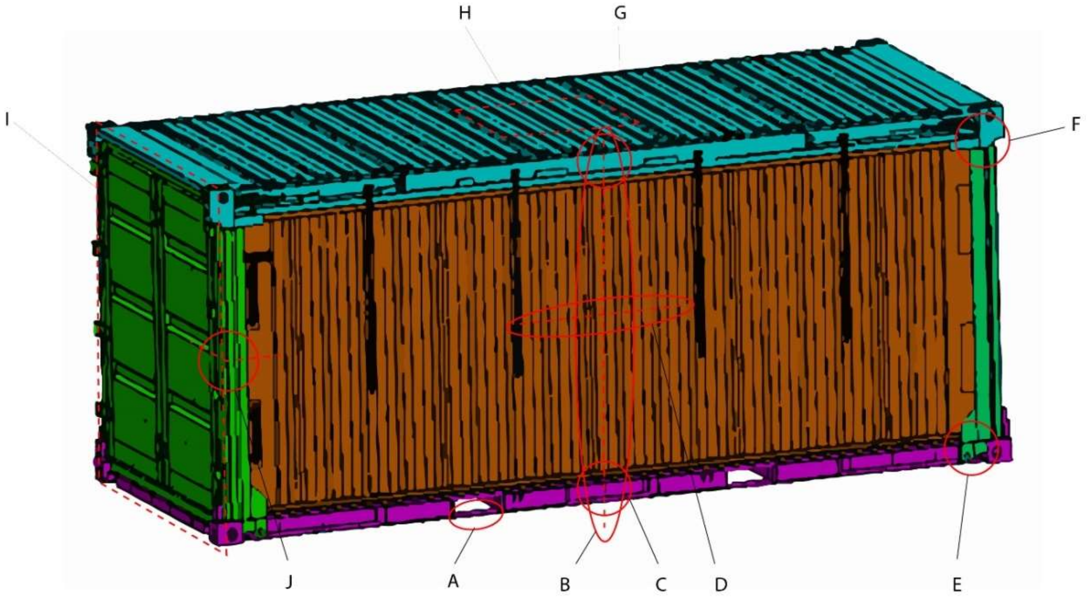


Figure 42 Critical location in the 20ft design

5.1.2 Detailed cross-sections

The three midplanes used to evaluate the section information relevant to the load cases are shown in Figure 43. For each of the midplane a cross-section is taken and the relevant details will be highlighted. The detailed section information is shown in Appendix B.

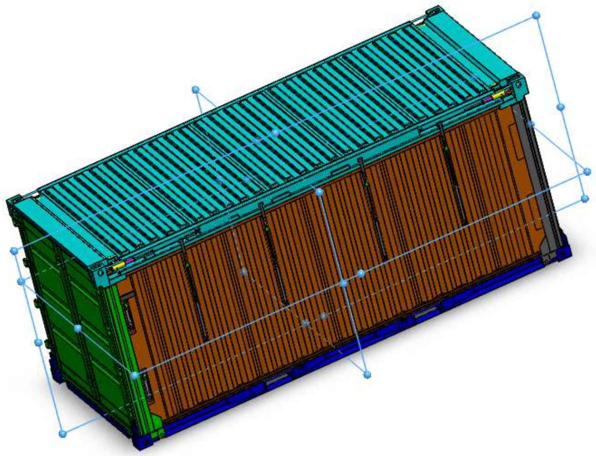
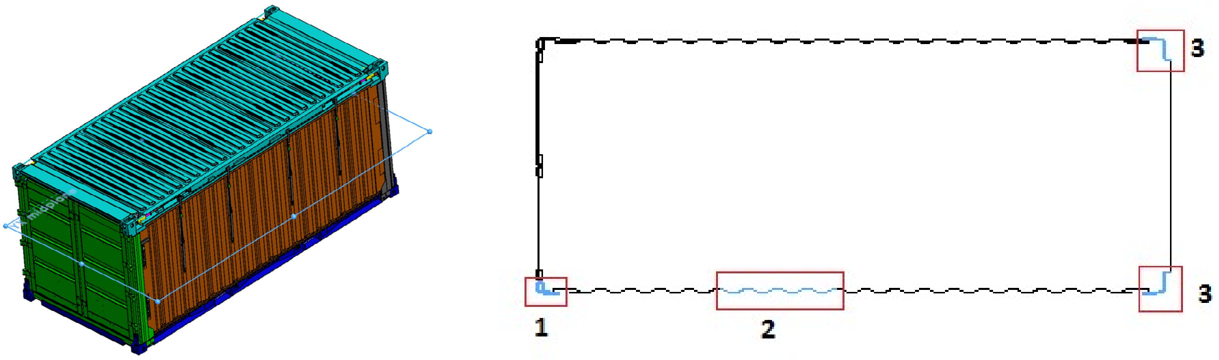


Figure 43 Midplane overview

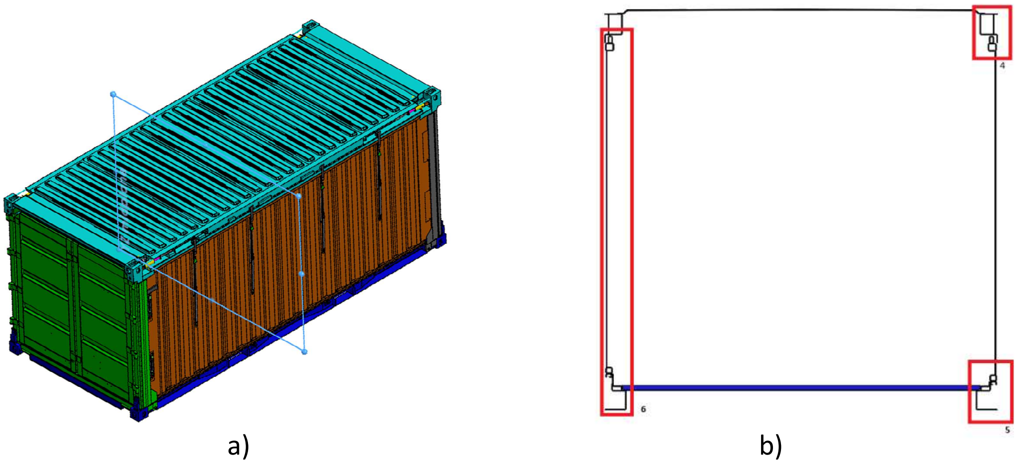
The first cross-section is the XY cross-section shown in Figure 44. The figure shows the location of the rear end corner post (1) the mid-section of the sidewall corrugation (2) and the front end corner posts (3). The relevant information for the calculations is given in Appendix B and will be used in the calculations in chapter 5.2. Is should be noted that due to the corrugation of all panel sections they are only considered is specific cases but in general are not taken into account.



a) b)

Figure 44 a) XY section location; b) XY section overview

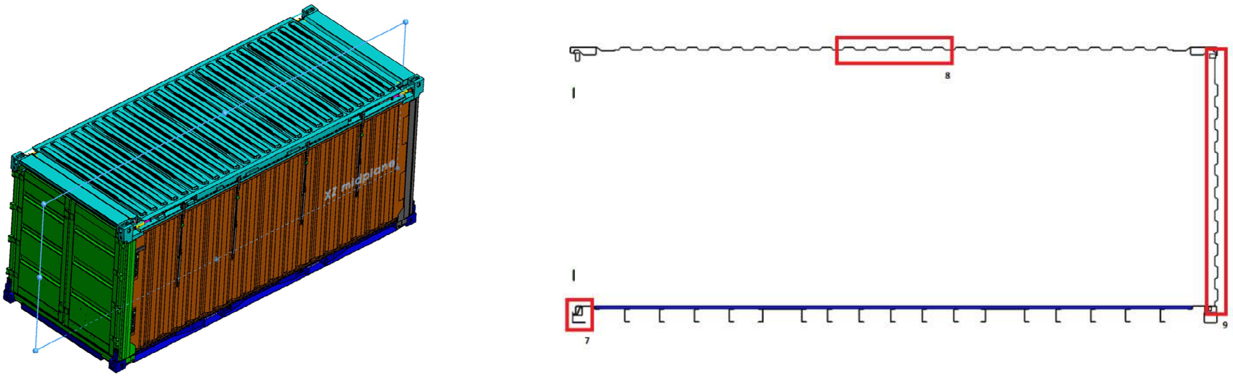
The YZ section shown in Figure 45 has three areas of interest: these are the top side rail section (4), the bottom side rail section (5), and the sidewall and bottom side rail section (6). The flooring is omitted for the general deformation calculations, since it is a different material type. It does however play a role in local force distribution. However, this way it is identical compared to a normal 20ft container and can be considered acceptable.



a) b)

Figure 45 a) YZ section location b) YZ section overview

The section view in Figure 46 show the rear end transverse member (7), roof panel section (8), and the front end wall (9). The rear end doors are not shown since the midsection in this area hold the rubbers of the door which are outside the scope of the design.



a) b)

Figure 46 a) XZ section location b) XZ section overview

5.2 ISO load cases

The following section details the calculations for each of the ISO load cases.

ISO load case 1 - Stacking

The ISO stacking load case, see Figure 47, has the following elements:

- Buckling of the corner post
    - rear corner post
    - front corner post
- Compression of the corner post
    - rear corner post
    - front corner post
- Bending of container
    - max tension stress
    - max compression stress
    - max displacement of the main member

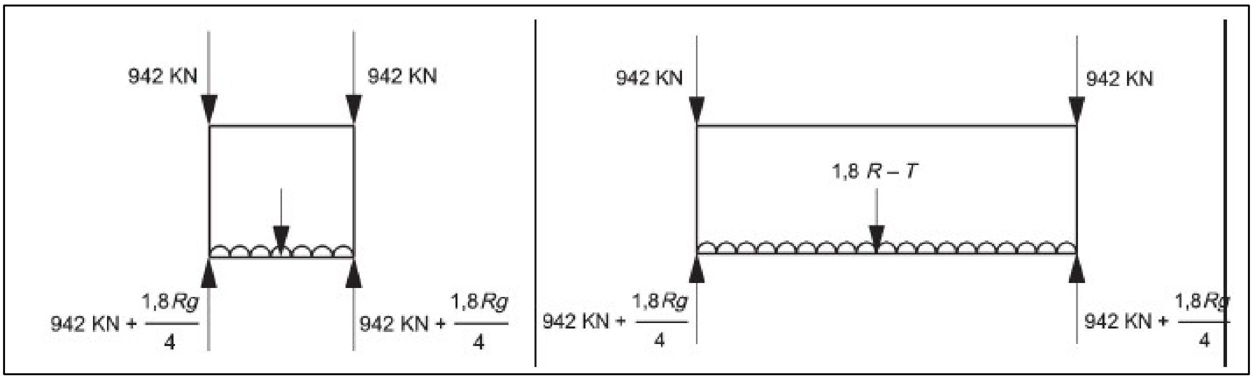


Figure 47 ISO 1496-1 figure A.1a

General information

stacking load F	942 kN
R load of the container	32500 kg
T of the container	3000 kg
gravity constant g	9.81 m/s^2

Eccentricity effects

The stacking load F is applied with an eccentric offset to the centroid of the corner post, see Figure 48. The eccentricity offset can be between the corner post centroids (case 1) or outside of the corner post centroids (case 2). These eccentricities would create a moment if the corner post was free standing, however for the foldable container this is not the case.

In the case 1, the resulting moment deforms the top side rail downwards. But since the top side rail is lying on top of the sidewall, the sidewall creates a reaction force to balance out the moment acting on the top side rail. So instead of creating a moment on the top of cornerposts the eccentricity of the stacking force creates an additional distributed load trough the sidewall on top of the bottom side rail. To assume the worst case scenario the distributed load only acts between the second and third sidewall lock.

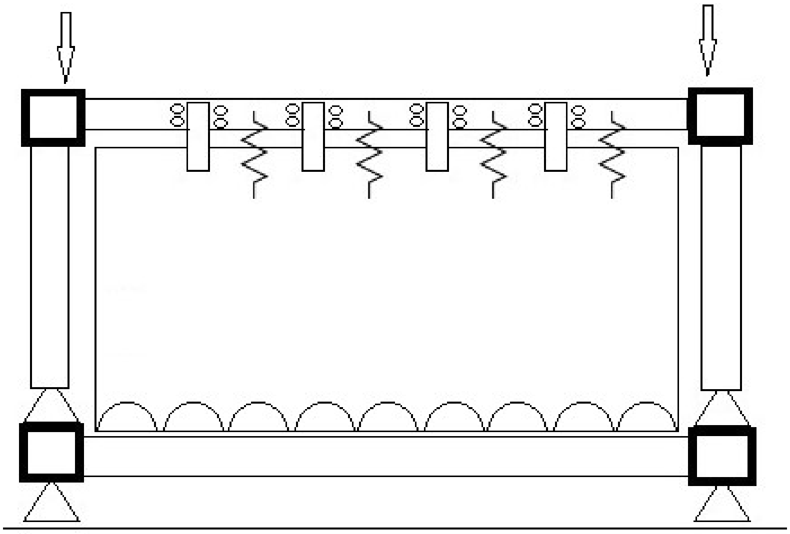


Figure 48 Simplified overview stacking load case for folded container

The result is that the additional moment is mitigated by the sidewall and that only a compression force works on the corner post. The eccentric effects are countered by reaction forces by the side wall.

Cornerpost buckling

With the compressive loads now known it can be checked if the cornerpost columns fail due to buckling. Where both the rear end as front end columns need to be checked.

For the rear end of the container there are three possible buckling failure modes.

1: the complete column buckling

2: the buckling of the column between the hinges of the door

3: plate buckling of the flaps of the cornerpost columns.

For the front end of the container only case 1 and 3 are a concern, since this side has no door.

In order to check if the column fails case 1 or 2 the slenderness of the column for each case needs to be determined. Buckling case 3 is countered by the design limitations in Chapter 4. There the minimal thickness of open plate sections is defined as the thickness needed for the critical buckling stress being higher as the yield stress.

For case 1 the buckling problem is simplified to a clamped pinned buckling problem. The bottom of the corner post is assumed to be pinned due to the hinge being the only connection point thus allowing for “free” rotation. The top of the corner post is assumed to be fixed due to the hammerlock connection. The hammer lock is of rectangular shape and does not allow rotation freely. The effective length for a clamped pinned buckling problem is 0.7. For case 2 the effective length is set at the height between the hinges. This is due to the stiffness increase from the hinges.

In order to evaluate what type of buckling effects can be encountered by the cornerpost the slenderness ratio is evaluated. The slenderness ratio is given by:

$$\frac{l}{r} = L.k.\sqrt{\frac{A}{I}} \tag{5.1}$$

The data for cases 1 and 2 is given in Table 12.

Table 12 Relevant data for cases 1 and 2

	Case 1	**Case 2**
I_{yy}	20,394,507 mm^4	
I_{xx}		3,473,487 mm^4
L	2100 mm	493 mm
l/r	$\frac{l}{r} = L.k.\sqrt{\frac{A}{I}} = 2100.0,7\sqrt{\frac{4590}{20394507}} = 22,1$	$\frac{l}{r} = L.k.\sqrt{\frac{A}{I}} = 493.1.\sqrt{\frac{4590}{3473487}} = 17,9$

To evaluate the critical buckling stress Johnson's formula is used (Equation 5.2).

$$\sigma cr = \sigma y - \frac{1}{E}.\left(\frac{\sigma y}{2\pi}\right)^2.\left(\frac{l}{r}\right)^2 \tag{5.2}$$

Johnson's formula shows that the lowest critical stress occurs at the largest value of *l/r*. This identifies case 1 as the critical buckling case for the rear end.

For the front end the slenderness is, using Equation 5.1:

$$\frac{l}{r} = L.k.\sqrt{\frac{A}{I}} = 2100.0,7\sqrt{\frac{5961}{30809777}} = 20,4$$

This results in critical yield strengths of 338 MPa for the rear end columns and 339 MPa for the front end columns.

Compression calculation

Since the buckling yield stress is lower than the compressive yield stress, the buckling yield stress is the critical stress that needs to be evaluated. This is done calculating the compressive stress in the columns using the maximum load encountered due to the eccentric loading. The maximum effect of the eccentric loading is 4% additional load. Since the stress at both locations is below the critical stress calculated using Johnson's formula the columns will not fail, see Table 13.

Table 13 Compression calculation

rear end wall compression			front wall compression		
σ	205	MPa	σ	316	MPa
F	942	kN	F	942	kN
A	4590	mm^2	A	2975	mm^2

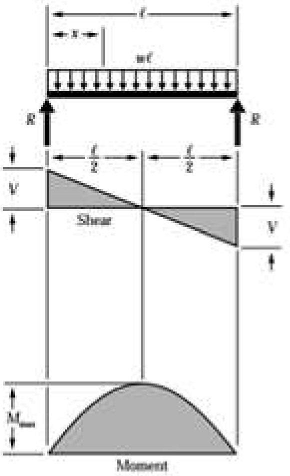
Bending calculation

The following assumptions are made for the calculation of the maximum stress and deflection in the container:

- The calculation is done for the main member of the base.
- The roof does not contribute to the distribution of the bending stress.
- The sidewall corrugation is assumed a simple plate with thickness identical to the sheet thickness.
- The container is simple supported.

- The top of the container experiences compressive stress.
- The bottom of the container experiences tension stress.
- None of the stacking forces are transmitted through the sidewalls.

The transverse members and the floor are identical to the standard parts used on the container. It is assumed that these parts do not fail and no calculation is needed. The main bottom side rail is a custom design and thus does need to be evaluated for bending and displacement. There is no stiff connection between the base-sidewall and the roof hence the roof section is omitted from the bending calculation. The corrugation of the sidewall panel ensures stiffness against movement in the y-plane of the container. But since the container experiences bending stress in the x-plane the corrugated plate is simplified to a flat plate with the same plate thickness.



$R = V \quad \dots\dots\dots\dots \quad = \frac{w\ell}{2}$

$V_x \quad \dots\dots\dots\dots \quad = w\left(\frac{\ell}{2} - x\right)$

$M_{max} \text{ (at center)} \quad \dots\dots \quad = \frac{w\ell^2}{8}$

$M_x \quad \dots\dots\dots\dots \quad = \frac{wx}{2}(\ell - x)$

$\Delta_{max} \text{ (at center)} \quad \dots\dots \quad = \frac{5w\ell^4}{384\,EI}$

$\Delta_x \quad \dots\dots\dots\dots \quad = \frac{wx}{24\,EI}(\ell^3 - 2\ell x^2 + x^3)$

Figure 49 Bending formulas

The calculation results from

Table 14 show that the maximum bending stress stays under the yield stress limit.

Table 14 bending calculation results

L	5,688	mm
W	47	N/mm
M (max)	193,553,752	Nmm
E	210,000	MPa
I	5,626,909,827	mm^4
C (comp)	1,416	mm
C (tens)	965	mm
delta max	0.55	mm
q (comp)	48	MPa
q (tens)	33	MPa

ISO load case 2 - Top lift

ISO load case 2, Figure 50, consists out of the following elements:

- Tension on the corner post
    - rear corner post
    - front corner post
- Bending of container
    - max tension stress
    - max compression stress
- Local buckling of the sidewall top beam

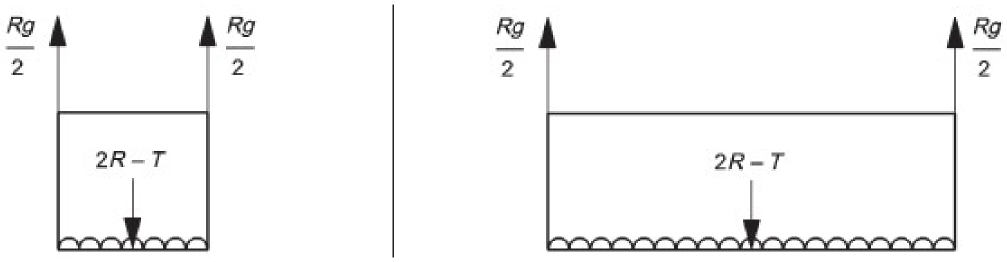
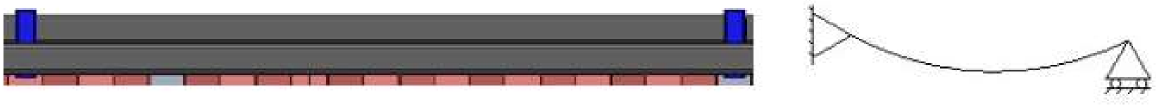


Figure 50 ISO 1496-1 figure A.3a

The bending of the container is identical to the situation given in ISO load case 1 and its schematic overview is given in Figure 50. The local buckling case is shown in Figure 51; it shows the section between the blue side wall locks and it graphical representation of the buckling case. The maximum distance between the two lock positions shown in blue is 1354 mm. since the top of the sidewall is not constrained in the inward y direction there is a risk of local buckling inward. The buckling case is assumed to be pinned - pinned since the sidewall locks have no rigid connection to the sidewall top beam. The maximum compressive force is deducted from the bending calculation. The maximum bending force depends on the distance from the centre of the side wall. To be on the safe side the maximum compressive stress is used to calculate this load.



a) b)

Figure 51 a) sidewall beam local buckling; b) its graphical representation

General information

Reaction force $R_g/2$	159 kN
R load of the container	32500 kg
T of the container	3000 kg
Gravity constant g	9.81 m/s^2
SPA-H steel yield strength	343 MPa
SPA-H steel ultimate tensile strength	481 MPa

Tension calculation

For the tension calculation the following assumptions are made:

- the full load is carried by the corner post section.
- the corner post section is only under tension stress.

It is assumed that the sidewall does not transfer load to the endwall and the roof. The worst case scenario is if not all locks are fully closed. This means that the distributed load is fully transferred to the bottom corner before its transferred to the top fitting. The area information is obtained from the Solidworks section information shown in Figure 79 and Figure 85 of apperndix B. The maximum tension stress is given by $\sigma = \frac{F}{A}$.

Table 15 ISO 2 tension calculation

rear end wall tension stress			front wall tension stress		
σ	35	MPa	σ	54	MPa
F	159	kN	F	159	kN
A	4590	mm^2	A	2975	mm^2

Bending calculation

The assumptions for the bending calculation are identical to ISO load case 1. The only difference is that the load is increased from 1.8R-T to 2R-T. The bending formula shown in Figure 49 is used to calculate the stresses and displacement. The results are given in Table 16.

Table 16 ISO loadcase 2 bending calculation

L	5,688	mm
W	54	N/mm
M (max)	226,684,575	Nmm
E	210,000	MPa
I	5.627E+09	mm^4
c (comp)	1,416	mm
c (tens)	965	mm
delta max	0.64	mm
q (comp)	68	MPa
q (tens)	40	MPa

Local buckling calculation

Maximum compressive stress	68 MPa
Cross section area	1055 mm^2
Maximum compressive load	71.7 kN
Distance between locks	1354 mm

The cross section information is retrieved from the Solidworks section shown in Figure 84 in appendix B. The compressive load is simplified to the cross section area times the maximum compressive stress. In reality this compressive load will be lower, but this is a conservative calculation. Besides the normal case shown in Table 17 an additional scenario is calculated to see if the container stays whole if one of the sidewall locks stays open. Both the normal case and the additional scenario, shown in Table 18, show that the container will not buckle.

$$\mathrm{Pcr} = \frac{\pi^2 EI}{L^2} \tag{5.3}$$

E	210,000	Mpa
I	275,186	mm^4
L	1,354	mm
P_{cr}	310,790	N
P_{load}	71,700	N
SF	4.3345886	

Table 17 Local sidewall beam buckling

E	210,000	Mpa
I	275,186	mm^4
L	2,700	mm
P_{cr}	78,158	N
P_{load}	71,700	N
SF	1.09	

Table 18 Local sidewall buckling one lock open

ISO load case 3 - Bottom lift

The bottom lift load case consists out of the buckling of a bottom sidewall section. The sidewall section lies between the first two transverse members. This is due to the reduction in compressive stress from the bending moment created by the load 2R-T, see Figure 52. For the folded container bottom lift case there is the risk of the bottom side rail buckling between the corner fittings, since the sidewall is folded in this case.

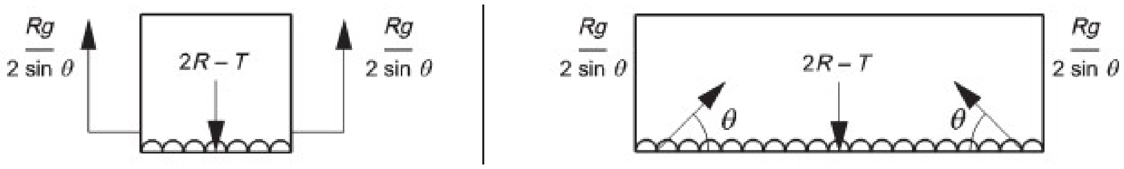


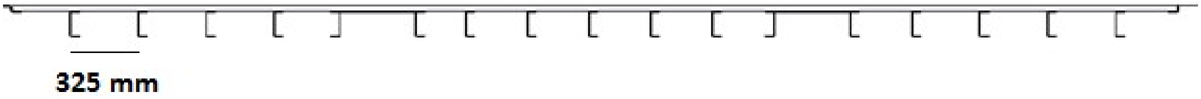
Figure 52 ISO1496-1 figure A.4a

General information

Angle θ	45 degree
A (bottom side rail)	2162 mm^2
L	5688 mm
L(section)	325 mm
R_g	32500*9.81 = 319 kN
Compressive load	451 kN
Compressive stress	208 MPa

Unfolded buckling calculation

For the unfolded top lift case the only buckling that can occur is the buckling of the bottom side rail between the transverse members, see Figure 53. However, the slenderness of the rail between the transverse members is only 8. For a short column the failure mode is crushing and with a compressive stress of 208 MPa, there is no risk of failure.



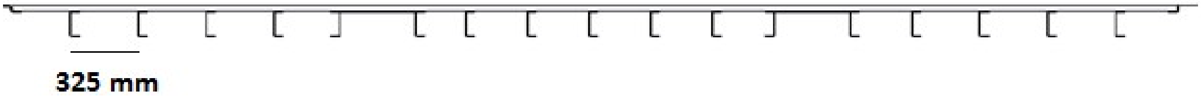


Figure 53 Transverse member locations on the bottom side rail

Table 19 Calculations for load case 3

I_x	2,876,160 mm^4
L	325 mm
$r = \frac{I}{A^{0.5}} = 36$	

$$\frac{L}{r} = 9$$

Folded buckling calculation

For the folded top lift case there is the risk of the complete buckling of the bottom side rail, see Figure 54.

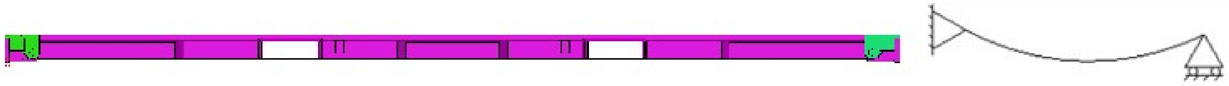


Figure 54 Folded bottom side rail buckling case

The critical stress for the bottom side rail was calculated. The safety factor between the critical stress and the compressive stress due to the load is 2.65 and thus the bottom side rail is safe. Since the compressive stress is lower than the yield stress the bottom lift case is passed.

R_g	15000 * 9.81 = 147 kN
Compressive load	208 kN
$\sigma_{critical}$	255 MPa
Compressive stress	96 MPa
SF	255/96 = 2.65
$r = I/A\text{^}0.5 = 63$	
$L/r = 9$	

ISO Load Case 4 –Restraint (longitudinal)

The restraint test results in a compressive and tension force in the bottom side rail, see Figure 55. The maximum compressive and tension forces are calculated in the mid-section of the bottom side rail. The length taken into consideration is the distance between the bottom corner castings.

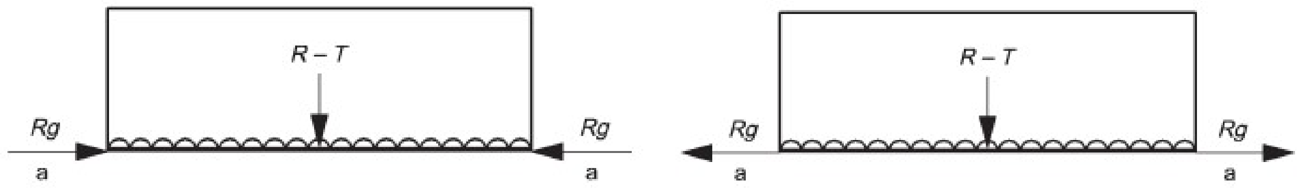


Figure 55 ISO 1496-1 figure A.5a and ISO 1496-1 figure A.6a

General information

Since the load is R instead of 2R-T these are the maximum loads:

A (bottom side rail)	2162 mm^2
L	5688 mm
R_g	32500 * 9.81 = 319 kN
distributed load	28 MPa

Bending calculation

L	5688	mm
W	28	N/mm
M(max)	226684575	Nmm
E	210000	MPa
I	5.627E+09	mm^4
c	965	mm
q	19	MPa

Compression / tension calculation

The maximum compression stress is 319/2.16 = 147 MPa and occurs next to the corner fitting. The compression is decreased towards the middle of the section due to the tension component of the bending stress. The maximum tension stress is 147 + 19 = 166 MPa and occurs in the middle of the bottom side rail due to the combination of the tension force and bending stress. Both of these values are below the maximum yield stress of the material.

ISO Load Case 5 – Strength of the end walls

Figure 56 shows the ISO endwall test. The goal of this test is to show that the endwalls don't fail if the load inside of the container comes loose. The endwall consist out of the following elements that all need to pass the test:

Rear wall:

- Doors
- Doorframe
- Rear cornerposts
- Rear end transverse member
- Rear end header

Front wall:

- Front wall plate
- Front wall cornerpost

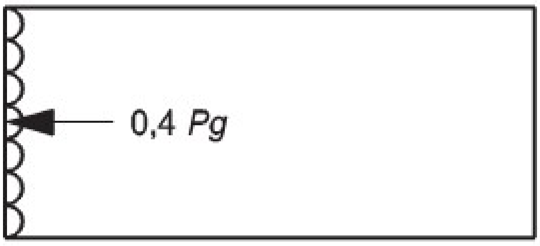


Figure 56 ISO1496-1 figure A.7

The 0.4PG load for the 20ft container is equal to 116 kN distributed evenly across the complete endwall. This is a pressure of roughly 0.03 MPa.

Rear wall case

The load in the rear wall case is transferred from the doors to the door frame and from there to the rear end wall corner post. Since the distributed load is small and the door, frame and corner post are roughly the same as the 4 fold 40ft door it is assumed that the door and the doorframe will pass the test and no calculation is needed. The maximum stress in the rear corner post is calculated using the bending stress formula (Equation 5.4).

$$\sigma = -\frac{My}{I} \tag{5.4}$$

It is assumed that ¼ of the 116 kN loads acts on the middle of the corner post and that the ends of the corner post are both simply supported. The I for the cornerpost is taken from the Solidworks section shown in Figure 79 of appendix B.

$$-\frac{29.000*1000*134}{17704248}\text{=219 MPa}$$

This is the worst case scenario resulting in a maximum stress of 219 MPa. This means that the corner post will not fail.

Front wall case

The cross section of the front wall cornerpost is taken from the Solidworks section shown in Figure 88 of appendix B. Due to the corrugation of the plate the load assumed to be transferred only to the front wall corner posts. This results in a distributed load on the front corner post of 29MPa. With the information shown in Figure 49 and Figure 81 it is now possible to calculate the maximum bending stress encountered in the middle of the front end corner post.

$$\frac{\mathrm{w.l^\wedge 2.y}}{8.I}=\frac{29.2000^\wedge 2.112}{8.15404888}=105\ MPa$$

The maximum stress of 105 MPa means that the front end cornerpost will pass this case.

ISO Load Case 6 - Strength of the sidewall

Figure 57 shows the ISO sidewall test. This test is to ensure that the sidewall does not fail when the cargo inside shifts around. The sidewall is not allowed to deform in such a way that it is rendered unusable. For the sidewall of the foldable container this means that all components of the sidewall need to stay under the yield limit. It also requires that the displacements under load are not exceeding the overlap between the sidewall and the top side rail. If the displacements are larger than the overlap the side wall can slip under the top side rail.

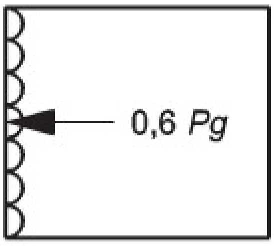


Figure 57 ISO 1496-1 A.8

In order to calculate the effects of this loadcase the following assumptions are made:

- The load of the load case is 174 kN.
- The load is distributed evenly between the top and the bottom of the side wall.
- The end walls are excluded from the calculation.
- The length of the sidewall is 5688 mm.

Bottom of the sidewall

The load on the bottom of the sidewall is distributed over the bottom hinge. This hinge is segmented in sections of 50 mm and has a pin of 6 mm. The load on each section is 764 N.

$$N = \frac{174000.50}{2.5688} = 764\text{N}$$

With a pin diameter of 6 mm this results in a stress of 27MPa with is well below the yield point. Since the hinge allows free rotation around the X axis, but no displacements the bottom of the sidewall passes the ISO test.

Plate section of the sidewall

The middle section of the sidewall is a corrugated plate. Due to the distributed load the section needs to be checked to see if the maximum bending stress does not exceed the limit. The maximum stress is calculated for the one of the four plate sections. The plate is assumed to carry 1/6 of the load. From the Solidworks section shown in Figure 80 the I of the section is 366,885 mm^4.

$$w = \frac{174000}{2000.6} = 14.5\ MPa$$

$$\frac{\mathrm{w.l\hat{}2.y}}{8.I} = \frac{14{,}5.2000\hat{}2.17}{8.366885} = 335MPa$$

The maximum bending stress stay below the limit of 345 MPa for SPH-A.

Top of the sidewall

Since the top of the sidewall is not directly connected to the top side rail the displacement of the components relative to each other is also of importance. In order to evaluate the displacement of the top side rail the torsional stiffness of the top side rail is needed for a simple calculation. However since the cross-section of the top side rail is not symmetric, see the Solidworks section shown in Figure 84 of appendix B, the calculation the torsion stiffness is not a simple equation. Instead of using a hand calculation it is opted to use ANSYS to evaluate the displacement of the top side rail. The ANSYS model will be used to calculate the maximum displacement and it will be checked if the side wall is not able to slip under the top side rail.

Figure 58 Sidewall test rig

Model simplification.

In order to use the available version of ANSYS the model needs to be simplified in due to the maximum allowed number of elements. The model is simplified by only using the top side rail and the locks on the sidewall, shown encased in red in Figure 59. The front and rear wall as well as the stiffeners around the locks are not modelled. This will increase the overall load on the top side rail as well as reduce the stiffness but both are conservative steps since the FEM analysis is done to assess the rotational movement of the top side rail.

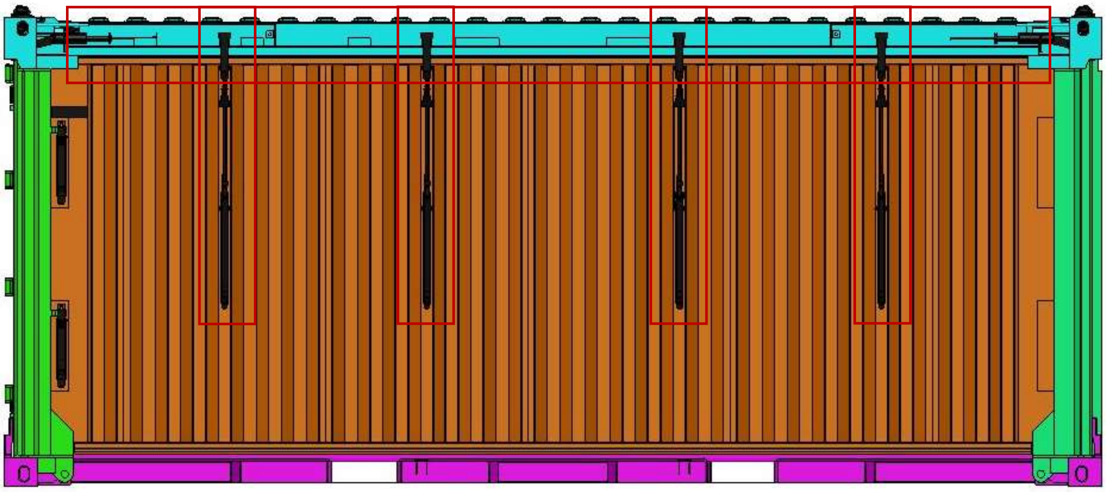
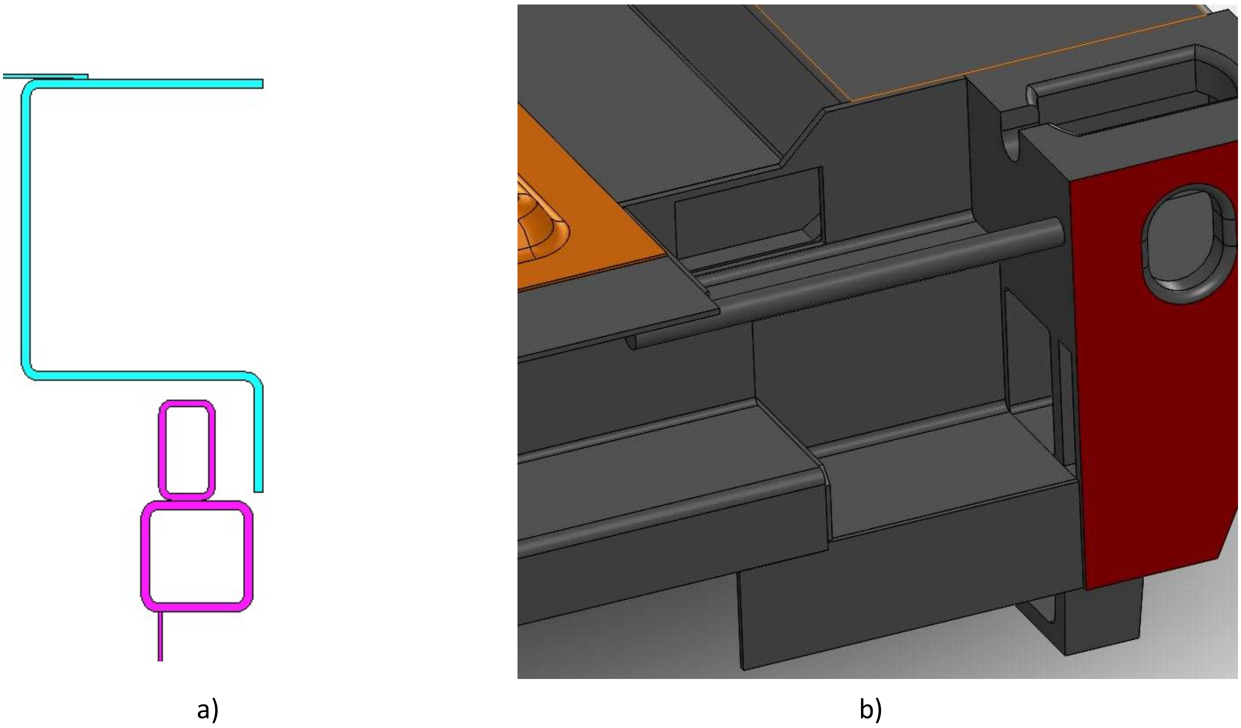


Figure 59 Sidewall overview



a) b)

Figure 60 a) Top side rail open section cross-section; b) Detail of the connection between the top side rail and the corner

The top of the sidewall is a relative stiff part of the assembly, see Figure 60a, but will be simplified to a line pressure acting on the lower edge of the top side rail. This is as conservative as the load application can be simplified to. This should result into the maximum displacement of the side rail. The details of the connection between the top side rail and the corner, see Figure 60b, are simplified to only the main section of the top side rail shown in Figure 60a. This is done to reduce the number of elements used in the FEM analysis. The effect of the simplification is that the stiffness is lowered and thus the displacement is larger. This may also increase the stresses endured at the corner connection. In order to check if the detailed connection meets the requirements a more detailed FEM analysis needs to be performed, but this is outside of the scope of this thesis.

ANSYS model

The ANSYS model consist out of a simplified top side rail and 4 simplified sidewall locks. The locks are essential to limit the displacement of the container. The model is simplified in the areas where the different parts connect. The results of these simplifications should be higher displacements and stresses. But since this model is used for evaluating the maximum displacement the model is useful.

Figure 61 Ansys top side rail model setup

The constraints on the model are shown in Figure 61 and can be explained as follows;

The ends of the top side rail are fixed to the top corner castings, constrained (D).These corner castings are part of the front- and rear endwall. Due to the use of the test rig, see Figure 58, these walls cannot deform. The top side rail is fixed on one edge in the Y direction, this is constrained (A). This is to simulate the roof. The top side rail is allowed to rotate around this edge. This is done since the connection between the roof and the top side rail is a simple plate creating an hinge point.

The last constraint is the fixation in Z direction of the sidewall locks, constrained (B) . This constrained is assumed due to the stiff connection between the sidewall locks and the sidewall itself. The load on the model is set to be a line pressure on the lower edge of the bottom flap. This is the worse location for the force to act on and thus it is chosen as the worst case scenario. It should be noted that sidewalls do not transfer any load to the front and rear wall. this is the absolute worst case for the top side rail. In reality the front and rear wall of the container will take up a portion of the load on the sidewall. The mesh for the model is autogenerated as a medium sized meshed, see Figure 62. The mesh on the locks is refined one level to ensure that more than one element is present.

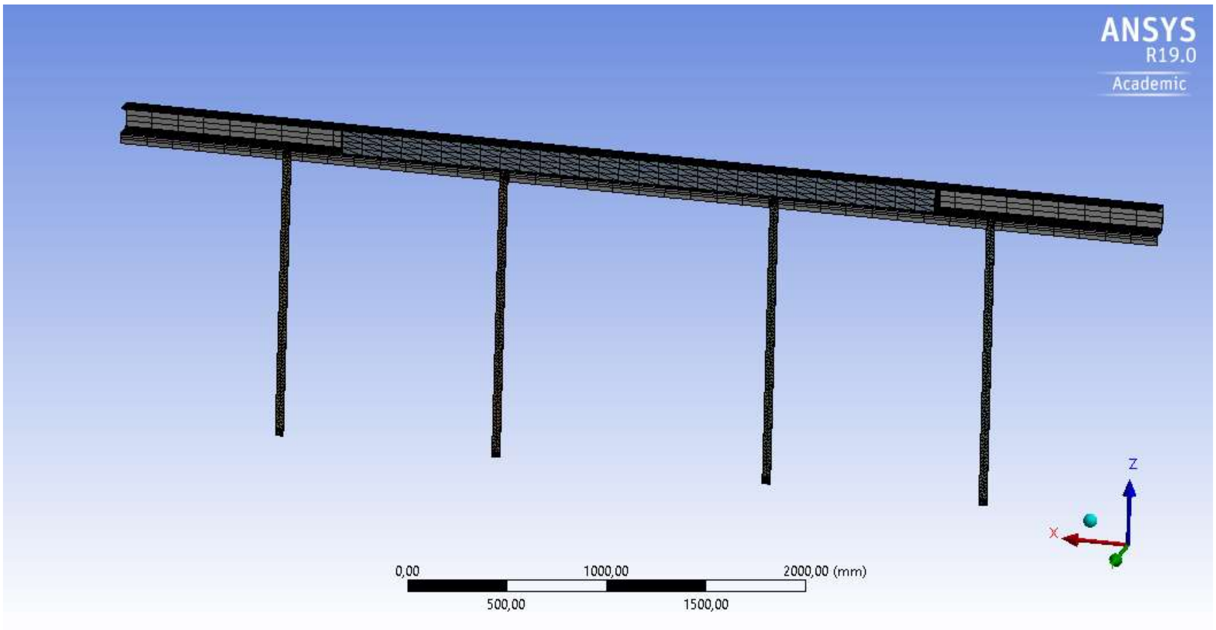
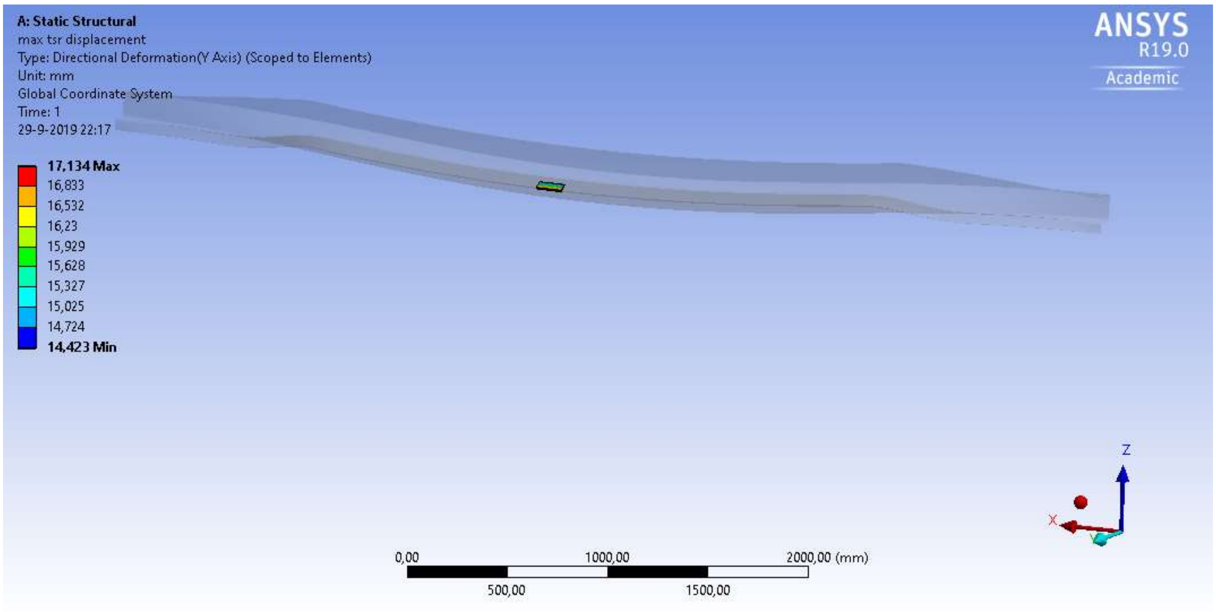


Figure 62 Ansys top side rail meshed model

ANSYS results

In order to evaluate the maximum displacement the displacement of the middle element is probed, see Figure 63. The magnitude of the displacement is in line with what is expected when looking to the 4 fold container model. The flap overlap is 50 mm so a displacement of 17 mm is well within the limit of the maximum allowed deformation.



A: Static Structural
max tsr displacement
Type: Directional Deformation(Y Axis) (Scoped to Elements)
Unit: mm
Global Coordinate System
Time: 1
29-9-2019 22:17

Figure 63 Ansys top side rail probe displacement

When looking to the equivalent stresses in the model, Figure 64, it shows that there are stress concentrations exceeding the limit in the locations where the model is simplified. Overall however the stresses are well within the limit. These corner locations should be investigated using a full model of the sidewall. In the full model the front and rear sides of the container take up some of the load acting on the tubular frame of sidewall. This full sidewall model is outside of the scope of this thesis.

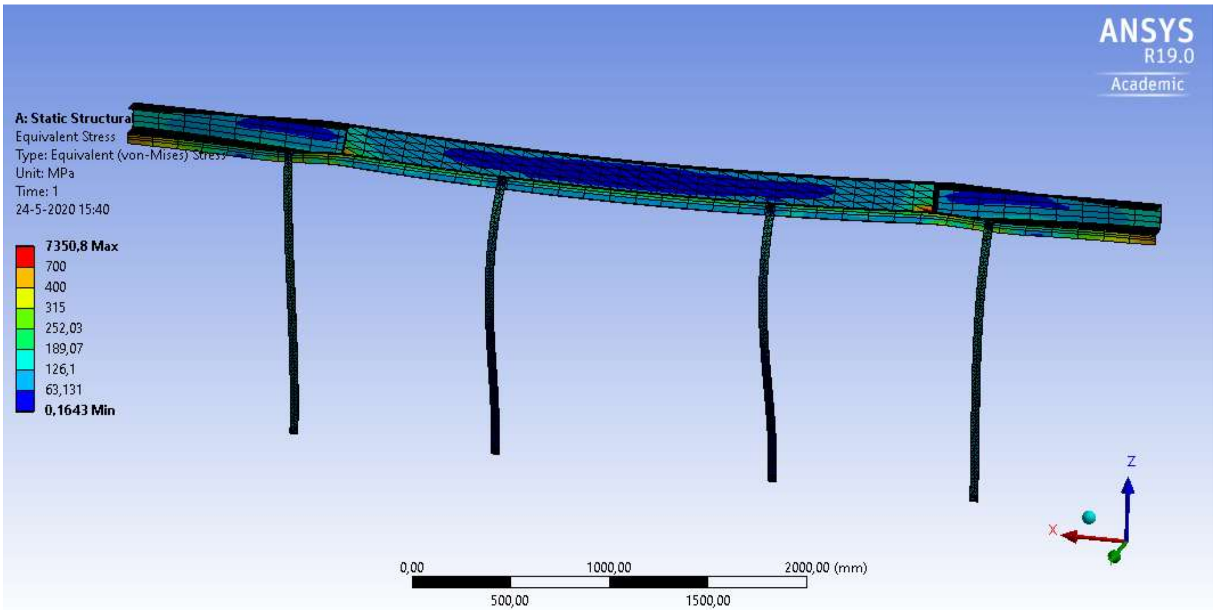


Figure 64 Ansys top side rail equivalent stresses

The peak stresses encountered in the model are in the edge elements of the stiffeners, see Figure 65. There is a rapid change in the local rotation stiffness in these elements as well as a sharp change in the element sizes. The stress also rises if the elements of the stiffener are decreased in size. If the problem returns in a complete fem model of the design it can be partially mitigated by slanting the stiffener. This will increase the construction cost but smooth out the change in rotation stiffness reducing the local stress.

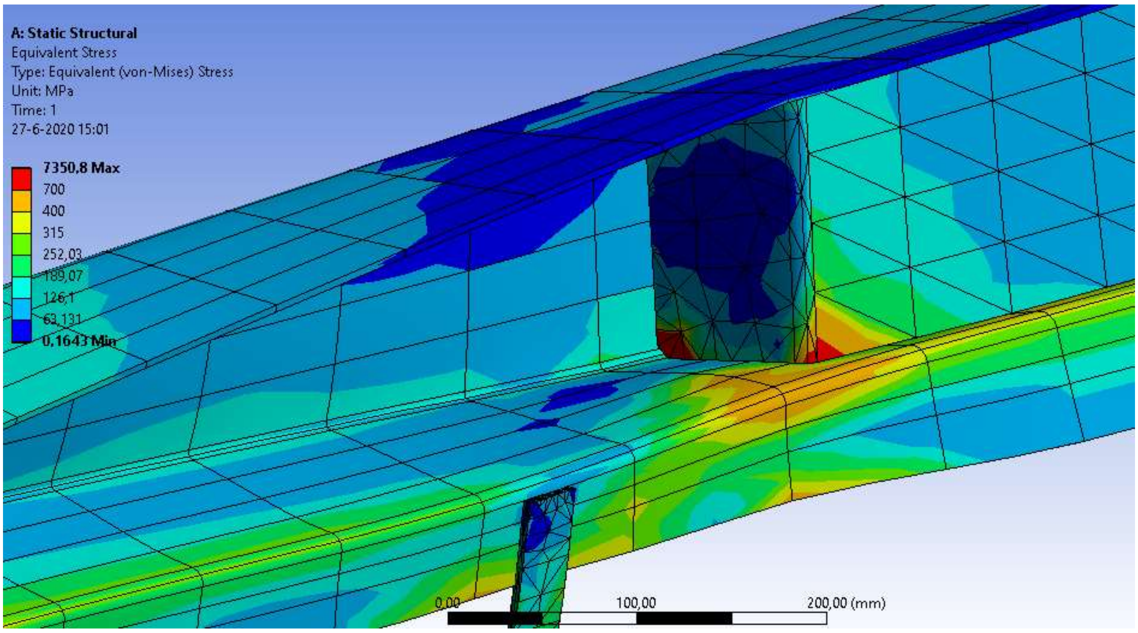


Figure 65 Ansys detail of the maximum stress locations

ISO Load Case 7 - Strength of the roof

The roof load case is required to ensure small repairs can be made to the top of the container. It assumes one worker with tools can safely work on the roof. This case is simplified to a distributed k_{load} of 300kg across a 600 x 300 mm rectangle on the roof. The weakest part of the container roof are the middle roofing plates.

The pass criteria is that the roof is not allowed to fail. This is translated into the maximum stress is not allowed to exceed the yield stress. There are no maximum displace requirements. Since the critical component is a standard part the container is assumed to pass this test.

ISO Load Case 8 – Floor strength

The floor strength test is used to test if the container handles heavy forklift trucks. The requirement is that the floor supports a loaded forklift on all positions. Since the transverse members under the floor and the floorboards are identical to those normally used in a 20ft container it is assumed that these transverse members will hold. What remains is to investigate the parts not used on a standard 20ft container the bottom side rail and the rear end transverse member.

Schematic overview and boundary conditions

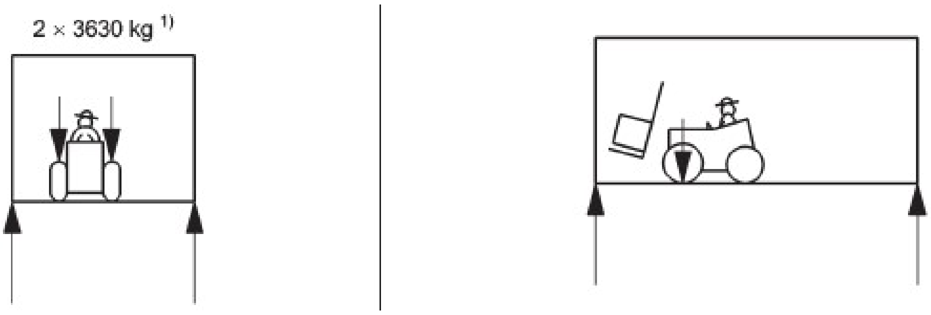


Figure 66 ISO 1496-1 figure A.10

It is assumed that due to the use of the standard parts the floorstrength is satisfactory. This can be validated when a complete FEM model is made.

ISO Load Case 9 - Rigidity (transverse)

Figure 67a and b show the ISO schematic for the transverse load case. The load case shows the ability of the container to take up racking forces. The location on the figure shows the 40ft fitting locations on a 45ft container but for a 40ft and 20ft container this translates to the location of the corner fitting. The pass criterion for this case is given as that the sum of change of the end wall diagonals under load must be less than 60 mm as is shown in Figure 68.

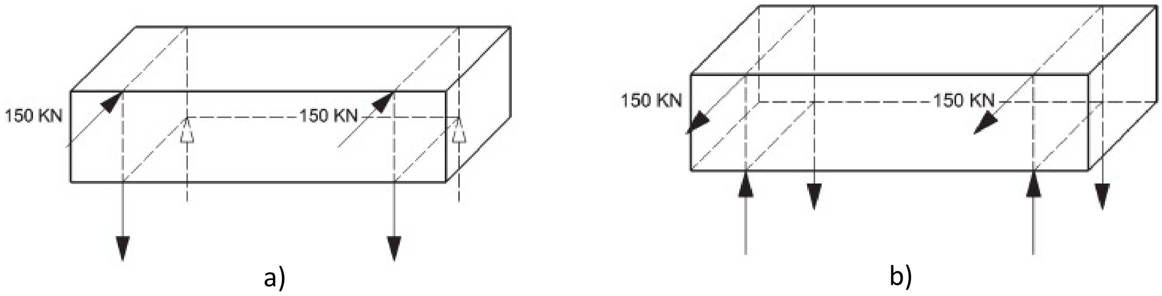


Figure 67 a) ISO 1496-1 figure A.11b; b) ISO 1496-1 figure A.12b

The procedure states that the container is placed on four level supports, one under each corner. The lateral restraint is only provided to the bottom corner fittings.

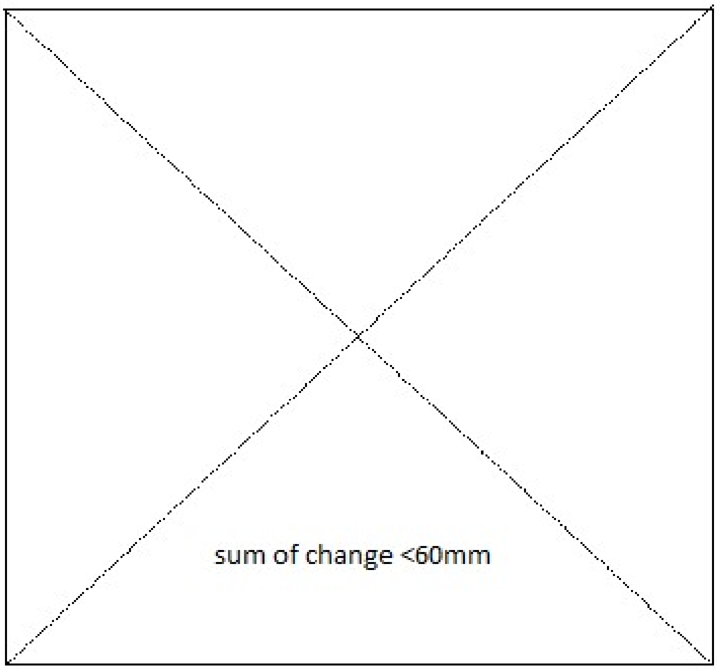


Figure 68 ISO criteria

Design overview

As can be seen in Figure 69a the rear container wall consist out of the rear container door and a doorframe. On the four corners of the frame the corner fittings are located. For the 20ft design the rear end wall is shown in Figure 70. The locking mechanism and rubber seals are not shown. It does show that the rear end wall door frame and the corner fittings are not welded. Instead the connection between the roof and the end wall frame is a hammer lock, shown in Figure 69b . The hammerlock is able to transfer moments and forces. The connection between the base and the end wall is the end wall hinge point shown in Figure 69b. The hinge is unable to transfer moments around its axis of rotation (Y).

a) b)

Figure 69 a) Rear container wall; b) endwall connections

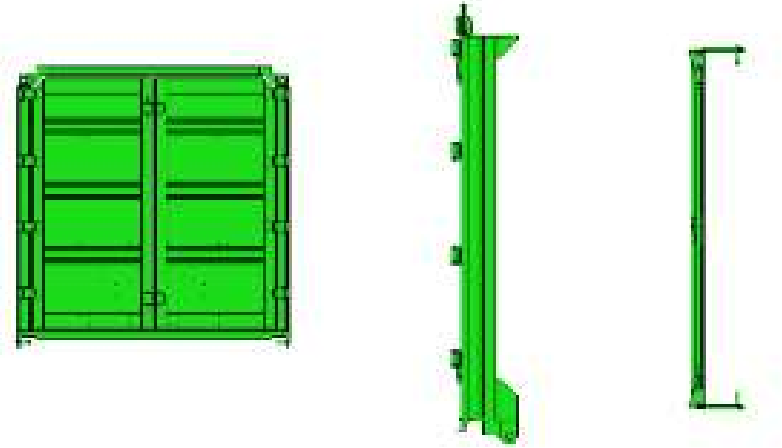


Figure 70 20ft rear end wall (rear view, side view and top view)

Schematic simplification and boundary conditions

In order to simplify the problem and assume the worst case scenario the following assumptions are made:

- the clearances between the base and end wall and the roof and end wall are at the wrong side at the start of the test and thus are counted double.
- the corner post flex normally until the anti-racking blocks touch and after that the corner post acts as if its split in three parts.
- The load is only carried through the rear end frame. The sidewalls base and roof are left out.
- The door locks are left out.
- the corners of the doorframe are rigid and are not allowed to rotate freely.

The first step in this process is creating a schematic overview of the rear end wall. This schematic and its components is shown in Figure 71. Depending on the boundary condition of the anti-racking block touching or not the loadcase can be described in two steps.

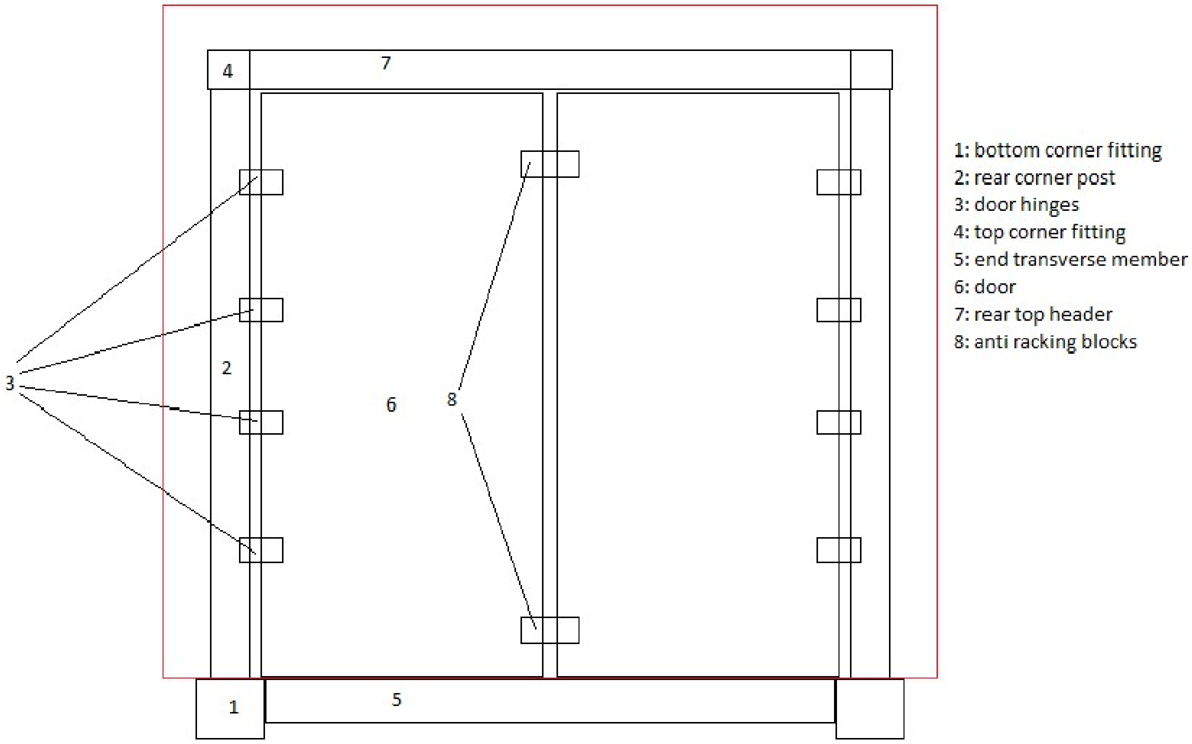


Figure 71 Schematic overview rear end wall door

The first case is the case where the anti-racking blocks are not touching. The load acts on the rear end wall trough a top corner fitting, as can be seen in Figure 67. Since the door lock does not carry any load the problem can be simplified to a portal frame under a side load. The bottom of the door frame has a rigid connection to the corner post and thus the corner post, top corner fittings and top header can be modelled as a simple fixed frame model shown in Figure 72a. This case 1 model is valid as long as the anti-racking blocks between the doors don’t touch each other, see Figure 72b, due to the deflection of the corner post.

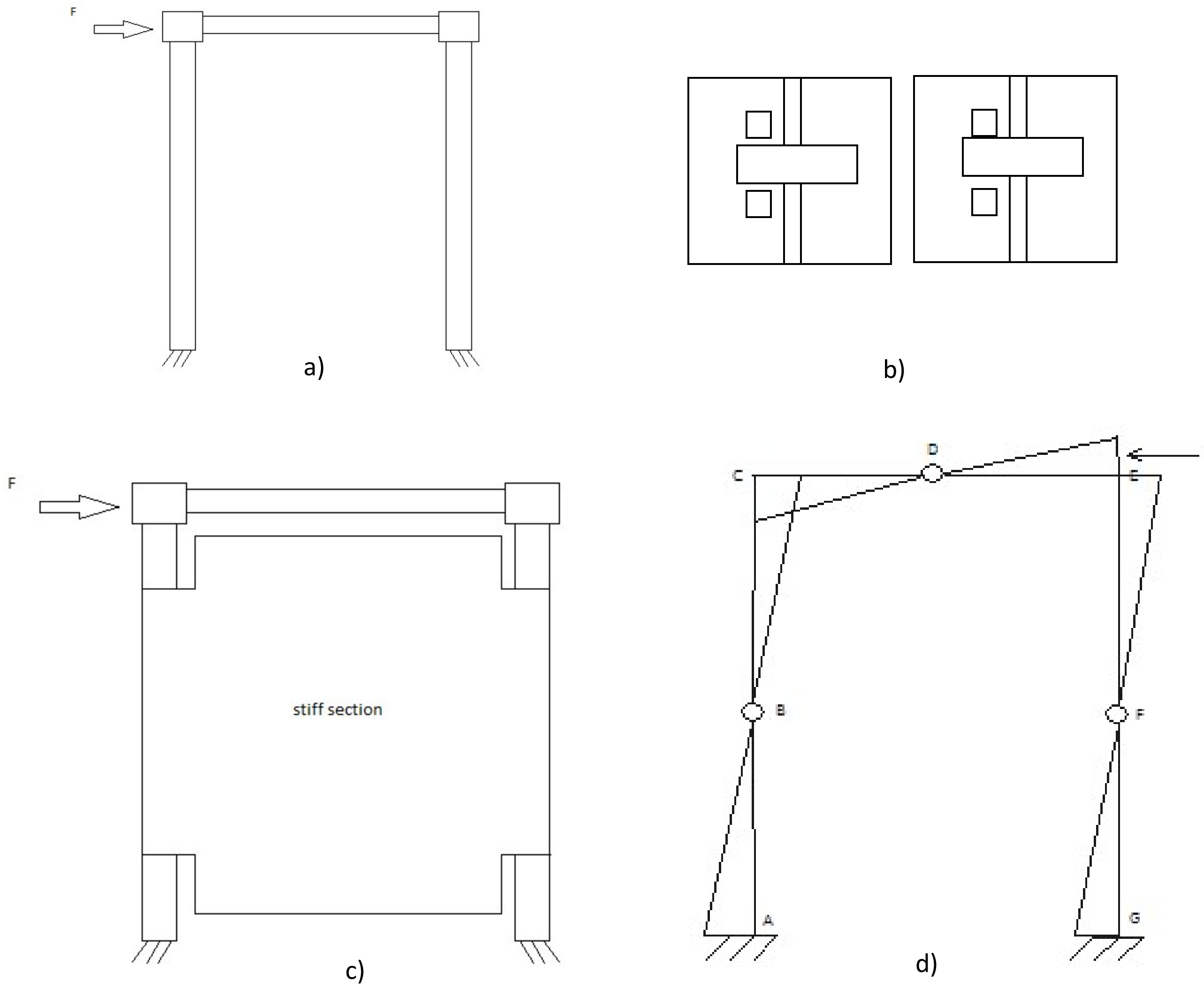


Figure 72 a) fixed portal frame (case 1); b) Anti-racking not touching and touching boundary condition; c) spit portal frame (case 2); d) moment diagram case 1.

The second case is when the anti-racking blocks do touch. When this happens the doors acts as a rigid section between the door hinges splitting the frame into two flexible sections with a rigid mid-section as can be seen in Figure 72c. In order to simplify the calculation it is assumed the displacement in case 1 does not require significant force and all load is carried by case 2. The maximum displacement from case 1 is added to the total displacement. This is the conservative approach.

Free body diagrams

Figure 73 shows the moment diagram for a fixed portal frame. This model is valid in both cases. In case 1 the length is the height of the corner post. In case 2 the length is the distance between the door hinge and the corner of the frame. It should be noted that the hinge in points B, D and F are located in the middle of the length of the beams. With similar cross-sections in beam AC and EG, the forces in A, B, C and E, F, G can be calculated.

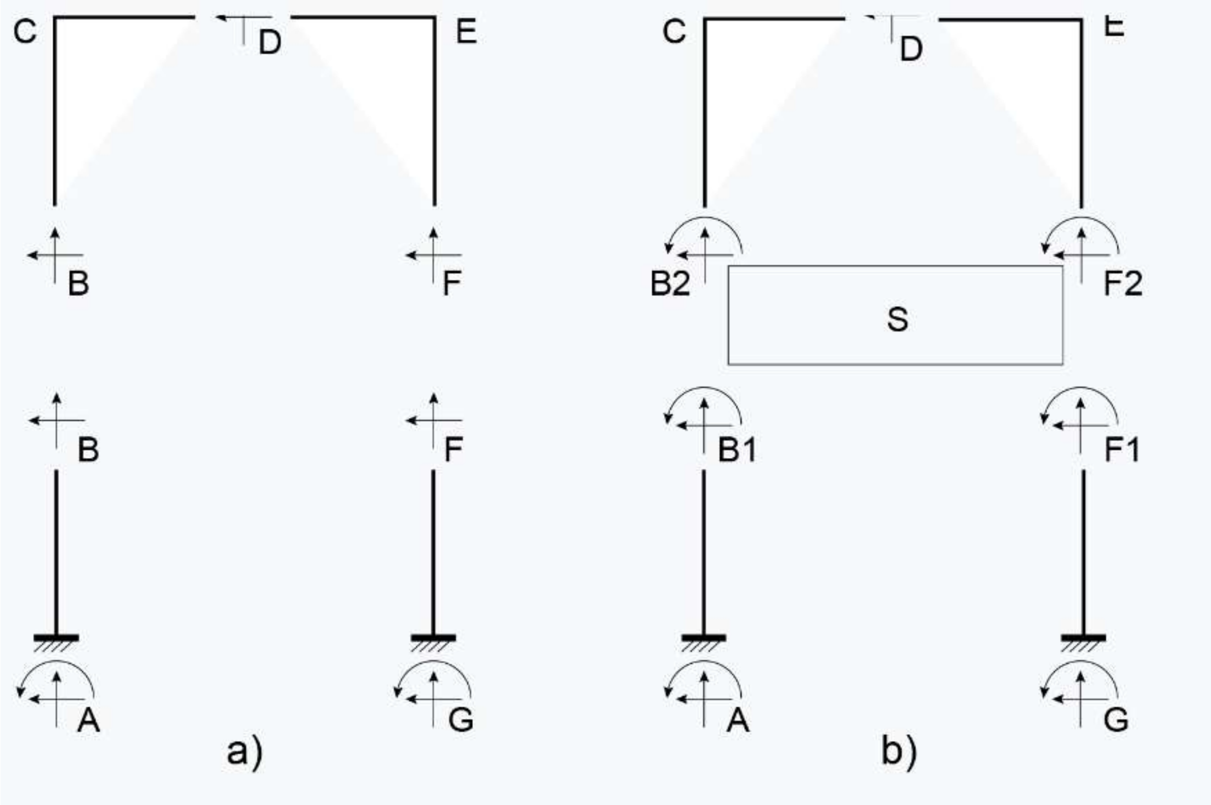


Figure 73 a) Free body diagram case 1; b) Free body diagram case 2

$$F_{horizontal} = 0$$

$$F_C + F_E - F_L = 0$$

$$F_A, F_B, F_C, F_E, F_F, F_G = \frac{F_L}{2} = 75kN$$

$$M_A - \frac{F_L}{2}.\frac{L}{2} = 0$$

$$M_A = \frac{F_L}{2}.\frac{L}{2}$$

Due to symmetry, the moments at point A, C, E and G are identical.

In case 2 these equations still hold except that length changes from the length of the corner post to the length between the corner and the door hinge, this results in the moment diagram shown in Figure 74.

Calculations

To calculate the displacement in a simple but conservative way the total displacement is the sum of the following displacements:

- Displacement in the tolerances
- Displacement that is allowed before the anti-racking block engages
- Displacement of the lower and upper part of the corner post.

The displacement of the corner post is calculated as a free hanging cantilever beam with a point force on the end. The length of the beam is the distance between the fixed end and the first hinge.

$$\Delta_{total} = 2.\Delta_{tolerances} + \Delta_{antiracking} + 2.\Delta_{beam\_displacement}$$

The displacement from the tolerances is 10 mm. Assuming the worst case scenario this displacement is counted twice. The available displacement before the anti-racking blocks touch is 5 mm per side of the door vertical displacement. Due to the geometry of the door this results in a displacement of 5 mm in horizontal direction.

The beam displacement is calculated using the following data:

Figure 74 moment diagram case 2

F	75 kN
L	494 mm
E	210000 MPa
I	6163746 mm^4

The length is the longest length between the end of the corner post and the closest door hinge.

This results in a displacement of:

$$\Delta = \frac{F.L^3}{3.E.I} = \frac{75000.494^3}{3.210000.6163746} = 2.33mm$$

$$\Delta_{total} = 2.10 + 5 + 2.2,33 = 24,66mm$$

With the horizontal displacement known the changes in the diagonals can now be calculated, see Figure 75.

$$L_{d1} = \sqrt{2591^2 + (2438 - 24,66)^2} = 3541mm$$
$$L_{d2} = \sqrt{2591^2 + (2438 + 24,66)^2} = 3574mm$$
$$L_d = \sqrt{2591^2 + 2438^2} = 3558mm$$
$$|L_{d1} - L_d| + |L_{d2} - L_d| = 33$$

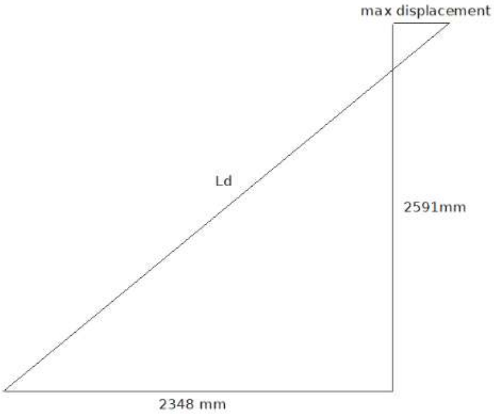


Figure 75 diagonal calculation

The sum of changes is the worst case scenario are lower than the limit given by the ISO code and thus it is assumed that the design meets this requirement, 33<60mm. When looking at the maximum stress present in the beam the maximum moment and section information is needed. The maximum moment is derived from Figure 73. L being 494 mm and P being 150 kN.

$$M_{\max} = \frac{P}{2} . \frac{L}{2} = \frac{P.L}{4} = \frac{150000.494}{4} = 18525000Nmm$$
$$\sigma = \frac{M_{\max} . y}{I} = \frac{18525000.80}{6163746} = 240MPa$$

The y-distance is the distance from the inside of the door to the centroid of the corner post. Since the rigidity test is preformed both ways this gives the highest stresses in the beam.

The maximum stress is 240 MPa which is below the yield stress of the material and thus the beam passes the maximum stress requirement.

The front end wall only has tolerance displacement and bending displacement since the wall has no door. The rigidity of the front end wall is assumed to be higher than the rear end wall so the displacement due to bending will be lower. This results in lower displacement of the front end wall compared to the rear end wall and it is assumed that this wall will pass the requirements as well.

ISO Load Case 10 – Rigidity (longitudinal)

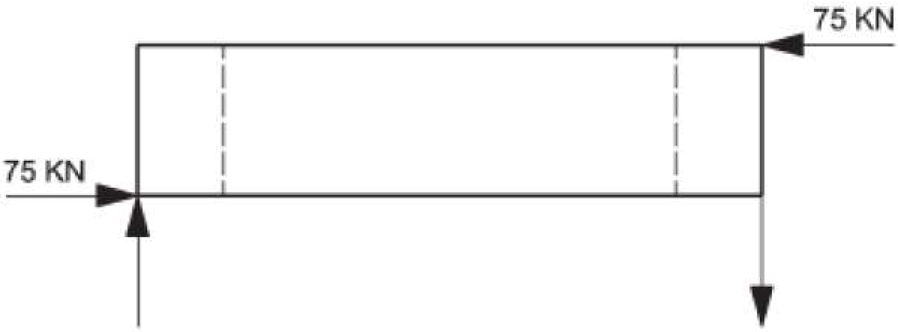


Figure 76 ISO1496-1 figure A17a

For the longitudinal Iso test the allowed deflection of the top of the container under full load shall not exceed 25mm.

Design overview

The displacement of the roof is limited by the sidewall locks and the support blocks on the sidewall. The allowed displacement before both the locks and the block have shifted their clearance is 6 mm. It is expected that the overall displacement is not far of from this and thus is less then the 25mm allowed.

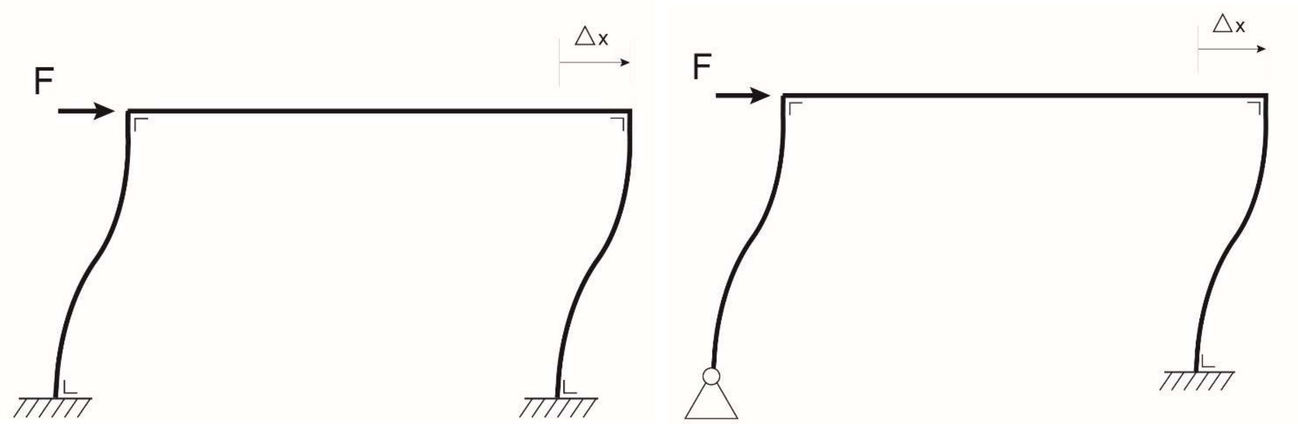


Figure 77 Schematic case normal container (left), foldable container (right)

Alternatively disregarding the stiffness of the sidewall the maximum displacement is given by the displacement of the both the endwalls., see Figure 77. The stiffness of the back end wall is the lowest of the two walls.

The worst case scenario is if the force is applied from the front end wall towards the back end wall. Since the front end wall hinges inward the stifness of the front end wall is set to zero in this case. The resulting case is shown in Figure 77 . The worst case scenario only take the stiffness of the back end wall into account but does not allow rotation of the top and bottom of the endwall since both these points are restricted in rotation. This reduces the problem to the case shown in Figure 78

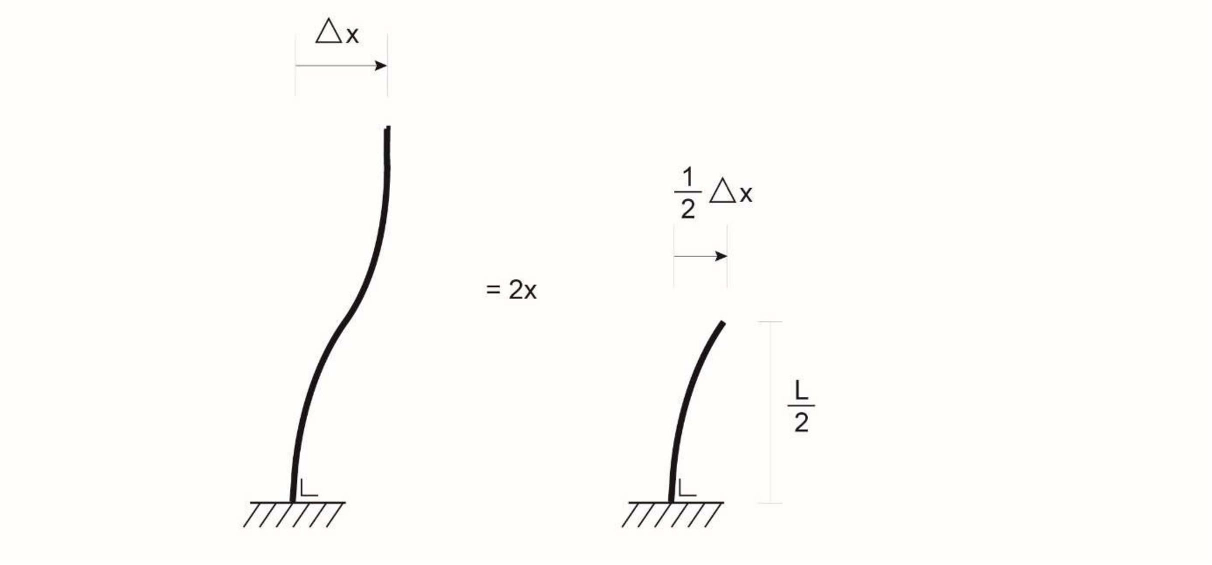


Figure 78 Simplified case only taking one endwall into account

Solving for the displacement this case gives a upper limit of displacement of 23 mm. The actual displacement will be between the two cases and can be checked whit a full FEM model or a prototype.

$$\Delta = \frac{F.L^3}{3.E.I} = \frac{75000.1144^3}{3.210000.15404889} = 11.59mm$$

$$\Delta_{total} = 2.11,59 = 23mm$$

ISO Load Case 11 – Lifting from the fork-lift pockets

The forklift load case for the 20ft container is different from the 40ft container in that the forklift must be able to lift a fully laden container compared to only be able to lift an empty 40ft container. Compared to a normal container the folded 20ft container also needs to be able to be lifted as a stack of folded containers.

Design overview

For the unfolded container the base and sidewall are relevant to this loadcase. The sidewall is held in place by both endwalls and thus it is assumed that the sidewall will not deform. As a conservative approach the endwalls and roof are not taken into account. This is due to the displacement that needs to take place in order for the slack to be taken up before load is transferred.

For the folded case it is assumed that both the base and roof section as well as the bottom of the frame part of the sidewall are load bearing members for this loadcase.

5.2 Normal 20ft comparisons

In this section, the specifications of the 20ft foldable design are compared to that of a normal 20ft container. Although the foldable container complies with the ISO standards for the outside geometry, thus the intermodal compatibility, the internal measurements are slightly different due to the space needed for the folding mechanism.

5.2.1 Specification sheet comparison

5.2.2 Main dimension comparison

Door *width*

The door width for the 20ft foldable container is 2200mm, this is identical to the 4fold 40ft container, so it is slightly smaller as the prescribed value by the ISO. HCI has deemed this difference to be acceptable, in consultation with their clients.

Door height

The door height for the 20ft design is 2289 mm. This is 61 mm lower than the ISO specifies. In order to check if this is high enough, the height of a forklift truck was checked. The height of the forklift varied from 2080 to 2250 mm, still allowing for a clearance to the top of the doorframe. The door height is therefore deemed acceptable, although this is also something that should be discussed with the clients of HCI.

5.2.3 Pallet scheme

The table below describes the number of pallets that fit next to each other on the surface of the floor for different standards. This is similar to normal containers for all main pallet types

ISO pallet	Region	Dimension	Number of pallets	Difference with regular 20ft container
1	North America	1016x1219	10	0
2	Europe	1000x1200	10	0
3	Australia	1165x1165	9	0
4	North America	1067x1067	10	0
5	Asia	1100x1100	10	0
6	Europe	800x1200	11	0

5.2.4 20ft comparison conclusion.

The overall comparison does show that the overall internal dimensions of the 20ft foldable container are a bit smaller than a normal 20ft container. Since a 20ft container is mainly used for heavy loads and the overall amount of pallets that can be loaded is the same the overall internal dimensions are considered adequate,

5.3 Other requirements

Weight analysis

An estimate of the weight of the complete container was done using Solidworks. All parts of the design have their material properties assigned, which is Corten-steel for most parts, except for the floor which is made of wood (Marine plywood). The mass evaluation of the entire design resulted in a weight of 2842 kg.

Since some components are left out of the Solidworks model, the weight of these additional components needs to be take into account as well. The weight for these components is taken from the 40ft 4fold design. The dampeners for the sidewall weigh 16 kg each. With 2 dampeners for each side this is a total of 64 kg additional weight. Additionally the weight for the rubber seals needed to be estimated. The values for all the rubber seals was taken from the 4fold design as well. The rubber seals totalled to 50 kg.

This results in a total weight of 2956 kg. This is lower than the 3000 kg requirement set for the tare weight of the container and thus this requirement is passed. However, the difference is not that large. This can be explained by the fact that the weight limit was taken into account from the start of the design process, so the weight of the components was checked periodically and compared with the components in the 40ft design (which is roughly twice as heavy). In addition, from the calculations above, some options for weight reduction were found. More on this is discussed in chapter 6 Recommendations.

5.4 Cost analysis

In order to evaluate whether the design meets the cost criterion, the construction cost needs to be calculated. Since the design of the 20ft container uses the same working principle as the 40ft container, the construction cost estimate for the 20ft foldable container is based on the cost estimation done for the 4fold 40ft container. The costs of the parts that have not undergone a drastic redesign can be assumed to be the same as for the 40ft container. The complexity of the assemblies is roughly the same as well. The overall construction estimate is composed out of the following items:

- the six main components
- the seven auxiliary parts
- main assembly cost
- shot blast and paint
- finish

Main component overview

For the six main components the costs are divided by sub-assembly. The costs for each sub-assembly consist of the material cost; the alignment time; the weld type and length; and any additional machining needed. For this calculation, the costs of alignment time, weld type and additional machining are assumed to be the same as in the 40ft design. From the total of 430 parts, the following parts have the biggest influence on the new cost, since these have undergone a significant redesign:

- Bottom side rail: the material cost will be lower due to a shorter and thinner design;
- Top side rail: the material cost will be lower due to a shorter and thinner design;
- Side wall panels: the material cost and weld length cost will be lower due to a reduced number of panels;

- Side wall beams: the material cost will be lower due to a shorter and thinner design;
- Roof panels: the material cost and weld length cost will be lower due to a reduced number of panels;
- Transverse members: the material cost and weld length cost will be lower due to a reduced number of panels;
- Floor size: the material cost will be lower due to a smaller floor surface.

For each of the components the cost where evaluated using the new size and weight whit comparable parts from the 40ft design. This results in a cost estimate for each component a sub assembly. The main differences to the cost of the 40ft are discussed in the next second but due to sensitive nature of these calculations most of the details are omitted from the report.

Total results

The effects of the differences in the cost of above mentioned parts on the sub-assemblies are given in Table 20. The cost figures for the 40ft are based on the cost calculation for one of the most recent 40 ft design. The cost price for the 20ft design are derived from the cost for the 40ft design looking at the changes is material use, setup times, and construction times.

	change (%)
Base Structure	-20%
Roof Structure	-14%
Side Walls Structure	-19%
REW Structure	Same
FEW Structure	Same
Shot blast and Paint	-25%
Main Assembly	Same
Finish	-29%
Base Hammer Locks	-100%
Roof hammer Locks	+10%
Double Twist Locks	Same
Side Wall End Wall Locks	+100%
Side Wall Roof Locks	-50%
Toggle System	Same
Damping System	-25%
Total	-20%

Table 20 cost comparison 4fold 40ft vs 4fold 20ft, source HCI cost calculation tool

As can be seen, some the costs of some parts are increased and for others decreased. For the base, roof, side walls, shot blast and finish the cost was reduced due to the container length reduction compared to the 4fold design. Although the length is reduced with 50%, these costs have not been reduced by 50%, this is because a large portion of the costs is not for the material, but work itself. The base hammer locks are no longer present in the design, thus this cost is eliminated. The top hammer locks have become more complex in design, therefore it was estimated this would result in more work. The change in the locks for the sidewalls can be explained by the 50% reduction in the amount of side wall locks, and the doubling of the endwall locks. The dampening system decreases from 3 units per side to 2 units per side, due to the length reduction. However, the cost only decreases by 25 % due to the fact that the height of the base is lower and the installation of the dampener is technically more complex, resulting in higher work costs.

The construction costs are evaluated using information on the 40ft design. The cost estimate for the 20ft container based on this calculation is below the cost requirement set and thus the requirement is passed.

5.5 Requirement list review

One requirement is not yet fulfilled. This is due to the energy storage systems can be identical in function to the systems used on the 40ft design. There is space to install this system in the design but the details of its installation are omitted from this design thesis. As the energy storage is left out of this design the securing for this storage cannot be fulfilled.

[V] is a passed requirement

[X] is a failed requirement

[-] is a unproven requirement

General		
• Comply with ISO 1496-1, ISO 1496-5, ISO 1161, ISO 668 where applicable	[V]	Ch 5.2
• Lifespan of 10 years	[-]	
• Door opening 2200 mm	[V]	Ch 5.3
• Internal width minimal 2324mm	[V]	Ch 5.3
Production		
• Unit cost max 10.000$	[V]	Ch 5.4
• Minimize construction failure risk	[-]	
Usage		
• The unfolded container can be used as normal container	[V]	Ch 3
• Maximum own weight of 3000 Kg	[V]	Ch 5.3
• Container rating:		
○ 32500kg	[V]	Ch 3
• Minimize critical damage risk	[V]	Ch 4
• The container will be designed for minimum maintenance and repair costs	[V]	Ch 4
• A single folded container should be moveable by standard handling equipment.	[V]	Ch 3
• All parts of the container must stay connected	[V]	Ch 4
Folding operations		
• The folded container can be bundled into the height of a normal container in a stack of:		
○ Five containers	[V]	Ch 3
• Can be folded with the same equipment as the 4fold container	[V]	Ch 3
• Interlocking mechanism should be integrated in the design	[V]	Ch 4
• Folding operations should be done in a maximum of 5 minutes using two persons	[V]	Ch 2
• Folding should be done in a safe and controlled manner	[V]	Ch 2
• The status of the locks (open/close) are clearly visually identifiable	[V]	Ch 4
• All locks and raisers have a second securing	[V]	Ch 4
• A safety (securing) is present on energy storing parts	[X]	
Intellectual property		
• The design should be:		
○ using current HCI patents	[V]	Ch 3

5.6 Conclusion

In this chapter, the design was evaluated to see whether it complies with all requirements from chapter 2. The hand calculations have shown that the design fulfils the ISO load cases. However, the calculations used simplified geometry and were done by hand. This combination means that there is a relatively large safety factor taken into account, to allow for a larger margin of error inherent to hand calculations. To reduce the margin of error, and in turn allow for a reduction in material to be used, the design can be made even lighter. This will require a full FEM analysis to verify that it still meets the ISO requirements. If less material can be used, the design will become cheaper. In addition, since the tare weight of the container is less, this will allow it to transport more or heavier load. Although the weight and cost requirements have passed for this design, improvements in these values will always benefit the viability of the design.

It should also be noted that the following aspects of the design are not implemented yet

- full door details
- detailed seal design
- detailed balancing system
- detailed toggle system

In conclusion, the design complies with all technical requirements as described in Chapter 2. The operational requirements outlined by HCI are assumed to have passed due to the use of the same folding method.

Chapter 6 Conclusions and recommendations

6.1 Conclusions

The main research question for this design project was:

What is a viable design for a foldable 20ft container for HCI?

The design presented in this report is a systematically designed foldable 20ft container that is viable for HCI. This design is realised by first answering the questions:

- What makes a foldable container viable?
- What is a viable folding method for the 20ft design?

In Chapter 2, the investigation on what makes a container viable was used to create the requirement list. Besides being ISO compliant the container also needs to be economically viable. This resulted in the following four key requirements:

- ISO compliant
- Rating of 32 500 kg
- 5-1 folding
- 4fold folding mechanism is preferred

The rating was increased from 30 480 kg to the next step of 32 500 kg. These rating steps are prescribed by the ISO. The increased rating compensates for the increased weight of the container itself compared to a normal container. The consequence of the higher rating is that the loads on the load cases involving the rating are increased as well. The 5-1 folding is a key requirement due to the competition already working on 5-1 folding. Starting the design for a lower amount of stacked folded containers creates a disadvantage towards the competition. Compared to the 4-1 40ft HC design this results in a reduction of the allowed folded height. The 4fold folding mechanism is a proven technology. In the conservative container shipping world the track record of a proven technology is a advantage. It removes the need of building a track record for the folding method itself since its proved to be working for the 40ft design.

The second step in the design process was to analyse whether the folding method used by HCI for the 4 fold 40ft HC container could be applied to a 20ft design. The result of this analysis was that the method is viable, but that the container components needed redesign in order to meet the requirements set out in the requirement list.

In Chapter 3, the key requirements were used to extract the essential design problem and thus answer the following sub question:

- What is needed to implement the 4fold folding method to design?

The essential problem for the design was reduced to a height allocation problem that would allow 5-1 stacking of the folded container. The problem was solved by allocating height allowances for each of the main components of the container. The height allowances allowed to further the design into the embodiment phase.

The embodiment phase of the design was described in Chapter 4. The first step in this phase was answering the sub question:

- What are the design limitations for the design?

These limitation are material based and are limited to the standard material used for container construction, SPH-A steel. Buckling of open sections was also identified as critical damage not allowed on the container. To prevent this critical buckling damage the minimal thickness of the opens section was determined. The minimal thickness is set to be such that the critical buckling stress is higher than the yield strength of the material.

Using these minimal thicknesses, the design was evolved such that all sub components that needed redesigning to meet the allowed height requirement were redesigned. The main areas that needed redesign were dubbed the main design challenges and subsequently solved. This resulted in the final design.

In Chapter 5 the design was evaluated using the ISO load cases. Since the load cases are leading in allowing a new container design to be operational, it is crucial that the design can pass the load cases. In the load cases assumptions are made about the use of the container, therefore no additional assumptions needed to be made. It was shown by using hand calculations and a conservative approach that the design meets the requirements set in these load cases. It is also shown that all relevant requirements set in chapter two are passed. The ISO load cases are used to pass the design under testing conditions. The assumptions made in the ISO load cases mean that a safety factor is already included in the design.

The final step was to answer the sub question:

- How does the design hold up to a normal 20ft container?

To answer this question a specification sheet was made comparing the design to the standard 20ft container. It showed that due to the increased container rating the allowed loads for the foldable container and the normal container are identical.

In conclusion, since the new design of the 20ft foldable container complies with all requirements (that can be determined at this stage of the design process), it can be said that it is possible to design a viable 20ft foldable container, and that the design described in this report is a viable solution for HCI.

6.2 Design recommendations

The design as presented here has been shown to be theoretically viable, however it still needs to be developed further before it is ready to be produced. The design complies with all requirements; however it is not yet optimized. The following steps can be taken in order to improve the design.

First, the design of the corner castings is not yet optimal and thus probably is overweight. The proper design of the casting needs to be optimized by means of a FEM analysis, and in collaboration with a producer to make it ready for manufacturing. Since they are relatively heavy, an optimized design can benefit both the costs of material and reduce the weight of the container.

Second, a detailed FEM model of the design can be created. Creating a detailed FEM model allows to check the assumptions made for the hand calculations and possibly show areas for improvement. Full detailed FEM modelling however can also increase the urge to create a complexed design. By keeping the design simple the costs of the individual components is kept in check. There is a trade-off of part complexity increasing the cost and material savings reducing the cost.

Third, a detailed design of the seals needs to be created. In the current design, there is space incorporated for the seals that is the same as in the design for the 40ft 4fold container; however they still need to be included in the design.

Finally, in this report it was theoretically proven that the design is viable. In order to prove that is practically viable as well working prototypes are required.

6.3 Future work

40ft 4fold recommendations

In the 20ft design the bottom lock present in the 40ft design was replaced by a heavy duty hinge point for transferring the load and displacement inhibitors on the sidewall. By examining if a similar approach could be used in the 40ft design, the 4fold 40ft design can be improved. This eliminates a failure risk of operating the lower lock as well as a reduction in overall parts, both in complexity and total amount. A first step in this process could be the following: Run the longitudinal ISO test on a 40ft HC container with its bottom lock open. This shows if the top locks successfully transfer the loads applied to the container. If this test is successful it can also be used to improve the safety of the folding operations.

The safety can be improved if the test is repeated with all locks open and the sidewalls folded. If the container does not deform the 4fold 40ft HC container is proved to be stable fully opened and accidently hit during folding operations.

Research recommendations

During the task clarification, it was found that very little research has been done on the effect of folding containers on the intermodal transport system. This is probably due to the fact that there are no (standard) technical parameters yet to build a model with.

The design in this report resulted in a set of technical parameters (5-1 bundle, and an own weight of 3000kg). With these parameters known it could be possible to do research into the effect of bundled empty containers on the effectiveness of the intermodal transport system.

In general the following questions are interesting;

- How much of a reduction in overall TEU volumes can be achieved dues to bundling of empty foldable containers? And what is gained in flexibility of container planning?

Every empty container that's loaded on transport medium needs to be unloaded as well. Reducing the number of empty container that need to be loaded reduces the overall TUE volume. In return this gives flexibility in routing and opportunity. The scarcity on the container availability after the Covid-19 disruption showed the vulnerability of empty repositioning.

One of the key nodes and the most expensive in the intermodal system is the sea harbour node. By introducing folded containers, the following aspects can be investigated:

- Is it possible to reduce the quay time?
- Is there a reduction of temporary offloading on multi legged ship routes?

Intermodal shipping of containers is often shown to be vessels moving from port A to port B. In reality shippers use larger and larger vessels that have multiple ports of call. Since the majority of shipping is from Asia to the rest of the world the empty containers become a problem. Due to stability requirements of the vessels empty containers need to be in the to of the container stacks. Shippers solve these problems by temporary offloading or using smaller coaster to move empty containers to the last ports of call before the larger vessel return to Asia. By using stacked folded containers this problem is reduced. How much there is to be gained is not yet modelled.

- Is there a shore based efficiency gains due to less empty transport?

Besides inside the harbour, research into the effect of folding containers on oceangoing vessels could also be interesting, in particular in the following areas: empty container placement locations; reduction of temporary offloading on multi legged ship routes; loading/ unloading time changes.

For road transportation, an interesting research area would be modelling if and how much foldable containers would reduce the number of empty kilometres driven, which could also affect congestion of known empty container traffic jam hot spots. In addition to this, for rail transportation, improvements in 20ft and 40ft imbalance routes could be optimized.

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Appendix A research paper

Introduction

The intermodal transportation transport is used to ship goods from A to B all over the world using different modes of transportation. The intermodal freight relies on the use of standardized containers for this transport. Due to the standardization of these containers, goods no longer need to be transferred individually between modes of transport. Instead the containers as a whole are transferred. The International Organization for Standardization (ISO) has standardized the containers for the intermodal system in ISO668.

The benefit of a standardized container is that all stakeholders in the intermodal system know exactly how to handle and what to expect from a container, independent of owner or manufacturer of the container. This also means that containers can be stacked on top of each other and repaired all over the world, and that a lot of container parts are standardized as well.

This shows that the greatest strength of the intermodal transport system is also its biggest weakness. All empty containers need to be shipped back to the areas where there is a demand for empty containers. Since a standard container is the shame shape, independent if it is loaded or empty, all nodes in the intermodal system have a significant portion of empty container moves.

To better understand the scale of this imbalance, K. Wang et al (2017) state that the imbalance in 2016 between Asia and the US was 8.4 million TUE. [3] The USA imported 15.8 million TUE and exported only 7.4 million TUE.

A lot of research is being done in order to optimize the throughput of the intermodal transport system process. However, this research is based on the standard container unit of FUE and TUE (40ft container and 20ft container). The standard container is the smallest unit in the process, therefore an improvement in this basic unit will only merit a small advantage.

Holland Container Innovations saw a different solution to the problem of empty container repositioning, by changing the basic unit in order to optimize the process, in the form of a foldable container. Folding a container can save on relocation costs of empty containers. When the container is folded all handling actions needed to move the container are reduced by a factor which is equal to the number of folded containers that create a container high bundle.

The first container product HCI launched is the 4Fold High Cube (HC) container. The outside dimensions of the container are similar to that of a normal 40ft container. The inside volume of the container lies between that of a normal 40ft container and a 40ft HC container, thus making it viable for the normal 40ft container market as well as a portion of the 40ft HC market. The container market however does not consist out only 40ft containers, another large portion of the container market are 20ft containers for which the same imbalances are occurring. HCI therefore wants to expand its portfolio with a 20ft foldable design as well.

Method

In this paper, the design process for the design of a viable 20ft foldable container is described. The end result of this project will be a concept that can be adaptable to a full commercial design. There are several aspects to the design of a new container: the technical requirements, economic and competitive requirements, and regulatory requirements. If only the technical requirements are taken into account, the end result will be a proof of concept, but this means limiting the design problem.

Konings and Thijs (2001) describe a number of conditions that are required for a successful container.[3] These conditions can be classified into two fields: product cost and product compatibility. Since HCI has expressed the desire to have a design that is economically viable in the market, this means all other requirements also have to be taken into account, therefore a design method was chosen that includes a broad initial approach to find out the key problems for a viable design. The design method used is the method described in Engineering Design: A Systematic Approach, Pahl (2007). [1]

The method describes four steps to create a complete design:

Task clarification.

In the task clarification step, the design problem is investigated and analysed in all its aspects, in order to come up with a comprehensive requirement list. The requirement list creates a guide that can be used to steer the subsequent design steps.

Conceptual design.

In the conceptual design step one or more possible principle solutions to the design problem are created. The principle solution can be transformed into preliminary layouts and then be evaluated. The result is that the most promising principle solution can be chosen for further development.

Embodiment design.

In this step the conceptual principle solution and initial layout are evolved into a detailed layout and checked whether it fulfils the requirement list.

Detail design.

In this step the detailed layout is prepared for production. This step in the process is not part of the design project and is passed on as a future development step.

Results

The first step in the design process is the task clarification phase. To understand how the foldable container should work in the intermodal system, it is valuable to answer the question: are there comparable container types and how do they work?

The most common foldable container that is already on the market is the foldable flat rack container. This container is used to ship abnormal loads that don’t fit inside a normal container, but don’t exceed the container length. Since it is used for oddly shaped goods, it is not shaped like a box, but it only consists of a base and two end walls. Since abnormal loads are highly route depended, these containers are foldable so that on the return trip these containers can be shipped more efficiently. The ISO 1496 takes these types of container into account regarding the load cases they need to pass.

The only ISO foldable general purpose container on the market is the 4fold HC container from Holland Container Innovations. The foldable container has to be useable as a normal container when unfolded, in order to ensure product compatibility within the chain of operations. When the container is folded and combined as a bundle it once again needs to function as a normal container in the intermodal process.

A folding container can be described as successful if the following requirements are met:

- The unfolded container is identical in its interactions with the environment to a normal container.

    - These interactions are standardized in the ISO 1496-1 requirements for the container, which describe its loads and displacement.
- The folded stack of containers is identical in its interactions with the environment to a normal flatbed container
    - Related to this are the ISO 1496-5 requirements for the loads of a flatbed container.
- Every stakeholder in the transport chain needs something to gain from the use of a foldable container

The third requirement is hard to quantify, but HCI has translated this requirement into several company requirements. But in general it can be argued that the increase in COPEX and APEX of a foldable container needs to be offset by the savings that can be achieved in the intermodal process due to the use of container bundles, instead of empty containers.

HCI has proven that their folding container design for the 40ft high cube container meets these requirements. This is achieved by the folding method and the robustness of the design. Using the same folding method opens up a lot of possibilities for synergies between the 20ft and 40ft design as well as faster acceptation by other stakeholders, due to similarity with the already proven design. The 4fold folding mechanism is already known and used by multiple parties, therefore they already understand the time and effort it takes to fold the container. Using a similar folding method for the 20ft container would ease the adaptation of the new container. Therefore, at the end of the task clarification it was decided to explore the feasibility of the 4fold folding method for the 20ft design.

The first step was to envision if ‘chopping’ the 4fold design would result in a viable design. A simple experiment showed that the folding method would fit in the adapted 20ft design, but that the bundle height of four folded containers did not meet the height restrictions set in the requirements. However, since the folding concept itself is viable, it is not necessary to develop an alternative folding concept. A detailed execution based on the current folding concept will be the preferred design, since this will fulfil most of the requirements.

The critical design problem was identified to be the folded container height. The new 20ft design needs to meet the five to one bundle size. This translated to the main requirement that the folded container needed to be one fifth the height of a normal container. And so the embodiment design was envisioned to be a redesign of the 4fold design by redistributing the allowed height for each main component of the container. The assumption in this step of the process was that the reduction in height would be offset by the reduction in length of the container. This assumption was tested after the design was finished and the design stresses where calculated based on the ISO load cases.

The height reduction requirements let to several dimensional design problems in which the design needed to be altered in order to house the parts needed for the folding process. After the spatial design problems were solved, the design was evaluated based on the ISO requirements. The assumption that the height reduction would be offset by the length reduction was proven correct, since only one load case was not passed the first iteration round. This problem was solved and the second iterations showed all load cases where passed.

The hand calculations have shown that the design fulfils the ISO load cases. However, the calculations used simplified geometry and were done by hand. This combination means that there is a relatively large safety factor taken into account, to allow for a larger margin of error inherent to hand calculations. To reduce the margin of error, and in turn allow for a reduction in material to be used, the design can be made even lighter. This will require a full FEM analysis to verify that it still meets the ISO requirements. If less material can be used, the design will become cheaper. In addition, since the tare weight of the container is less, this will allow it to transport more or heavier load. Although the weight and cost requirements have passed for this design, improvements in these values will always benefit the viability of the design.

In conclusion, the design complies with all technical requirements but room for improvement for the design. The operational requirements outlined by HCI are assumed to have passed due to the use of the same folding method. Therefore, no model was built to test the folding method.

Discussion

The main research question for this design project was:

What is a viable design for a foldable 20ft container for HCI?

The focus here was on the word viable, which means that there is not just a technical design to be developed, but that there are more aspects that have to be considered. These aspects where outlined in the task clarification phase of the project:

- The unfolded container is identical in its interactions with the environment to a normal container.
- The folded stack of containers is identical in its interactions with the environment to a normal flatbed container.
- Every stakeholder in the transport chain needs something to gain from the use of a foldable container.

These three main criteria were broken down to a full requirement list, where all aspects of the design were taken into account. From the requirements it was found that it was preferred to use the same folding method as for the 40ft design, since all stakeholders are already familiar with this folding method. In addition, it makes more sense for a product family to employ the same working principle. It was shown in chapter 2 that this principle solution could fit within the geometric constraints of the 20ft design. It also showed that a simple adaptation would not fulfil the height requirement, and thus a number of parts had to be redesigned in order to come to a viable design.

The new design was evaluated on strength, and displacement, and it was compared against a regular 20ft container. From these calculations it was shown that it is identical in its interactions with the environment as a normal container, and folded as a flatbed container. However, for a few requirements it was not possible to show whether they were identical to that of a regular 20ft container; for instance for the water ingress test. In order to determine this, the design of the entire seal would first need to be finalized. This fell outside the scope of the main design. A prototype would have to be built to test this properly.

The last requirement is important because it determines the economic viability of the design. This is reflected in a number of technical requirements drawn up by HCI. The new design complies with these as well, as was shown in chapter 4. In addition, the bundle size, tare weight, construction cost and efficient folding process all fall within the defined boundaries.

In conclusion, since the new design of the 20ft foldable container complies with all requirements (that can be determined at this stage of the design process), it can be said that it is possible to design a viable 20ft foldable container, and that the design described in this report is a viable solution for HCI.

The design resulted in a set of technical parameters (5-1 bundle, and an own weight of 3000kg). With these parameters known, it could be possible to do research into the effect of bundled empty containers on the effectiveness of the intermodal transport system.

In general the following questions are interesting:

- Is there a reduction in overall TEU volumes dues to bundling of empty foldable containers?
- How do foldable 20ft and 40ft containers compare to 40ft 20ft crossdocking?

One of the key nodes and the most expensive in the intermodal system is the sea harbour node. By introducing folded containers, the following aspects can be investigated:

- Is it possible to reduce the quay time?

- Is there a reduction of temporary offloading on multi legged ship routes?

- Is there a shore based efficiency gains due to less empty transport?