Universitetet i Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program/specialization: Mechanical and Structural Engineering and Material Science/Mechanical Engineering	Spring semester, 2017 Confidential
Author: Finn Inge Røsholm	…………………………………… (signature of author)

Program coordinator/academic supervisor:

R.M. Chandime Ratnayake

External supervisor:

Samuel Bauer

Title of master's thesis:

Optimization of Elevator Guide System on Ships

Credits (ECTS): 30

Keywords: High-level assessment Concept development FEM-simulation Optimization Ship motion Guide rail Brackets	Number of pages: 73 + supplemental material/other: 45 Stavanger, 15.06.2017 date/year

Acknowledgment

This paper is written as a Master`s Thesis for the Faculty of Science and Technology at the University of Stavanger and in collaboration with thyssenrup Elevator during the spring of 2017. The main part of the study is conducted at the marine department of thyssenkrupp located in Ålesund, where the company provided both office space and expertise during the research period.

The academic supervisor for this project is Chandima ratnayake, who deserve a great deal of credit for establishing the company relation and for helpful input and support, operating as the university link. To the external supervisor Samuel Bauer, head of marine and offshore division in Norway, much obliged for identifying the issue as a suitable thesis and for executing the necessary arrangements, making the project possible.

Appreciation is directed towards Geir Hansen, general manager of thyssenkrupp Elevator in Norway, for approving the project. The utmost respect and gratitude is given to the entire marine department in Ålesund for exceptional treatment, superior guidance and a large amount of patience.

Finn Inge Røsholm

Abstract

The marine department of thyssenkrupp Elevator in Norway is looking for opportunities to optimize their installations for elevators on ships. Traditionally, their methods are based on the expertise from land-based installations, where the dimensions of the critical components are increased drastically in order to compensate for the potential impacts caused by the maritime conditions. In relation to this, there are reason to suspect over-engineering that effects both the weight and cost of the finished product. In order to get an installation certified, the system must be validated against the requirements for marine operations set by the notifying body. When the ship motions are introduced, the elevator components responsible for maintaining the structural stability is referred to as the Elevator Guide System. This system contains a set of guide rails that shall provide a sufficient support of the moving elements within the shaft and several brackets along the guide that connects the rail to the trunk wall.

An extensive study on existing standards and internal documents related to the issue is conducted in order to identify the essential requirements and how they relate to the application. Based on this research, the mathematical relationships are defined and applied for the appropriate components in order to develop an optimized method for sizing of the guide rails. In addition, a structural analysis is performed for the system, using two alternative constructions for the bracket solution. The alternative methods for executing the installation of the guide system are defined as four separate concepts that are assessed against the principles of complexity, risk and cost.

The analytic results reviled an applicable and highly effective method for sizing of the guide rails, where the optimal dimension within the requirements is suggested for any given project. The conducted FEM-simulation provided a sufficient validation for both bracket solutions against the applied worst-case load conditions that were identified. An estimation of the potential savings across the concepts for installation indicated a significant difference in expenditures related to the applied specifications on sizing method and bracket solution.

The assessment carried out in this study suggests that the concepts based on the traditional method of sizing should not be considered for future installations as the overall reduction potential indicates a substantial advantage of implementing the optimized method, which has been approved by DNV GL as an appropriate method for validation. In addition, the applied bracket solution can severely influence the installation time. However, the preferred bracket is only applicable for elevator trunks with smooth surfaces, which really is the case, as shipyards tend to locate the necessary stiffeners on the inside of the elevator shaft. To resolve this issue, it is recommended that thyssenkrupp establish customer relationships that allows for dialog and discussions regarding the installation related to the elevator specifications in the early stages of a project. In doing so, it should be possible to conduct certain arrangements so that the preferred bracket can be applied. In doing so, the opportunity of implementing the best possible solution for each individual installation should be made feasible.

Content

List of figures

List of tables

Acronyms & Symbols

ABS   :   American Bureau of Shipping

BRK   :   Bracket

CW   :   Counterweight

DNV GL   :   Det Norske Veritas Germanischer Lloyd

EGS   :   Elevator Guide System

GR   :   Guide rail

ISO   :   International Organization for Standards

LR   :   Lloyds Register

PL   :   Passenger lift

SL   :   Service lift

WoR   :   Weight on rope

a   :   Acceleration [m/s^2]

b_1 :   Guide rail width [mm]

c   :   Width of the connecting part of the foot to the blade [mm]

D   :   Depth of bulkhead [m]

E   :   Module of elasticity [GPa] (210)

e   :   Distance from the rear surface to the center of gravity of the guide rail [mm]

EUR   :   Euro [€] (9.3 NOK)

f   :   Width of the connecting part of the foot to the blade [mm]

F   :   Force [N]

g   :   Foot depth at its extremity in a transverse plane [mm]

g*   :   Gravity [m/s^2] (9.81)

H   :   Total height of mass [m]

h   :   Radius as height for centered shaft [m]

h_1 :   Guide rail height [mm]

I   :   Moment of inertia of the cross-sectional area of the guide rail [cm^4]

i   :   Radius of gyration [cm]

k   :   Blade width [mm]

l	:	Bracket distance [mm]
M_b	:	Bending moment [Nm]
n	:	Blade height [mm]
NOK	:	Norwegian kroners [kr]
P	:	Sum of car weights [kg]
q	:	Linear density for a finished guide rail [kg/m]
Q	:	Rated load [kg]
r_s	:	Foot radius [mm]
S	:	Cross-sectional area of the guide rail [cm^2]
T	:	Rotation angle [°]
V	:	Cross-sectional area modulus [cm^3]
W	:	Total weight on rope [kg]
Z	:	Effective height of mass [m]
δ	:	Deflection [mm]
θ	:	Period [s]
λ	:	Coefficient of slenderness
σ	:	Stress [MPa]
ω	:	Bucking factor

1. Introduction

As an increasing trend, shipyards are building there vessels with elevator trunks implemented in the design and the demand for elevator installations on ships is raising in the Norwegian marked. The company thyssenkrup Elevator is one of the leading supplier of lifts worldwide and their marine department in Norway is conveniently located in Ålesund with immediate proximity to the largest shipyards in the country. Historically, the department have been conducting projects for land-based installation, but is now directing their focus towards the marine industry.

When the elevator components are transferred from the steady land-based conditions and installed for the purpose of operating in marine conditions, a series of associated requirements appears, which must be fulfilled in order to obtain the structural stability of the components. In order to get a marine installation certified, the system must be validated and approved by a notifying body.

As a respectable, but relatively new supplier of marine elevators, thyssenkrupp is looking for research opportunities within this field in order to increase knowledge, optimize their products and stay competitive against more experienced suppliers.

1.1 Problem definition

As the marine elevators will be exposed to ship motion, a new specter of load cases is introduced in addition to the effects from the vertical travel, where the components are subjected to impacts in the horizontal direction as well. In this case, the components responsible for supporting the moving elements within the shaft must possess the structural abilities to withstand the resulting loads. These elements combined are referred to as the Elevator Guide System and is considered as the essential part in the installation with respect to the validation and certification of the elevator.

The existing design of this system is mainly based on the expertise from the land-based elevators, where the dimension of the components are increase drastically to compensate for the maritime load cases. Over-engineering is strongly suspected and the main objective of this research is to identify the main requirements set by the notifying body and process the information in order to develop an optimized solution for the system, reducing both cost and weight. In addition, the system must be validated in an appropriate mater so that the suggested solution can be certified and applied for the specific project.

In order to achieve this, an extensive study on existing standards and internal documents related to the topic must be conducted and set in system. Based on the findings, necessary mathematical relationships is to be defined and calculated accordingly. In addition, the structural ability of the system must be examined by performing FEM-simulations for the worst load cases established in the study. Based on the alternative methods for executing the installation of the system, a selection of different concepts shall be identified and reviewed through a high-level assessment with respect to the principles of complexity, risk and cost.

1.2 Constraints

Amongst the several certification societies within the industry, thyssenkrupp is making use of the services provided by DNV GL for the majority of the marine projects that are to be validated. As a consequence of this, the requirements set by this notifying body will be the main focus throughout the research.

When reviewing the Elevator Guide System, the parts that are to be evaluated in this study mainly includes the components that are directly influenced by the specific requirement and the internal products provided by the company. The remaining parts are considered as accessories and are assumed to perform in a sufficient manner as to what is intended.

The work related to the structural analysis of a system is considered to be quite complex and extensive, and in order to complete a sufficient evaluation within the research period, the number of different solutions are limited to a total of *two* separate constructions. These models are to be exposed to several load cases that will identify their structural abilities against the potential worst-case maritime conditions.

In order to produce a fair estimate of the potential savings, it is necessary to perform a series of assumptions and generalizations regarding the installation aspects. These simplifications are not intended to result in precise budgeting, but rather to provide a narrative indication on the potential cost reduction in relation to the choice of installation concept.

In an attempt to pass an objective judgement on the different concepts, a weighted screening is to be performed based on the individual performance against the principles of complexity, risk and cost, and the impact they may have on the installation process. In order to conduct such a screening, the more concise results retrieved in the research is to be combined with a series of estimations made in relation to the potential severity

The disposition in this report consists of five main parts reflecting the work performed in this research. Chapter *two* contains the documentation of the important factors that this study is based on. This includes the definition of the system components, the identification of rules and requirements related to the marine applications and installation specifications. Chapter *three* describes the structural methodology as to how the work is conducted, based on criteria for screening, process of evaluation and assumptions made for the estimations. In chapter *four*, the analytic results are presented in accordance to the processes described in the previous chapter. The discussion in chapter *five* is divided into two parts where a higher level assessment is conducted for the concepts before the general aspects of the research is discussed in greater detail. The main conclusions are drawn in chapter *six* and further recommendations are stated based on the research as a whole.

2. Documentation

The documentation for some of the important factors that influence the decisions made in this research are presented in this chapter.

2.1 State of art

For elevators on ships, it is common for the shipyard to provide the specified dimensions of the inbuilt trunk where the supplier can install the components of the elevator system. The system consists of complex structural, mechanical and electrical unites. For a typical traction elevator, the main components are illustrated in *Figure 1*.
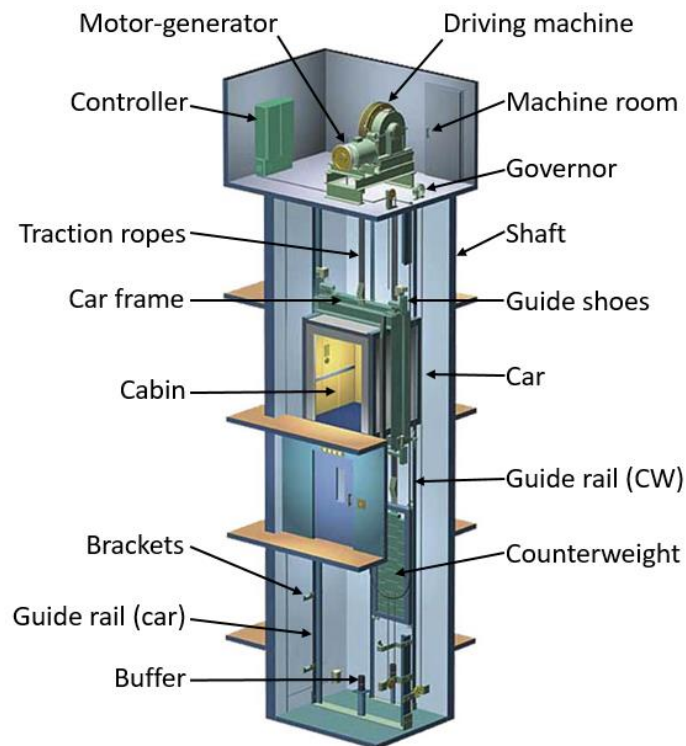
Figure 1 *Elevator Components [1]*

The cabin is placed inside a car frame which provides the supporting structure of the car. Multiple traction ropes are attached to a crosshead beam on top of the car and travels around a driving machine located in the machine room above the elevator shaft. The power needed to drive the elevator is generated by an electrical motor and contained by a controller system. In order to compensate for the weight of the car, a counterweight, which contains a steel frame filled with secured weight plates is connected at the other end of the traction ropes. The traction elevator can also be installed as machine room-less, where the complete traction system is connected and supported from a massive crosshead beam at the top of the elevator shaft. Various safety components are common to be included in the installation. Amongst these are the governor, which provides an emergency stop in case of increased velocity, and the buffers which function as dampers when contact occurs at the bottom surface.

An alternative to the traction elevator is a hydraulic solution, where the traction system is replaced by a hydraulic telescope cylinder, providing a vertical motion from below the car-deck. Common for both solutions is the *Elevator Guide System*, maintaining the positioning of the car within the shaft.

2.2 Elevator Guide System (EGS)

The system consist of several components and is installed on each side of the car providing guidance during the vertical travel. The intermediates are welded to the trunk wall and connected to one or two brackets in order to adjust the positioning of the T-shaped guide rails. *Figure 2* shows an example of how the EGS can be installed inside the shaft on a ship.
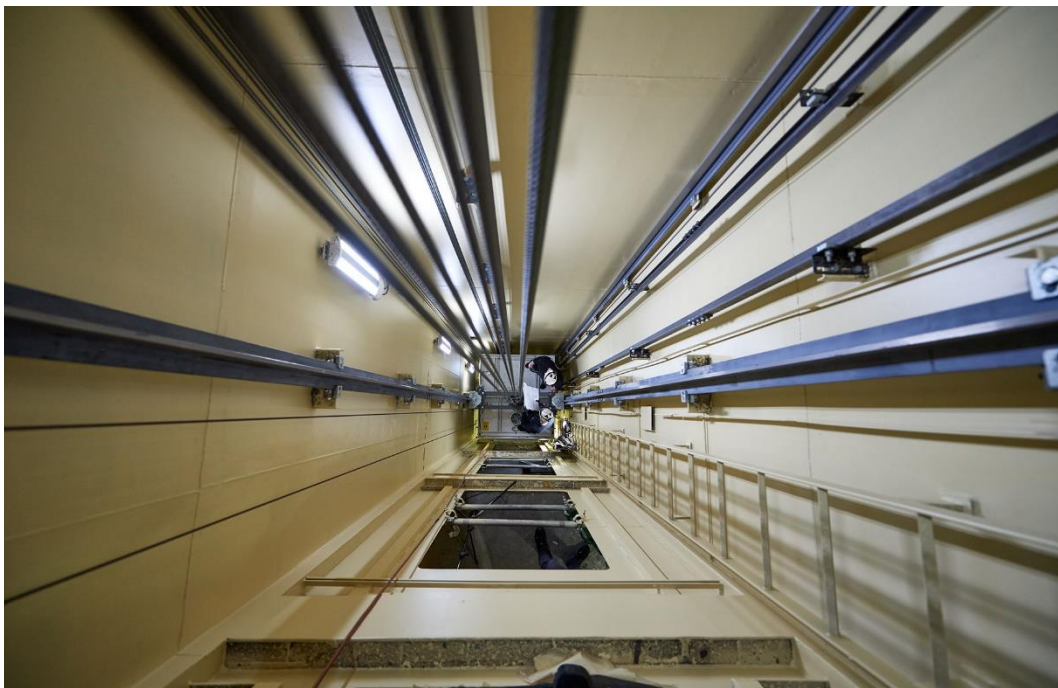
Figure 2 *Elevator Guide System inside ship shaft*

For vertical motion, the EGS is not exposed to loads, other than the weight of its own components, when normal conditions applies. For elevators installed on ships, the support system is subjected to both longitudinal and transverse loads when the ship motion is introduced. The car is connected to the guide rails through a total of four guide shoes (or roller guides) integrated at the top and bottom of the car frame at each side. The same principle is applied for the guide support of the counterweight. The EGS ensures a one dimensional elevator movement even when loads caused by the ship motion is applied.

The ESG is vital for any elevator shaft and plays an even bigger role in the event of marine use. It is important that the system is able to withstand the loads that can occur in challenging weather conditions, but both space and weight is a constant concerns for the shipyards and the arrangements on board can cause for difficulties regarding the installation. In order to avoid over-engineering, but still fulfill the rules and requirements, an extensive investigation of the EGS is required.

2.2.1 Guide rails

The EGS-component responsible for guiding the moving parts of an elevator in a vertical direction is the T-shaped guide rail, illustrated in *Figure 3*. These are standardized products with specific shape and dimensions that results in a broad range of rails with different properties and performance. Depending on the choice of dimension, this variety of component sizes may severely influence both the cost and weight of a single project.

Figure 3 T-shaped guide rail

Figure 4 shows how the elevator car can be connected to the EGS trough four guide shoes that slides vertically along the rails. For stationary installations, like most land based projects, the guide rails are usually not subjected to any significant strain during elevator travel. In this case, the sizing of rail dimension is mainly determined by its ability to carry the vertical lodes in case of an emergency stop. The T-shaped rail geometry possess a high tolerance for this load condition and the requirements are seldom problematic to preserve in these cases.
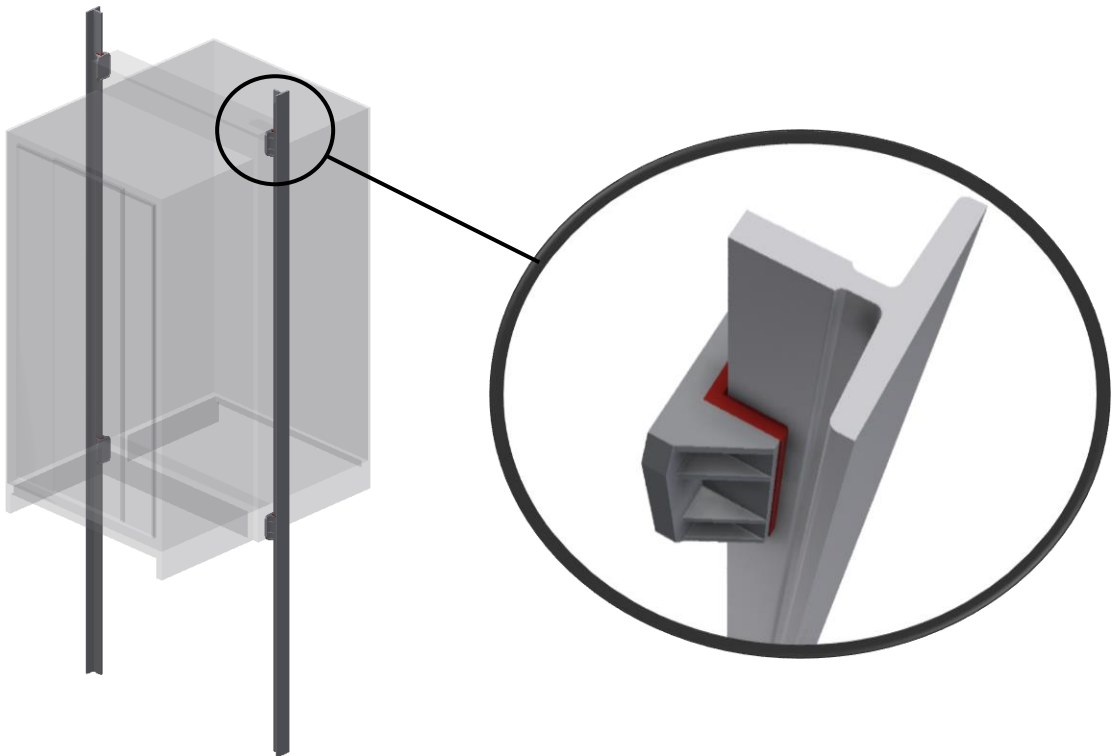
Figure 4 Guide rails supporting elevator car trough guide shoe connection

For elevators installed on ships, the evaluation process becomes more complex as the maritime guide rails, in addition to the vertical lodes, must fulfill the requirements to withstand rather large motions in both longitudinal and transverse direction. Depending on the elevator specifications, the resulting horizontal loads are often of grate magnitude and the strict tolerance area forces the supplier to install the EGS with massive components to ensure approval by the certification society.

The guide rails may be cold drawn or machined and are casted from liquid steel where the raw material should have a tensile strength between 370 MPa and 520 MPa. For this purpose, it is recommended, according ISO 630 [2], to use steel grade E 235 B for cold drawn rails and E 275 B for machined rails. After a semi-continues steel rolling process, the rails are cooled down before rough straightened in both horizontal directions. In addition, the guide rails are surface treated and should be cut in lengths of 5 meters before becoming a finished product.
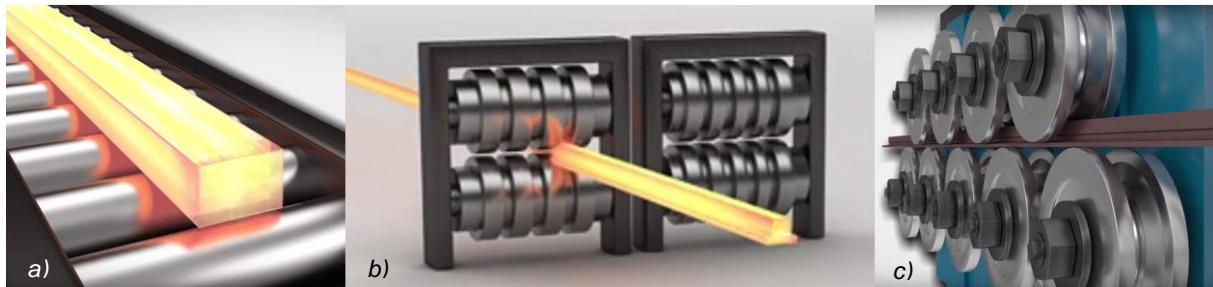
Figure 5 *Production process [3]; a) liquid steel casting, b) steel rolling, c) strengthening*

The manufacturers are to produce the guide rails following specific ISO-codes and with precise dimensions according to the values listed in *Table 1.* In this case, the codes are retained from ISO 7465 "*Guide rails for lift cars and counterweights*" [4], where the first letter, *T*, illustrates the rail shape. The second element of the code implies the foot width, b_1, and the last element suggests the manufacturing process, where */A* indicates cold drawn and */B* indicates machined guide rails. *Figure 6* shows a cross-section with indicators corresponding to the table values.

Table 1 *Guide rail dimensions corresponding with Figure 6 and according to ISO 7465*

Dimension (ISO-code)	b_1 [mm]	h_1 [mm]	k [mm]	n [mm]	c [mm]	f [mm]	g [mm]	r_s [mm]	e [mm]
T70/A	70	70	9	35	7,9	8,5	8,5	1,5	22,1
T82/B	82	68	9	26	7,5	8,3	6	3	19,8
T89/B	89	62	16	34	10	11,1	7,9	3	20,3
T90/B	90	75	16	42	10	10	8	4	26,1
T114/B	114	89	16	38	9,5	11,1	8	4	28,7
T125/B	125	82	16	42	10	12	8	4	24,3
T127/B	127	89	16	51	14	15,9	12,7	5	25
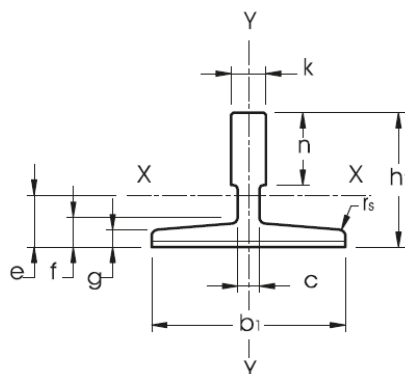
Figure 6 *Cross-section of a guide rail with indications corresponding with Table 1 [5]*

These geometrical differences makes for a huge variability regarding the weight and performance of the standardized rail dimensions. Based on the mass per meter, *q,* the products are divided into four classes, from light to massive, according to the color coding in *Table 2*. In addition, the geometrical properties for a given cross-section is essential for the sizing of the guide rails. The area, *S*, is used for determination of tension and shear, where as other properties are related to the affecting direction. These include moment of inertia, *I*, for rail stiffness, area modulus, *V*, for strength and radius of gyration, *i*, for compression. Any relationship between these properties is highly dependent on the geometry in question and established according to ISO 7465.

Table 2 Technical characteristics for guide rails according to ISO 7465

Dimension (ISO-code)	q [kg/m]	S [cm^2]	$I_{x\text{-}x}$ [cm^4]	$V_{x\text{-}x}$ [cm^3]	$i_{x\text{-}x}$ [cm]	$I_{y\text{-}y}$ [cm^4]	$V_{y\text{-}y}$ [cm^3]	$i_{y\text{-}y}$ [cm]
T70/A	8,83	11,25	52,81	10,79	2,16	24,62	7,03	1,48
T82/B	8,55	10,90	49,40	10,20	2,13	30,50	7,40	1,67
T89/B	12,38	15,77	59,83	14,35	1,95	52,41	11,8	1,83
T90/B	13,55	17,25	102,0	20,86	2,43	52,48	11,7	1,75
T114/B	16,40	20,89	179,3	29,70	2,93	108,6	19,1	2,28
T125/B	17,91	22,83	151,0	26,16	2,57	159,1	25,5	2,64
T127/B	23,18	29,53	198,8	31,10	2,59	229,6	36,2	2,78

Light	Medium	Heavy	Massive

The guide rail is in general the most crucial component of an EGS, but for elevators on ships maybe also the most influencing component all together considering both weight and functionality. The technical characteristics of each ISO-code results in individual performance criteria and is of major importance while designing the EGS for a marine project. Because of this, the orientation of the guide rails must also be considered in order to determine whether the component can withstand the loads in the determining direction.

By developing efficient and precise methods to determinate the optimal rail dimension for a specific maritime project, based on requirements and technical characteristics, the EGS could potentially be optimized to a great extent from the traditional massive installation and severely impact the quality and cost of the finished product.

Figure 7 Pack of guide rails ready for shipment from the factory [3]

2.2.2 Brackets

Connecting the guide rail to the trunk wall is a set of intermediate constructions containing the components known as the brackets. This part of the EGS exists in multiple shapes and versions, but with the sole purpose of holding the guide rail in the required position within the elevator shaft. A typical example of this can be seen in *Figure 8.* For elevators on ships, the bracket frames are welded to the trunk wall with an interval distance between 1.5 and 2 meters up along the shaft. By increasing the bracket distance, the number of components per shaft is reduced, saving both installation- and material cost. However, an increased distance will result in a decrease in the guide rail performance with respect to the stiffness and its ability to remain within the strict tolerance area. Because of this, the possibility of obtaining an optimal relation between the bracket distance and the guide rail characteristics could prove to be a great advantage in the optimization process.
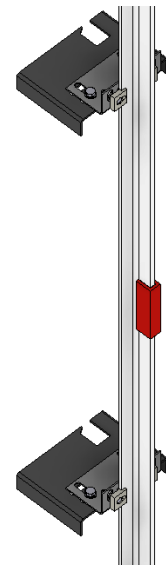
Figure 8 Brackets

Since there are no standardized regulations as to how the brackets are to be shaped or produced, the EGS supplier is responsible for validating whether the chosen bracket solution is suitable for a specific project. Similar to the evaluation of the guide rails, this process becomes more complex in maritime conditions where several load cases must be considered. Despite a wide selection of possible choices, only two different bracket solutions are considered in this research. This decision is based on company input in relation to previous experiences, current practices and future trends. The two solutions are composed by multiple components, where one of them represents a traditional and well known construction, whiles the other represents a flexible and more resent type.

Welded bracket solution

For marine elevators, the shipyards tends to place the wall stiffeners inside the trunk in order to save space. In doing so, the trunk walls are no longer smooth and challenges may occur for the bracket installation. Because of this, the regular practice in thyssenkrupp has been the use of a so called welded bracket with a carved space for the stiffeners. These brackets are customized to fit a specific shaft and produced by a local steel industry. This component is quite robust and constitutes the bottom part of the construction illustrated in *Figure 9.*
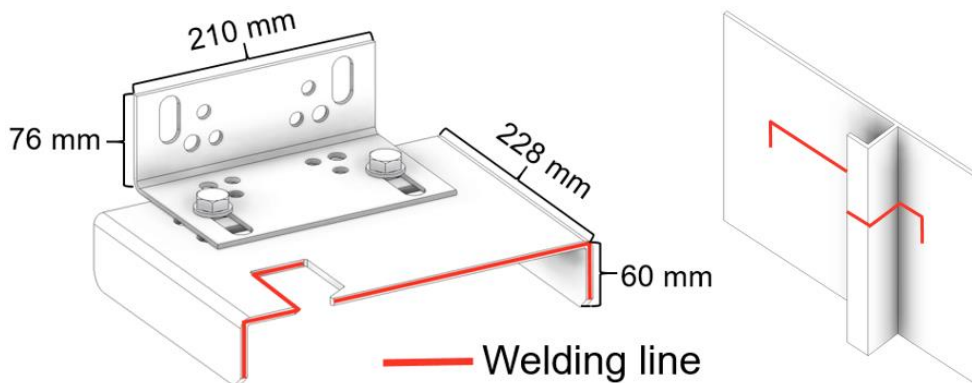
Figure 9 Welded bracket with indicated welding line to the trunk wall and stiffener

The top part of the construction is a mass produced component made by the company in Germany. This is the bracket that is directly connected to the guide rail and can be adjusted to some extend to fit the desired positioning. A series of holes are carved out in the plate so that the bracket is applicable for the various rail dimensions. With a thickness of only 4 mm, this component is deliberately constructed to deflect slightly in order to provide a somewhat flexible support. Through two bolts, this bracket is connected to the thicker welded bracket. This structure is extremely stable with an original thickness of 8 mm, which is unnecessarily thick. In case of future installations using this solution, the thickness is reduced to 6 mm in this research. A further reduction is not considered as this could influence the quality of the weld.

The actual welding is executed by the shipyard, but the installers from thyssenkrupp still have to perform the marking of the brackets. This process is known to be exceedingly time consuming and could drive the installation cost to a less lucrative level.

Adjustable bracket solution

The second solution contains the same upper bracket as in the welded solution. The bottom part of the construction is a bracket with the same shape, but twice the thickness. The reason for this is that the solution is intended to be fastened to a framing system and tightened with quite some magnitude through a set of bolt connections. If the plate thickness is too small, the material will yield under the pressure. This framing system is an external patent called Halfen, which is a simple concept that allows the bolts to slide in a horizontal direction along the rail until tightened. The idea behind this solution is to let the shipyard weld the Halfen rail to the trunk wall, so that the brackets can be applied in a simple and efficient manner. In addition, the method provides a fairly flexible solution in terms of adjustments. This system is illustrated in *Figure 10* where the Halfen rail and bolts are indicated as transparent parts.
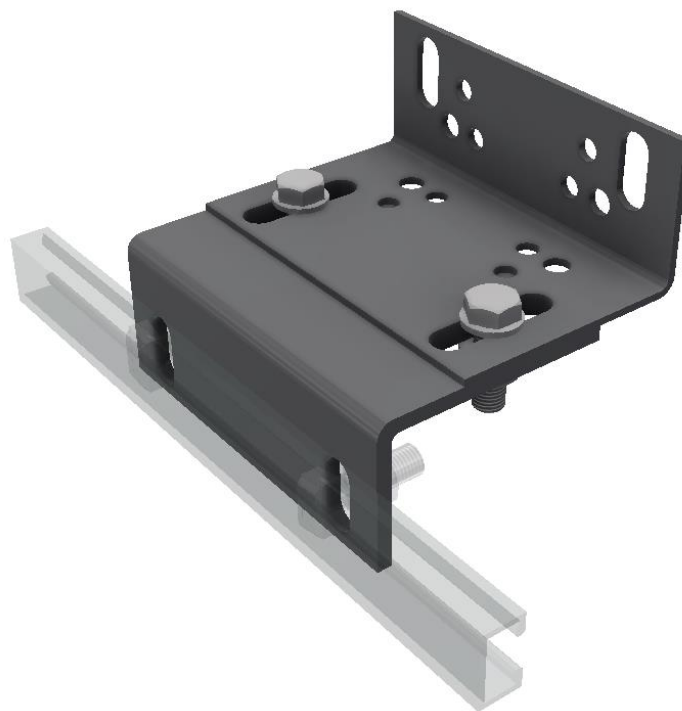
Figure 10 Adjustable bracket solution

The adjustable bracket solution is mass produced by the company in Germany and part of the standard elevator set that is delivered to the marine department in Norway. The drawback with this method is that the trunk should be smooth in order for the shipyard to install the Halfen rails according to thyssenkrupp`s specifications. As a result, this solution is considered less applicable for marine projects than the welded solution. However, this issue could be resolved by getting involved in the project from an early stage. If the necessary engineering is done before the trunk is built, thyssenkrupp can influence the structure by convincing the shipyard to install the stiffeners on the outside of the trunk, at least in the required bracket positions. In doing so, the advantageous can be quite significant, also affecting the shipyard.

2.2.3 Accessories

In addition to the guide rails and brackets, the EGS consist of several types of fasteners. These accessories serve specific purposes, ensures component connection, framing or support.

Figure 11 EGS accessories [3]

Halfen framing system

As mentioned in paragraph 2.2.2, the Halfen system is an external system implemented when the adjustable bracket solution is used. The concept contains a hollow rail with a unique form that allows the bolts with the same head form to slide sideways until tightened to the bracket. The rail is intended to be welded directly to the trunk wall, at specified locations, so that the installers from thyssenkrupp can mount the brackets in the shafts using only bolt connections. The ability to slide, together with the available adjustment options for the bracket solution, results in a larger tolerance in mounting errors.
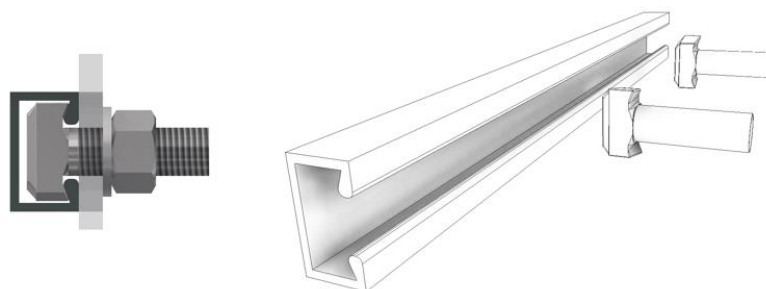
Figure 12 Halfen framing system and its components

Rail clips

Depending on the guide rail dimension, different versions of the component illustrated in *Figure 13* are used in the EGS to connect the rail to the bracket solution. These rail clips, or duck beaks, are tightened so that the foot width of the rail is pressed against bracket plate, but should not exceed such a pressure equivalent to withstanding a vertical lode grater 5000 N at each attachment, according to internal documents. This is because the system is designed to yield in seatrain conditions in order to allow for vertical deflection of the guiderail. A rail clip used for the T90/B guide rails is shown in *Figure 13,* which also illustrates how the rail is mounted to the bracket.
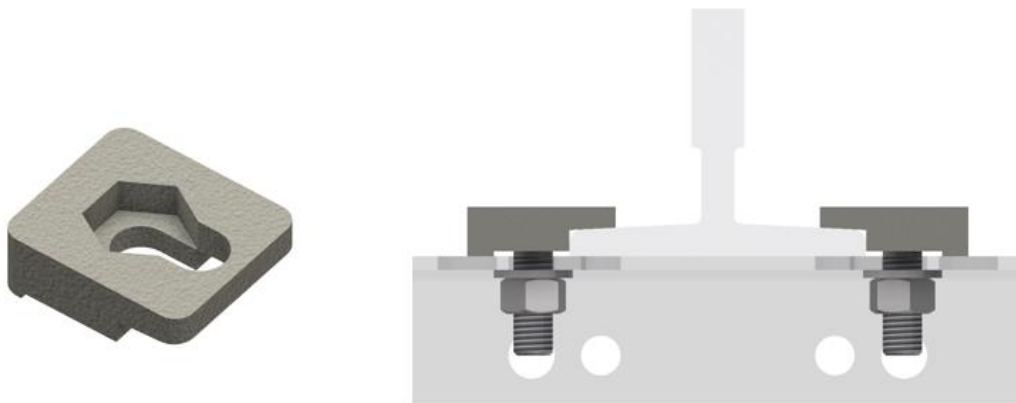
Figure 13 Rail clip and how it is implemented in the EGS, supporting the guide rail

Fish plates

The guide rails are often delivered in lengths of 5 meters and must be mounted together to act as one single component all the way from the top of the shaft to the bottom. To achieve this, a standardized component, known as a fish plate, function as an intermediate connection between the rails. The dimension of the fish plate depends on the on the guide rail and shall correspond to characteristic values specified in ISO 7465. These plates are quite massive and provides a sufficient amount of support to avoid reduced performance in the joint. *Figure 14* illustrates a fish plate used for the T127/B guide rail.

Figure 14 Fish plate

2.3 Rules and requirements

In order to get an elevator installed, documentation must be provided to the notifying body containing proof that the components are suitable for the operation in question. A vital part of this documentation is validating the performance of the guide rail for the specified load cases. Several rules and requirements are established by the standardization society and must be fulfilled in order to get a project approved by the notifying body.

In this contexts, the notifying body is an external organization certified to perform official approvals of installations or procedures across the industries for their customers. Within the maritime, oil & gas and energy industries the Norwegian organization DNV GL provides their services worldwide and their certificates is recognized as a proof of high quality. For installations performed by thyssenkrupp in Norway, the vast majority is certified by DNV. The requirements set by DNV is based on international standards, technical and operational experiences, risk methodology and industry knowledge. The interpretation on how to produce a satisfying proof of capability may differ from the various organizations, but the end result is usually in correspondence with each other. Because of this, the DNV requirements are used as the foundation to perform the necessary validations in this research. In addition, DNV`s methods tends to be the most conservative, which means that the requirements from other notifying bodies would most likely be fulfilled.

2.3.1 Buckling

For land based elevator installations, under normal conditions, the determination factor in order to get certified is the guide rail ability to tolerate the vertical force imposed during safety gear operations. In collaboration with experienced personal in the thyssenkrupp installation team, instantaneous safety gears with captive rollers are assumed for the elevators. This provides a conservative evaluation method, where the estimated lodes represents the force acting on each guide rail when a fully loaded car is stopped almost momentarily from a vertical fall.

$$F_z = 15(P + Q) \tag{1}$$

F_z	: Buckling force when safety gear with captive roller is activated [N]
P	: Sum of car weights [kg]
Q	: Rated load [kg]

The embedded factor of 15 in *Function 1* includes the consequence of gravity, as well as a small damping effect provided by the captive roller. This damping effect is important for elevators installed on ships in order to reduce the risk of possible damages if the rail were to act as a weight plunger on the pit and hull. According to DNV GL`s Rules for Lifts on Ships [6], this formula provides the buckling load that should be compared to the guide rail tolerance.
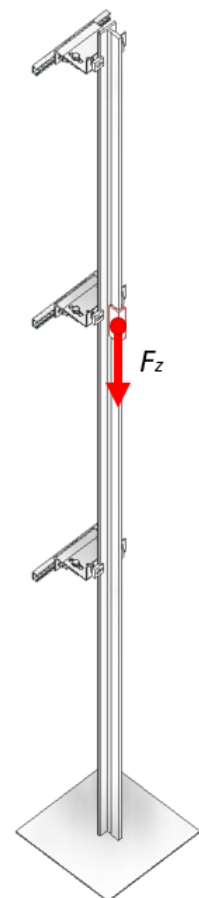
Figure 15 Bucklin load

The maximum allowable buckling force depends on the characteristic and material properties of the guide rail and standardized values retrieved from tables found in the DNV registry.

$$F_{z,max} = \frac{\sigma_k \cdot A}{\omega}$$

(2)

$F_{z,max}$	: Maximum allowable buckling force [N]
σ_k	: Allowable buckling stress [MPa]
S	: Cross-sectional area of guide rail [cm2]
ω	: Bucking factor obtained from DNV tables

The allowable buckling stress depends on the material quality and should not exceed its yield stress. For the buckling factor, a coefficient of slenderness must be determined in order retrieve the specific value. This coefficient is defined as;

$$\lambda = \frac{l}{i_x}$$

(3)

λ	: Coefficient of slenderness
l	: Effective buckling length (bracket distance) [mm]
i_x	: Radius of gyration corresponding to the x-x axis [cm]

Considering the specific load condition that occurs when the safety gear is activated, radius of gyration is set in relation to the x-x axis. This is because the rail is assumed to be bending around this axis when the captive roller grips the outer guide blade. Using the coefficient of slenderness, the buckling factor can be found from the DNV tables provided in *Appendix A*. Inserting the factor in *Function 2*, the allowable buckling force can be estimated and compared to the actual buckling force. Granted that $F_z < F_{z,max}$, the guide rail is suitable for the application. In most cases, the guide rails tend to be quite resistant to these lodes and small dimensions are often applicable. However, for guidance involved in passenger travel, dimensions below T90/B should not be applied. In doing so, extensive activity within the cabin could cause the EGS to exceed the allowable limit of deflection.
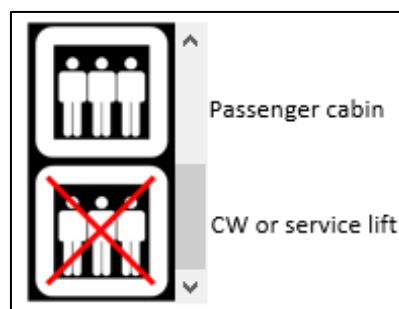
Figure 16 *Illustration: Guide application must be considered*

Even though this documentation may be sufficient for the evaluation of land based installations, it is merely considered as the foundation basis and bare minimum requirement when evaluating the EGS for a maritime installation.

2.3.2 Ship Motion

When maritime conditions are introduced, a new specter of load conditions are expected as the ship motion will influence the fixed shaft and accelerate the moving components. In order to estimate the resulting loads that are used to evaluate the EGS, it is important to establish how they occur and what impact it may have on the system. In accordance to *Figure 17,* the ship hull is assumed to be subjected to motion in six degrees of freedom with the origin from the where the ship is rotating, referred to as the rotation point.
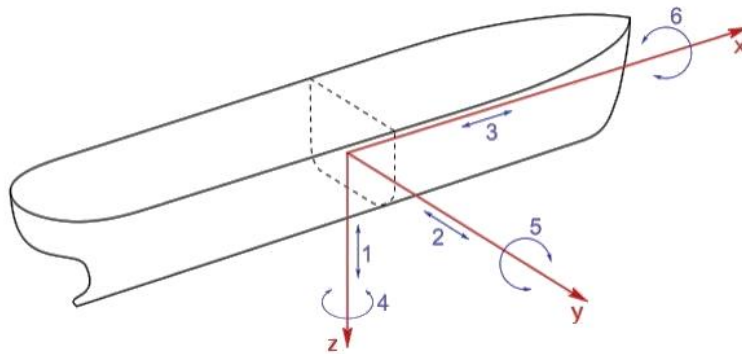
Figure 17 *Ship motion in six degrees of freedom [7]*

Degrees of freedom:

1) Heave: This represents an elevating motion along the vertical z-axis. Heave may occur whiles sailing in waters with big waves and can influence the vertical acceleration of the moving components within the elevator trunk.

2) Sway: If the hull side is exposed to crushing waves in the transverse direction, this motion could be perceived as a static stroke generating lodes acting on the guide rails along the y-axis.

3) Surge: For the motion parallel to the ship`s direction of navigation, a constant velocity will not impact the elevator components. However, when subjected to rolling waves in the longitudinal direction, the ship may experience sudden variations in the acceleration along the x-axis. This phenomenon is most common amongst smaller vessels and seldom an issue for larger ships.

4) Yaw: In special circumstances, he ship hull could be subjected to rotation around the z-axis. These motions are rarely of considerable magnitudes and will not affect the elevator components in particular.

5) Pitch: The magnitude of rotation around the y-axis of the ship is referred to as the pitch angle. Pitching is considered a common condition of maritime environments and the effect is likely to decrease with the overall boat length. For an elevator component, this rotation results in longitudinal acceleration corresponding to its height above the rotation point.

6) Roll: Rotation around the x-axis is known as roll and expected to produce the largest contribution to the to the ship motion. Roll produces acceleration in similar manner as pitch, but in the transverse direction and with an angle of grater magnitude. This is because the narrow ship width is more exposed to rotation around the rotation point.

Even though the ship motion in reality is influenced by several thermodynamic factors based on both maritime conditions and hull design, the only factors of interest are the specified rules and requirements set by DNV GL. This statement is based on the merits of optimizing the EGS according to the rules for certification of lifts in ships.

The resulting loads from the ship motion acting on the EGS originates from the acceleration of the moving mass inside the trunk. According to the standardization community, this acceleration is generated by the rotation around the ship`s rotation point and exclusively determined using the specified characteristics of pitch or roll. These characteristics consists of the rotation angel, θ, indicating the deviation from the vertical axis and the period, T, representing the time to for one complete fluctuation. In order to get an installation certified, proof must be provided that the system can tolerate specified requirements when exposed to lodes produced in these conditions. The standards distinguish between operating and stowed conditions, where the stowed requirements are quite conservative and most likely to be the determining factor.

Table 3 *Standardized requirements for roll and pitch in operating and stowed conditions*

Condition	Standard	Roll		Pitch	
		Rotation angle	Period	Rotation angle	Period
		θ	T	θ	T
Operating	DNV GL	±10°	10s	±5°	7s
	ISO 8383 [8]	±10°	10s	±5°	7s
	ABS [9]	±10°	10s	±5°	7s
	LR [10]	±10°	10s	±7.5°	7s
Stowed	DNV GL	±22.5°	10s	±7.5°	7s
	ISO 8383	NA	NA	NA	NA
	ABS	±30°	10s	±10°	7s
	LR	±22.5°	10s	±7.5°	7s
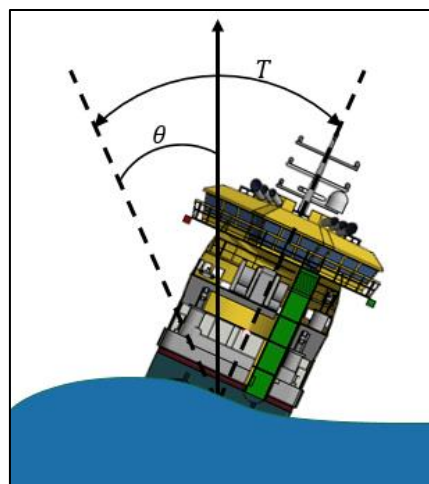
Figure 18 *Rotation angle and period for a rolling ship*

Table 3 lists requirements for the various conditions set by different standards. These specifications are based on historical experience, statistics and probabilistic calculations. Even though the expected motions in a ship lifecycle are completely individual depending on size, hull design or operating waters, the rules for classifications are the same for every project. For instants, an EGS in a huge cruise liner operating in the calm waters of the Southern Caribbean must be must be able to tolerate the same conditions as in a small supply vessel operating in the vast waters of the North Sea.

Assuming that an elevator shaft is placed directly on the rotational point of the ship, the acceleration normal on the EGS can be considered as equal to the tangential acceleration produced by the fluctuations. In accordance to *Function 4,* this is the magnitude the vertical and the respective horizontal acceleration.

$$a_{t,Roll} = \sqrt{a_y^2 + a_z^2} \quad and \quad a_{t,Pitch} = \sqrt{a_x^2 + a_z^2} \tag{4}$$

a_t : Tangential acceleration [m/s^2]
a_x : Acceleration in x-direction [m/s^2]
a_y : Acceleration in y-direction [m/s^2]
a_z : Acceleration in z-direction [m/s^2]

As an example, this relationship can be illustrated in *Figure 18* where a simulation for roll, with the period of 10 seconds, is performed in three intervals. The biggest contribution is in the horizontal direction, which also indicates the fluctuation cycle within the period. Combined with the vertical contribution, the resulting tangential acceleration peaks two times within the period, exposing the EGS for maximum load when the rotation angel is at its largest at each side.
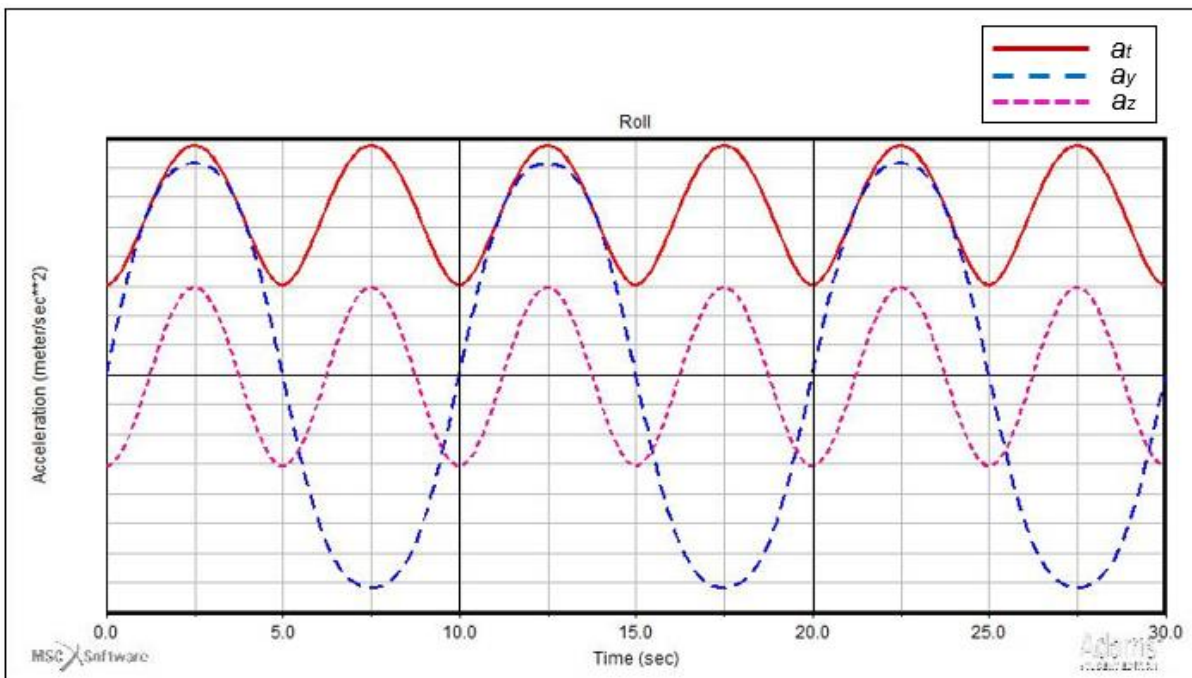
Figure 19 *Magnitude of acceleration from simulation with the period T=10 seconds*
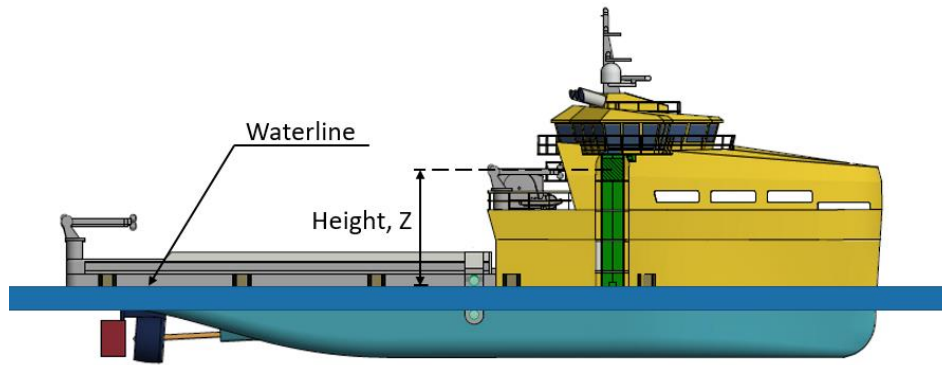
***Figure 20** Indication on how the height of the moving mass can be considered*

For the specified values of roll and pitch, the accelerations are determined by the height of the mass acting on the EGS. This height, *Z*, is illustrated in *Figure 20* and considered as the distance from the ship`s rotation line to the center of the cabin, when stowed in the top position of the shaft. The rotation line is set parallel to where the waterline crosses the horizontal floating ship and may vary depending the cargo and whether the ship is heavy loaded or not. As an estimate, this line is often assumed as half the depth of the bulkhead, *D*, which is the distance from the main deck to the bottom of the ship. The bulkhead depth is one of the key figures related to a specific vessel and should be provided by the shipyard on request. The effective height of the mass can therefore be defined according to *Function 5.*

$$Z = H - \frac{D}{2} - 1.5 \qquad\qquad (5)$$

Z	: Effective height of mass [m]
H	: Total height of mass [m]
D	: Depth of bulkhead [m]

The height of the mass is measured from the top position in the shaft in order to validate the system at the worst-case scenario, since increased distance from the rotation line results in increased acceleration normal on the EGS. *Figure 21* illustrates how the heights can be estimated for elevator shafts installed on a ships, where the center of mass is assumed to be approximately 1.5 meters below the deck floor.
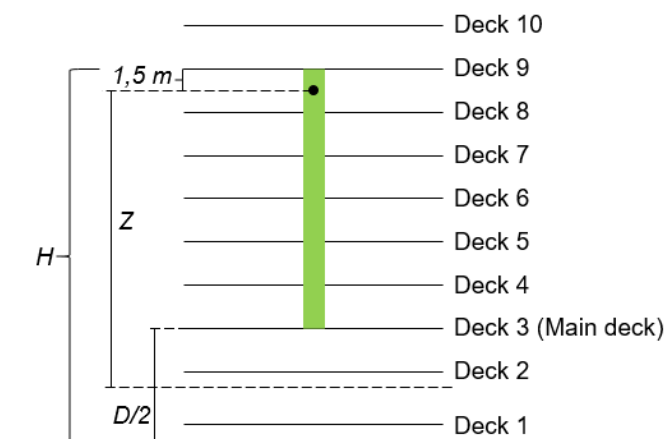
***Figure 21** Determination of height for ship elevators*

Based on the height, *Z*, and the pitch and roll requirements the acceleration acting normal on the EGS can be calculated using *Formula 6.*

$$a = \left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z \tag{6}$$

a   : Acceleration normal on EGS [m/s²]
T   : Fluctuation period [s]
θ   : Rotation angle [°]
Z   : Effective height of mass [m]

This equation does not take into account the possible offset in location from the rotational point of the ship. However, it is concluded in this research that the resulting tangential acceleration for an elevator shaft placed directly on the rotation point is equal to the acceleration acting normal on an offset elevator shaft. This conclusion can be supported by the illustration displayed in *Figure 22* and the following five-step proof.
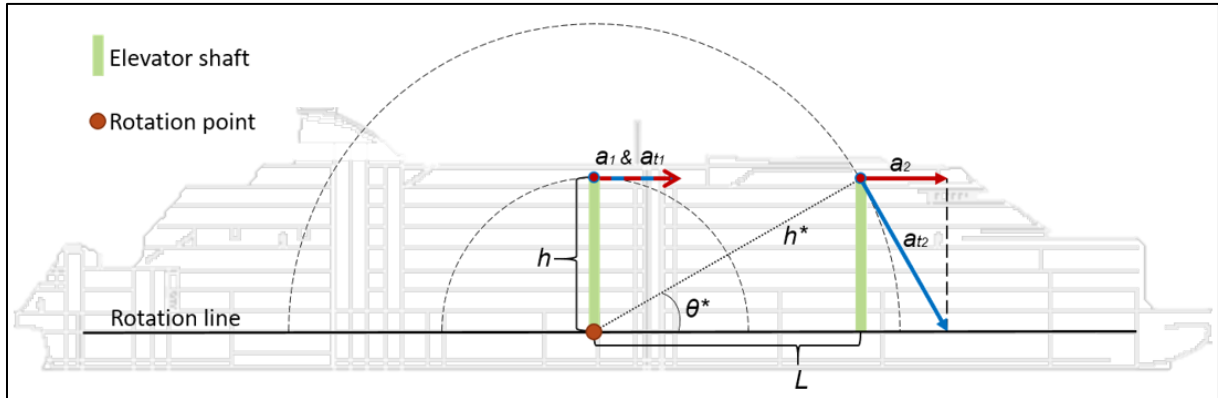
Figure 22 *Comparison of mass acceleration for centered and offset elevator shafts*

Step 1) $a_1 = a_{t1} = \underbrace{\left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi}_{a_{rad}} \cdot h = a_{rad} \cdot h$ (7)

Step 2) $a_{t2} = a_{rad} \cdot h^*$ (8)

Step 3) $h^* = \sqrt{h^2 + L^2}$ (9)

Step 4) $\theta^* = \sin^{-1}\left(\frac{h}{h^*}\right)$ (10)

Step 5) $\underline{a_2} = a_{t2} \cdot \sin(\theta^*) = a_{rad} \cdot \cancel{h^*} \cdot \frac{h}{\cancel{h^*}} = a_{rad} \cdot h = \underline{a_1}$ (11)

a	: Acceleration normal on EGS [m/s²]	*L*	: Offset length [m]
aₜ	: Tangential acceleration [m/s²]	*T*	: Fluctuation period [s]
a_rad	: Radial acceleration [rad/s²]	*θ*	: Rotation angle [°]
h	: Radius as height for centered shaft [m]	*θ**	: Angle of reference [°]
h*	: Radius as height for offset shaft [m]		

According to this proof, the determining acceleration can be considered as the tangential acceleration of a centered elevator shaft, determined in *Function 6,* and any offset positioning can be neglected in the optimization process.

A mass working in the direction normal to the guide rail also possesses an acceleration generated by its own gravity, a_g. The contribution of this acceleration depends on the size of the rotation angle, $θ$. Gravity pulls in the vertical direction, which means that the more horizontal the guide rail becomes, the greater magnitude of the of the load is working on the rail.
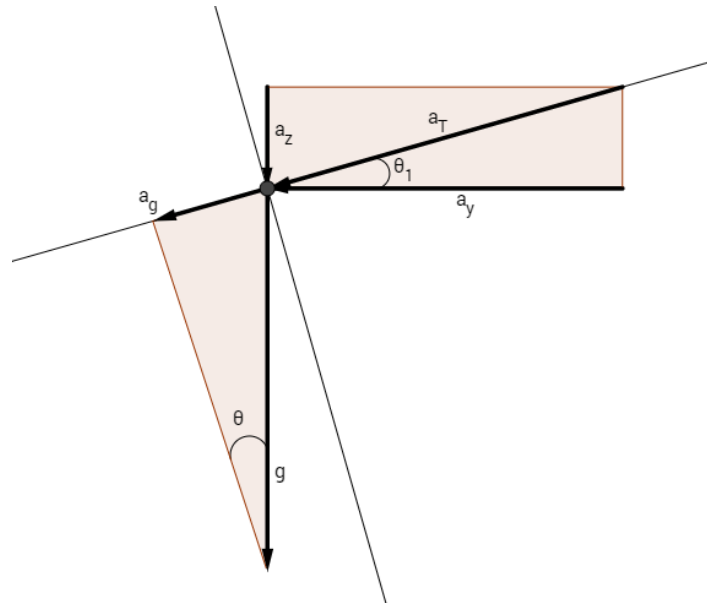
Figure 23 *Free body diagram of accelerations acting on a mass in rolling conditions*

In *Figure 23* a free body diagram is provided, illustrating how the accelerations may act on a mass influenced by the rolling ship motion. In order to determine the actual load working on the guide rail, the mass is multiplied by the sum of the normal acceleration contributions.

$$F = W \cdot \left(\underbrace{g \cdot \sin(\theta)}_{a_g} + a_t \right)$$

(12)

F	: Force from mass normal on the guide rail [N]
W	: Weight of mass [kg]
g	: Gravity [m/s^2]
θ	: Rotation angle [°]
a_t	: Tangential acceleration [m/s^2]
a_g	: Acceleration caused by gravity [m/s^2]

When the ship motion is determined, special load cases for the specific installation projects must be established in order to provide the proper validation of an EGS.

2.3.3 Load cases

The magnitude of the mass acting on the EGS is defined as the *weight on rope*. This is the total amount of the moving mass influenced by the acceleration acting normal on the guide rails. For an elevator car in operation condition, the estimated load is considered as the sum of bout the car weights and the rated load. In general, this is the equivalent of an elevator car with a fully loaded cabin, where the rated load, *Q,* should be based on the standardized relationships between available area and number of passengers listed by DNV in tables from EN 81-20 [11] presented in *Appendix B.* In stowed conditions, the cabin is assumed to be empty and the estimated load is considered as the weight of the car components only. Even though this results in reduced weight, the stowed load conditions are still assumed to produce the biggest loads considering the vast requirements for roll and pitch.

Weight, W = Total weight on rope
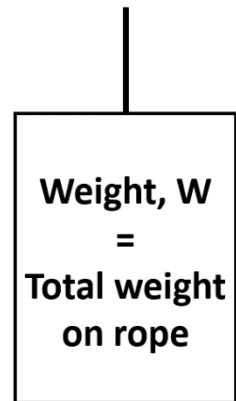
Figure 24
Illustration; Weight hanging from cable

The weight of the counterweight is usually set in accordance to *Function 13*. This weight is the same in both operating and stowed conditions and is therefore expected to produce the largest loads on the EGS.

$$W_{CW} = Q + \frac{P}{2} \tag{13}$$

W_{CW}   : Weight of counterweight [kg]
Q   : Sum of car weights [kg]
P   : Rated load [kg]

With respect to the guide rail, the determining loads are defined in two directions, normal on the x-x axis and normal on the y-y axis. This is illustrated in *Figure 25,* where the force acting on the rail is generated by the direction of the moving mass, through the connected guide shoe. Since the frame of the car and the counterweight is connected to guide shoes at both the top and bottom, the analytical weight used to determine the load is considered as half the total weight on rope.
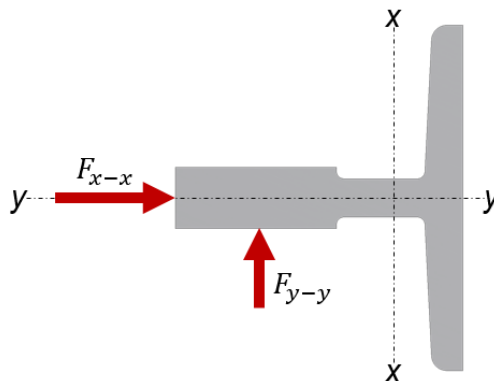
Figure 25 *Force on guide rail*
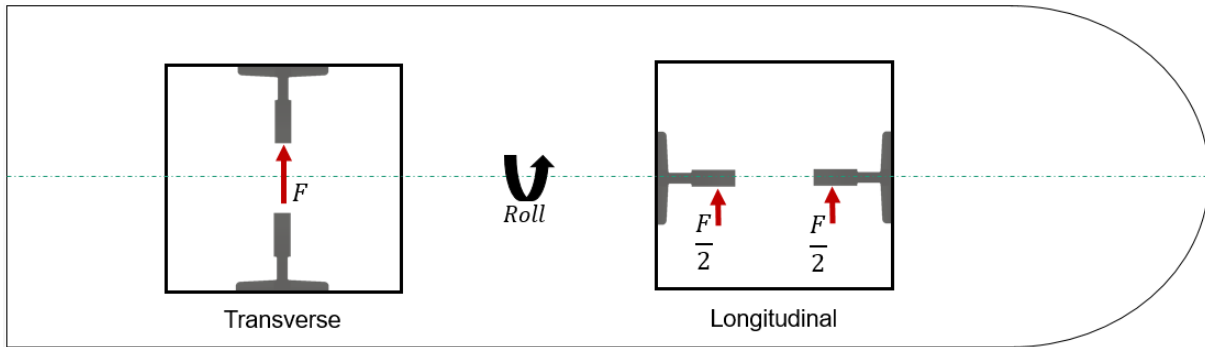
Figure 26 Positioning of guide rails in ship and acting forces during roll

Depending on the direction of rotation, the positioning of the guide rails in relation to the hull must be considered. The rails provide support on both sides of the mass, which means that a load acting normal on the y-y axis of the rail is distributed by the two, whiles one rail carries the entire load when normal to the x-x axis. For pitching, load is normal on the x-x axis when the guide rails are oriented in the longitudinal direction and normal on the y-y axis when oriented in the transverse direction. For rolling, the opposite applies according to the illustration in *Figure 26*. Considering the orientation of the guide rails and following the specifications for the roll and pitch requirements, the determining force can be calculated using *Function 14* and *15*.

$$F_{x-x} = \frac{W}{2}\left(\sin(\theta) + \frac{1}{g} \cdot \underbrace{\left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z}_{a} \right) \tag{14}$$

$$F_{y-y} = \frac{W}{4}\left(\sin(\theta) + \frac{1}{g} \cdot a \right) \tag{15}$$

F_{x-x}	: Force related to the x-x axis [N]	T	: Fluctuation period [s]
F_{y-y}	: Force related to the y-y axis [N]	g	: Rated load [kg]
W	: Total weight on rope [kg]	Z	: Effective height of mass [m]
θ	: Angle of rotation [°]	a	: Acceleration normal on EGS [m/s^2]

For guide rails, the worst load case is considered to occur when the force is acting in the middle between to bracket supports. In this case, the force is evenly distributed between the brackets and the reaction force is divided by two according to the principle illustrated in *Figure 27*. This results in the largest bending moment, which can be found using *Function 16*. It should also be noted that the relative length is defined as half the bracket distance, *l*.
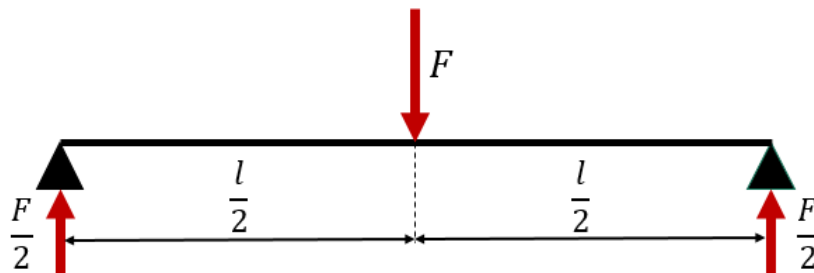
Figure 27 Force on guide rail centered between two bracket supports

Following these simple principles of beam theory, the maximum bending moment can be calculated in accordance with *Function 16.*

$$M_b = \frac{l}{4} F \tag{16}$$

M_b : Bending moment [Nm]
F : Force on guide rail [N]
l : Bracket distance [mm]

After establishing the maximum bending moment, the actual guide rail stress is determined by the characteristic cross-sectional area modulus, *V,* related to the load direction, for the specific ISO-code.

$$\sigma = \frac{M_b}{V_{x-x}} \qquad or \qquad \sigma = \frac{M_b}{V_{y-y}} \tag{17}$$

σ : Guide rail stress [MPa]
V_{x-x} : Cross-section area modulus related to the x-x axis [cm^3]
V_{y-y} : Cross-section area modulus related to the y-y axis [cm^3]

The stress found for the specific load case is compared to the yield stress of the material. If the established stress is less than the yield stress, the criteria should be approved by the notifying body. A measure taken in this research, with regards to safety factors, is the implementation of a stress factor of 0.8 for cold drawn guide rails and 0.68 for machined. The allowable stress in this optimization process is therefore set according to *Function 18.*

$$\sigma_{all} = 0.8 \cdot \sigma_{yield} \qquad or \qquad \sigma_{all} = 0.68 \cdot \sigma_{yield} \tag{18}$$

σ_{all} : Allowable stress [MPa]
σ_{yield} : Yield stress [MPa]

For machined guide rails in particular, this is quite conservative in the merit of validating a specific stress case and results in a rather large margin for error.

Another criteria to be fulfilled in the validation of the guide rails is the strict requirement related to the deflection. The geometrical and material properties contributes in determining the magnitude of deflection for the direction in question. Allowable deflection is set to a maximum of 3 mm, which is generally considered as a rather strict criteria. Because of this, no additional safety factor is included in *Function 19*, when validating the requirement for deflection. In this relationship, the bracket distance, *l,* is stated in the power of three and will severely influence the result. Therefore, this factor is of vital importance in the optimization process.

$$\delta = \frac{F \cdot l^3}{48EI_{x-x}} \qquad or \qquad \delta = \frac{F \cdot l^3}{48EI_{y-y}} \tag{19}$$

δ : Guide rail deflection [mm]
I_{x-x} : Moment of inertia related to the x-x axis of the guide rail [cm^4]
I_{y-y} : Moment of inertia related to the y-y axis of the guide rail [cm^4]
E : Module of elasticity [Gpa]

2.3.4 Material

According to ISO 7465, it is recommended to use steel grade E 235 B for cold drawn guide rails and E 275 B for machined rails. There are no further specifications as to what material should be used for the brackets and the associated accessories. For the purpose of validation in this study, regular construction steel of grade E 235 B is considered for these components.

Depending on the component thickness, the steel grades provides different yield strengths. This is because of the material properties developed during heat conduction when cooled down in the production process. For increased thickness, the cooling process slows down, which results in reduced yield strength. This relationships are listed in *Table 4* in accordance with ISO 630.

Table 4 *Yield strength of steel grade depending on thickness*

Thickness [mm]	Yield strength [MPa]	
Interval:	Steel grade E 235 B:	Steel grade E 275 B:
t < 16	*235*	*275*
16 < t < 40	*225*	*265*
40 < t < 63	*215*	*255*
63 < t < 80	*215*	*245*
80 < t < 100	*215*	*235*
100 < t < 125	*195*	*225*

A generalization is made for the guide rails studied in this research, where the material strength is considered as the yield strength corresponding to a thickness between 16 and 40 mm for the two steel grades. For the evaluation of the brackets and accessories, all components are less than 16 mm thick and assumed to perform according to the steel grade indication. For the evaluation of the guide rails, the material factors of 0.8 and 0.68 are applied before defining the allowable stress. These specifications are listed in *Table 5,* where the allowable stress is the determining values used in the evaluation process for the various components.

Table 5 *Component stress*

Components	Material	Yield strength, σ_{yield}	Allowable stress, σ_{all}
Machined guide rails	*E 275 B*	*265 MPa*	*180 MPa*
Cold drawn guide rails	*E 235 B*	*225 MPa*	*180 MPa*
Brackets and accessories	*E 235 B*	*235 MPa*	*235 MPa*

2.4 Installation and product specification

In order to carry out a representative and concise estimate of the potential savings related to the optimized solutions, an assessment of the installation process must be conducted based on internal benchmarking, such as experience, industry knowledge and a series of assumptions made from educated guesses. In addition, some regular expenditures and fixed rates can be established for the assessment.

For the comparison of the concepts assessed in this paper, three different sizes of guide rails are considered. In *Table 6,* the cost and weight for these products are listed, where the prices are retrieved from internal sails papers in thyssenkrupp and the weights are determined by the technical characteristics listed in *Table 2*. These three dimensions are chosen because the massive T127/B rail is considered as the most commonly used dimension in the traditional installation concept, whereas the T90/B and T70/B, based on external benchmarking, are considered as possible alternatives in the optimized installation concept. The values apply to the five meter long products provided by the manufacturer.

Table 6 *Cost and weight for spesific guide rail products à 5 m*

Product cost and weight for guide rails		
Dimension	Price	Weight
T127/B	*257 €*	*116 kg*
T90/B	*154 €*	*68 kg*
T70/A	*68 €*	*44 kg*

An important factor, severely influencing the actual installation cost, is the hourly rate of the thyssenkrupp technicians. For installing the EGS in an elevator shaft on a ship, a considerable amount of work hours is expected, especially when the welded bracket solution is applied. In *Table 7* the hourly rate provided by the company is specified in both NOK and EUR.

Table 7 *Hourly rate for technicians during installation*

Cost pr. technician (hourly rate)	
NOK	EUR
700 kr	*75 €*

3. Structural methodology

This chapter contains the identification of the methods used to assess the concepts investigated in this report, as well as a description of the various validation processes developed during this study.

3.1 Screening criteria

Considering the components discussed in the in previous chapter, two concepts with separate bracket solutions are investigated in this research. An extensive analysis of both structural abilities and installation expenditures is conducted in order to provide a thorough and objective assessment of the different solutions illustrated in *Figure 28* and *Figure 29.*
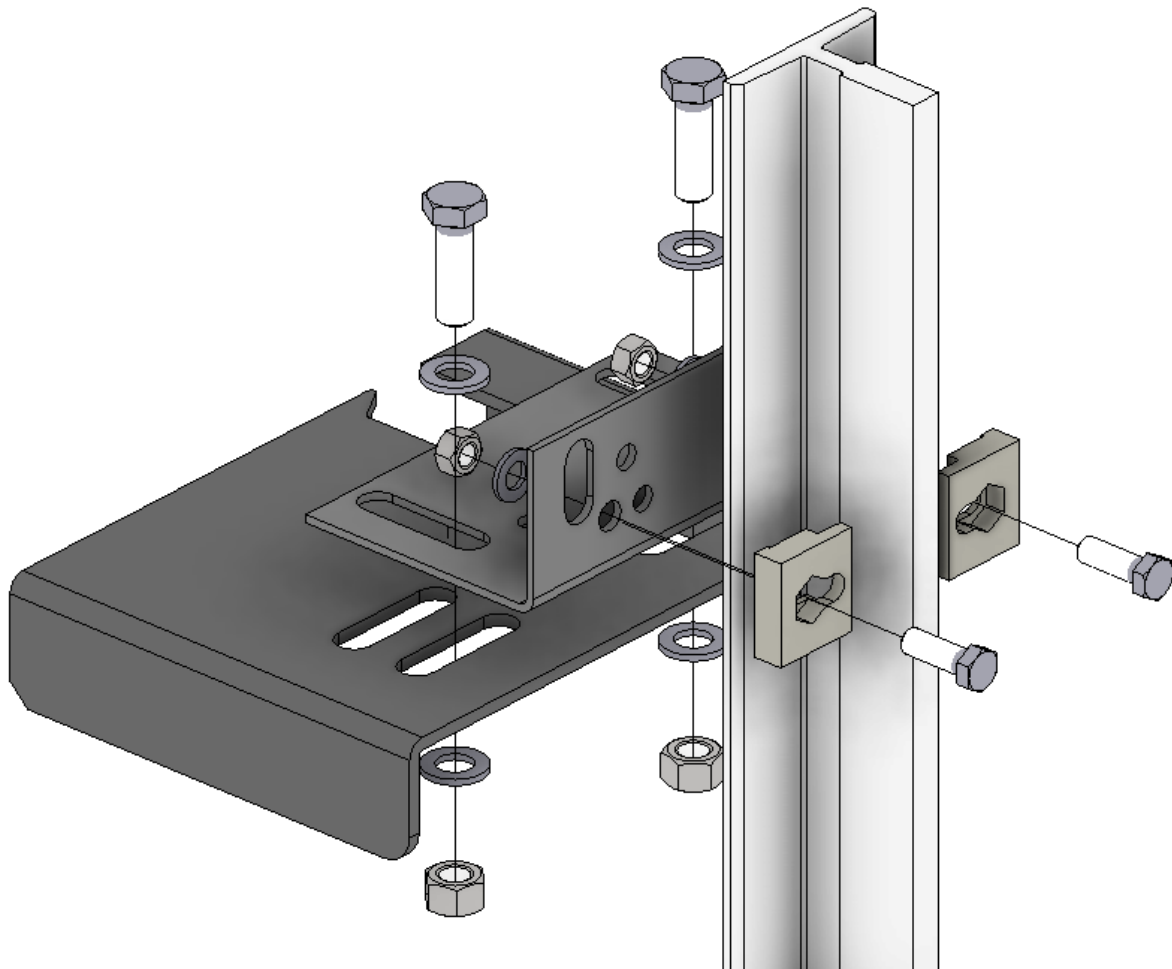
Figure 28 Exploded view of the welded bracket solution
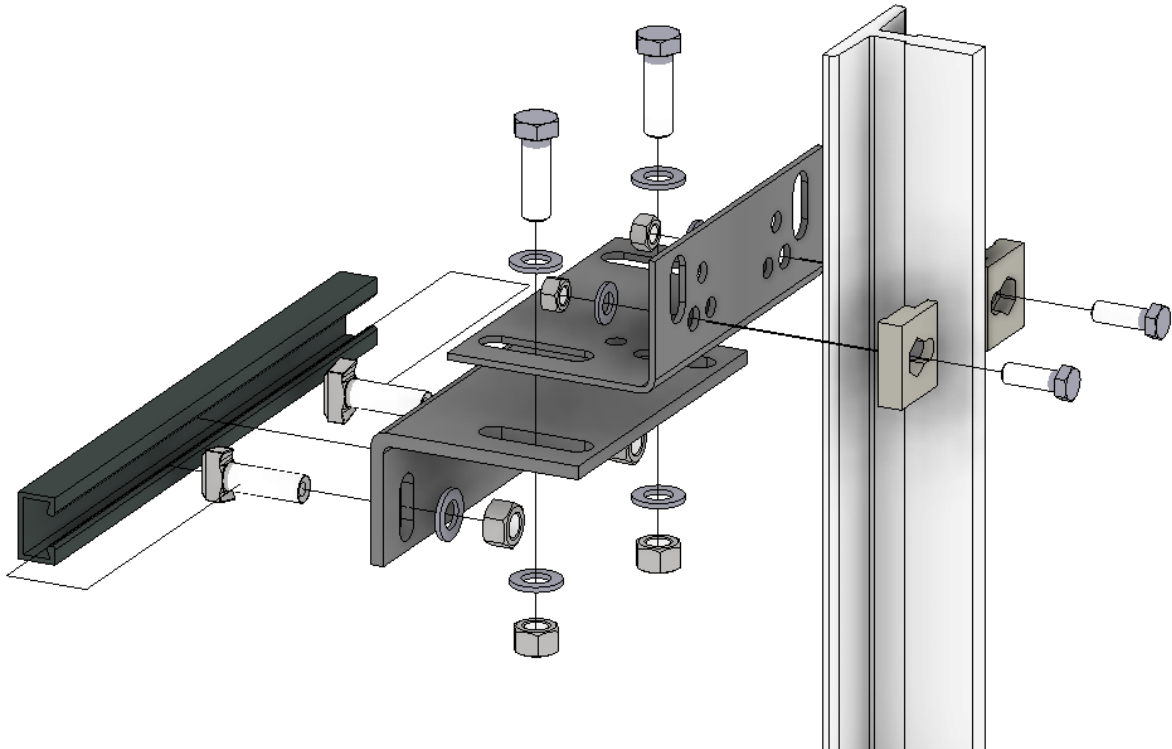
Figure 29 Exploded view of the adjustable bracket solution

In addition, the two solutions will be considered with the implementation of both the traditional and the optimized sizing method. As a result, this amounts to a total of four different EGS-concepts, which are listed in *Table 8.*

Table 8 EGS-concepts

Concept 1:	Concept 2:	Concept 3:	Concept 4:
TRADITIONAL WELDED	**TRADITIONAL ADJUSTABLE**	**OPTIMIZED WELDED**	**OPTIMIZED ADJUSTABLE**
Welded bracket	Adjustable bracket	Welded bracket	Adjustable bracket
Traditional sizing		Optimized sizing	

With regards to the concept criteria, the assessment is based on three screening principles; complexity, risk and cost. This in order to highlighting the various aspects related to the solution in question.

The principle of complexity is determined by the concept feasibility regarding implementation capacity, resources and technical complications. For elevators installed on ships, this can be related to the installation time, whether the stiffeners must be removed or the possibility of reducing the weight on board. The risk is tied to the actual performance of the EGS- concept, whether there could be potential harm to people, as well as the likeliness of asset damage and the severity a technical failure might cause. As long as the minimum requirements for certification is fulfilled, the overall impression of a concept is often determined by the final cost, which is most likely to be the major driving principle in a selection process.

3.2 Evaluation process

Traditionally, the internal EGS evaluation process within tyssenkrupp has been conducted using two methods of determination. When the company is asked to install elevators on a specific marine project, necessary information is retrieved from the shipyard and applied in an internal data base used for evaluation of land-based elevators according to the specifications discus in section *2.3.1* for buckling. This is the first stage in the process, where a minimum criteria for the guide rail dimensions are determined and the marine applications are yet to be applied. This starting point often suggests quite lean dimensions for the project, but history shows that these sizes seldom are considered for further evaluation by the engineering department in Neuhausen who is conducting the calculations. For the second stage of the process, massive dimensions are usually chosen for the system when marine applications are applied. However, the determination of the size for the guides supporting the counterweights are usually less conservative. A possible explanation for this can be a misinterpretation of the DNV requirements related to the application of rated load during stowed conditions. An example of a real project validation is attached in *Appendix C*, where a suggested solution is already established before validated against the requirements to withstand the ship motion stated in DNV GL`s rules for lifts on ships. For these traditional solutions, the bracket distance is generally set to a maximum of 1500 mm when validated, even when calculation results indicates larger capacity. As a result, greater distances cannot be considered, since the system is not validated for this. Also, shorter distances than 1500 mm is not desirable and should be avoided, as this would complicate the installation process and aggravate the end product.

In an attempt to avoid over-engineering, the traditional evaluation process is put under review and possible optimization methods are investigated through an extensive study on the topic, where the main focus is directed towards the specific rules and requirements needed to certify the EGS. An important aspect of this research is also to provide a streamlined method for conducting the entire evaluation process of the system. Instead of evaluating a suggested solution for the EGS, the objective of an optimized method is to generate several options with indicated performance, based on the specified parameters provided by the customer. Ultimately, the intention is to develop a tool that requires a minimum amount of input to generate the optimal solution for a specific project that is guaranteed to be approved by notifying body. If succeeded, this will provide an efficient and precise method applicable in the process of evaluating offers and with the potential to severely reduce costs and improve quality. The evaluation process related to the EGS mainly concerns the sizing of the guide rails and the determination of the bracket distance, but in order to apply the desired solution, a validation of the brackets must be conducted to ensure that they can provide the necessary support to the fully loaded guides. However, ones the brackets are sufficiently validated, the process does not have to be repeated, whiles the sizing of guide rails is a continuous process, as the parameters may vary for every EGS.

3.2.1 Sizing of guide rails

The first step in optimizing the process is developing a more transparent system, providing evaluation for a variety of different rail dimensions at the same time. The user should be able to insert the desirable parameters, depending on the elevator specifications and the requirements related to the loaded condition in question. In distinguishing between the loads acting on the x-x axis and the y-y axis of the guide rail, one can established the orientation of the guides by inserting the requirements for roll and pitch with respect to the indicated working direction. In doing so, the resulting parameters should be given for both roll and pitch in accordance with the chosen load case and the desired bracket distance. For manual sizing, the user should also be able to evaluate the guide rails for both operating and stowed conditions, or even alter the input completely for experimental or alternative purposes. For the purpose of validating the guide rails, the relationship between the parameters must be set according to the formulas presented in section *2.3.3* for load cases. Such a relationship was developed and obtained using the calculation software Mathcad Prime 2.0 and can be seen in *Appendix D*. These calculations are implemented in an exclusive calculation tool specifically developed for manual sizing of guide rails. This method is approved by DNV through the mail correspondence provided in *Appendix E*. Using Excel as the foundation, the tool produces values for the desired output parameters and indicates the safety factor against the tolerance for certification. Results validated according to the requirements discussed in this paper, will be valid for the DNV certification as long as the worst-case scenario indicates a satisfying safety factor for the rail dimension in question.
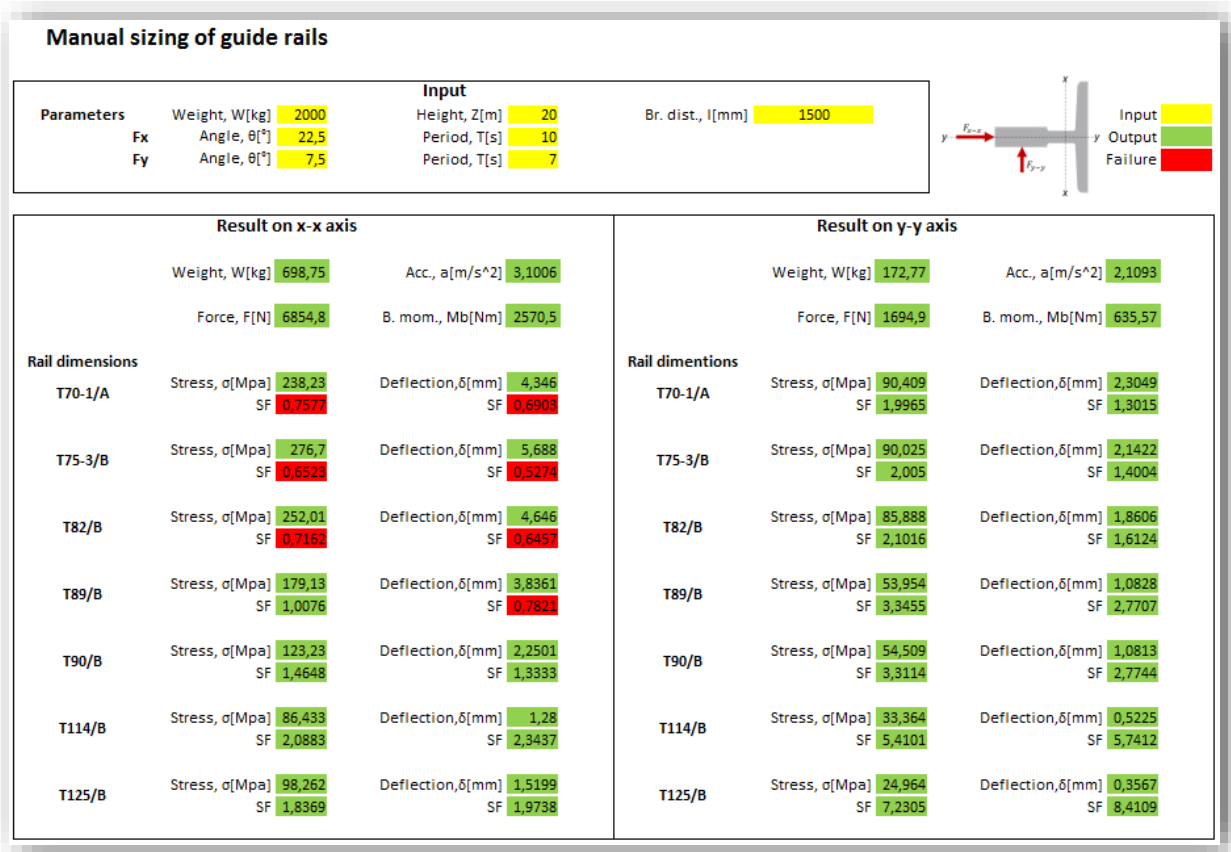
Figure 30 *Interface of the manual calculation tool*

Figure 30 illustrates the interface of the manual calculation tool and how it may be utilized. In this typical example, the weight on rope is set to 2000 kg and the height, which indicates the distance to mass, is set to 20 meters. In the manual sizing, a desired bracket distance is part of the input and in this example set to 1500 mm. Furthermore, the requirements for rolling are set in relation to the x-x axis on the rail and to the y-y axis for pitching. This means that the guides are oriented in the transverse direction on the ship. This concludes the input specifications of the color coded sheet with following indications.

Input:	The yellow cells allow the user to insert desired conditions.
Output:	The green cells display the resulting mathematical relationships.
Failure:	The red cells indicate failure to fulfill specific requirements.

Results are displayed for bout load direction in the manual calculation tool. The net weight, acceleration, force and bending moment acting on the respective guide rail axis are obtained in accordance with the calculations provided in the attached Mathcad file and displayed as common factors for the rail dimensions. The results separating the rail dimensions are the distinctive stress and deflection calculations. Included in these formulas, *Function 18* and *19* respectively, is the technical characteristic for the individual ISO-codes. Also, these factors determine whether a guide rail is suitable for the defined load case. If these values exceed the allowable tolerance, the safety factor drops below *one* and indicates failure. For the case illustrated in this example, a rail dimension of T90/B should be suitable for the application.

The parameters are set accordingly to the properties listed in the *Acronyms and Symbols*, but can be changed in the program settings.

Figure 31 *Various rail dimensions [12]*

T90/B - Maximum distance between brackets [mm]

Weight [kg]	Height [m] 8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	2912,42	2854,53	2800,98	2751,24	2704,85	2661,45	2620,7	2582,33	2546,12	2511,86	2479,37	2448,5	2419,11	2391,09	2364,31	2338,7	2314,17	2290,63	2268,02	2246,28	2225,35	2205,17
600	2740,69	2686,21	2635,82	2589,02	2545,37	2504,52	2466,17	2430,07	2395,99	2363,75	2333,18	2304,13	2276,47	2250,1	2224,91	2200,8	2177,71	2155,56	2134,29	2113,83	2094,13	2075,15
700	2603,42	2551,67	2503,81	2459,34	2417,88	2379,08	2342,65	2308,36	2275,99	2245,36	2216,32	2188,72	2162,45	2137,4	2113,47	2090,58	2068,64	2047,6	2027,39	2007,96	1989,25	1971,21
800	2490,08	2440,59	2394,81	2352,28	2312,62	2275,5	2240,66	2207,86	2176,9	2147,61	2119,83	2093,44	2068,31	2044,35	2021,46	1999,56	1978,58	1958,46	1939,13	1920,54	1902,65	1885,4
900	2394,21	2346,62	2302,6	2261,71	2223,58	2187,9	2154,4	2122,86	2093,09	2064,93	2038,22	2012,84	1988,68	1965,64	1943,63	1922,58	1902,41	1883,06	1864,47	1846,6	1829,39	1812,81
1000	2311,59	2265,64	2223,14	2183,66	2146,84	2112,39	2080,05	2049,6	2020,86	1993,67	1967,88	1943,38	1920,05	1897,81	1876,56	1856,23	1836,76	1818,07	1800,13	1782,87	1766,26	1750,25
1100	2239,3	2194,79	2153,62	2115,38	2079,71	2046,34	2015	1985,51	1957,67	1931,32	1906,34	1882,61	1860,01	1838,46	1817,88	1798,18	1779,32	1761,22	1743,84	1727,12	1711,03	1695,52
1200	2175,29	2132,05	2092,06	2054,9	2020,26	1987,84	1957,4	1928,75	1901,7	1876,11	1851,84	1828,79	1806,84	1785,9	1765,91	1746,78	1728,45	1710,87	1693,99	1677,75	1662,11	1647,05
1300	2118,02	2075,92	2036,98	2000,8	1967,07	1935,5	1905,87	1877,97	1851,63	1826,72	1803,09	1780,64	1759,27	1738,88	1719,42	1700,79	1682,95	1665,83	1649,39	1633,58	1618,35	1603,68
1400	2066,34	2025,26	1987,27	1951,98	1919,07	1888,27	1859,36	1832,14	1806,45	1782,14	1759,09	1737,19	1716,34	1696,46	1677,46	1659,29	1641,88	1625,18	1609,14	1593,72	1578,87	1564,55
1500	2019,36	1979,22	1942,09	1907,6	1875,44	1845,34	1817,09	1790,49	1765,38	1741,63	1719,1	1697,7	1677,32	1657,89	1639,32	1621,57	1604,55	1588,23	1572,56	1557,48	1542,97	1528,98
1600	1976,38	1937,09	1900,76	1867	1835,53	1806,07	1778,42	1752,38	1727,81	1704,56	1682,51	1661,56	1641,62	1622,6	1604,43	1587,05	1570,4	1554,43	1539,09	1524,33	1510,13	1496,44
1700	1936,84	1898,34	1862,73	1829,65	1798,81	1769,94	1742,84	1717,33	1693,24	1670,46	1648,85	1628,32	1608,78	1590,14	1572,34	1555,3	1538,99	1523,33	1508,3	1493,84	1479,92	1466,5
1800	1900,29	1862,52	1827,58	1795,12	1764,86	1736,53	1709,95	1684,92	1661,29	1638,93	1617,74	1597,59	1578,42	1560,13	1542,66	1525,95	1509,94	1494,58	1479,83	1465,65	1451,99	1438,83
1900	1866,35	1829,25	1794,94	1763,06	1733,34	1705,52	1679,41	1654,82	1631,62	1609,66	1588,84	1569,06	1550,23	1532,27	1515,11	1498,7	1482,97	1467,89	1453,4	1439,47		
2000	1834,71	1798,24	1764,51	1733,17	1703,95	1676,61	1650,94	1626,77	1603,96	1582,37	1561,91	1542,46	1523,95	1506,29	1489,42	1473,29	1457,83	1443,01				
2100	1805,11	1769,23	1736,04	1705,21	1676,46	1649,56	1624,3	1600,53	1578,08	1556,85	1536,71	1517,58	1499,36	1481,99	1465,4	1449,52	1434,32					
2200	1777,34	1742,01	1709,33	1678,98	1650,67	1624,18	1599,31	1575,9	1553,8	1532,89	1513,06	1494,23	1476,29	1459,19	1442,85							
2300	1751,19	1716,39	1684,19	1654,28	1626,39	1600,29	1575,79	1552,72	1530,95	1510,35	1490,81	1472,25	1454,58	1437,73								
2400	1726,53	1692,21	1660,47	1630,98	1603,48	1577,75	1553,59	1530,85	1509,38	1489,07	1469,81	1451,51	1434,09									
2500	1703,19	1669,34	1638,02	1608,94	1581,81	1556,42	1532,59	1510,16	1488,98	1468,95	1449,95	1431,89										
2600	1681,07	1647,66	1616,75	1588,04	1561,26	1536,21	1512,69	1490,54	1469,64	1449,87	1431,11											
2700	1660,05	1627,06	1596,54	1568,18	1541,75	1517	1493,78	1471,91	1451,27	1431,74												
2800	1640,05	1607,45	1577,3	1549,29	1523,17	1498,72	1475,78	1454,17	1433,78													
2900	1620,98	1588,76	1558,96	1531,27	1505,46	1481,3	1458,62	1437,26														
3000	1602,76	1570,91	1541,44	1514,07	1488,54	1464,65	1442,22															

δmax	3 mm	E	210 Gpa	Ix-x	102 cm^4	θ	22,5 °	T	10 s

Value

- Max distance, l > 2900 mm
- Max distance, 2900 mm > l > 2500 mm
- Max distance, 2500 mm > l > 2000 mm
- Max distance, 2000 mm > l > 1500 mm
- Max distance, 1500 mm > l > 1000 mm
- Max distance, l < 1000 mm
- Exceeds maximum allowable stress

*Maximum allowable distance between brackets is 2900 mm

$$l_x = \sqrt[3]{\dfrac{\delta_{max} \cdot 48EI_{x-x}}{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right)}}$$

For loads on the x-x axis

Figure 32 Maximum bracket distance for loads on the x-x axis of a T90/B guide during roll

The second stage in optimizing the process is to establish the limitation for the various rail dimensions and determine the ultimate performance for the whole realistic range of load cases in which the EGS might be applied. In order to do so, a wide specter of combined conditions was defined in both load directions and for every ISO-code investigated in this study. By exploiting the absolute requirements and the mathematical relationships based on the methods approved by DNV GL, *Function 19* could be altered to generate the larges allowable bracket distance for a specific load case. The combined conditions were sorted in specific matrices similar to the one illustrated in *Figure 32*, where loads apply on the x-x axis and every cell returns a value corresponding to *Function 20.*

$$l_x = \sqrt[3]{\frac{\delta_{max} \cdot 48EI_{x-x}}{\frac{W}{2}\left(g \cdot \sin\theta + \left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z\right)}} \tag{20}$$

l_x : Maximum allowable bracket distance for lodes on the x-x axis [mm]

In this example, the matrix processes data related to the T90/B guide rail and considers requirements for rolling conditions. In general, this means that if the generated value is chosen for evaluation of the specific load condition, the rail deflection is at the absolute maximum of three millimeters and the safety factor is exactly *one*. A complete list of matrices are attached in *Appendix F.*

Because the bracket distance is set to the power of three in relation to the determination of deflection, the chosen length has a major influence on the end result and whether the solution is within the requirements or not. The matrices are color coded based on defined length intervals illustrated in the example. The yellow cells indicates lengths between 1,5 and 2 meters, which is considered to be the main area of application. The reason for this is that larger distances tend to result in deflections exceeding the allowable limits. Bracket distances shorter than this is seldom desirable and even though a reduction of the length in theory would improve performance considerable, the limit for allowable stress would eventually be exceeded. Cells that exceeds the maximum stress is engraved in the matrix, which means that the indicated load case for the specific rail dimension is not valid regardless of the bracket distance.

The engraved area originates from a corresponding matrix composed in a similar manner, where the cells generate values for the resulting stress. The matrix presented in *Figure 33* on the next page corresponds to the discussed example, with the same rail dimension and the same load conditions. In this case, *Function 18* is altered, but with respect to the bracket distance, where the value is returned from *Function 20*. The cells in the stress matrix for this example generates values according to *Function 21* and identifies the values exceeding the maximum of 180 MPa with the color red. This red field of failure is the same field indicated as engraved in the matrix for bracket distances.

$$\sigma_x = \frac{\frac{W}{2}\left(g \cdot \sin\theta + \left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z\right)l_x}{4 \cdot V_{x-x}} \tag{21}$$

σ_x : Stress for lodes on the x-x axis as a result of the maximum bracket distance [MPa]

T90/B - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	Height [m]																						
	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	43,5813	45,3669	47,118	48,8372	50,5266	52,1882	53,8238	55,4349	57,0229	58,5891	60,1346	61,6605	63,1678	64,6573	66,1298	67,5861	69,0269	70,4528	71,8644	73,2623	74,647	76,0189
600	49,2139	51,2303	53,2077	55,1491	57,0568	58,9332	60,7801	62,5994	64,3927	66,1613	67,9066	69,6297	71,3318	73,0138	74,6766	76,3211	77,9481	79,5583	81,1524	82,7309	84,2946	85,8438
700	54,5405	56,7751	58,9666	61,118	63,2323	65,3117	67,3586	69,3748	71,3621	73,3222	75,2563	77,166	79,0523	80,9163	82,7591	84,5816	86,3847	88,1692	89,9358	91,6852	93,418	95,135
800	59,6184	62,0611	64,4566	66,8083	69,1194	71,3925	73,6299	75,8338	78,0062	80,1487	82,263	84,3504	86,4123	88,4499	90,4643	92,4565	94,4274	96,3781	98,3091	100,221	102,116	103,992
900	64,4885	67,1307	69,7218	72,2657	74,7656	77,2243	79,6445	82,0285	84,3783	86,6958	88,9828	91,2407	93,4711	95,6751	97,854	100,009	102,141	104,251	106,34	108,408	110,457	112,487
1000	69,1811	72,0155	74,7952	77,5242	80,206	82,8436	85,4399	87,9974	90,5182	93,0043	95,4577	97,88	100,273	102,637	104,974	107,286	109,573	111,837	114,078	116,297	118,495	120,672
1100	73,7195	76,7399	79,7019	82,61	85,4677	88,2783	91,045	93,7702	96,4564	99,1056	101,72	104,301	106,851	109,37	111,861	114,324	116,762	119,174	121,561	123,926	126,268	128,589
1200	78,1122	81,323	84,462	87,5437	90,572	93,5506	96,4825	99,3704	102,217	105,025	107,795	110,53	113,232	115,902	118,542	121,152	123,735	126,291	128,821	131,327	133,809	136,269
1300	82,4042	85,7804	89,0915	92,3421	95,5364	98,6782	101,771	104,817	107,82	110,781	113,703	116,589	119,439	122,255	125,039	127,793	130,517	133,213	135,882	138,525	141,144	143,738
1400	86,5777	90,1249	93,6036	97,0188	100,375	103,676	106,925	110,126	113,28	116,392	119,462	122,493	125,488	128,447	131,372	134,265	137,127	139,96	142,764	145,541	148,292	151,017
1500	90,6528	94,367	98,0095	101,585	105,1	108,556	111,958	115,309	118,612	121,87	125,085	128,259	131,394	134,493	137,556	140,585	143,582	146,548	149,484	152,392	155,272	158,126
1600	94,6383	98,5158	102,318	106,052	109,72	113,328	116,88	120,379	123,827	127,228	130,584	133,898	137,171	140,405	143,603	146,766	149,894	152,991	156,056	159,092	162,098	165,078
1700	98,5416	102,579	106,538	110,426	114,246	118,003	121,701	125,344	128,934	132,476	135,97	139,42	142,828	146,196	149,526	152,819	156,077	159,301	162,492	165,653	168,784	171,886
1800	102,369	106,563	110,677	114,715	118,683	122,586	126,428	130,212	133,942	137,621	141,251	144,836	148,376	151,875	155,334	158,754	162,139	165,488	168,804	172,087	175,34	178,562
1900	106,126	110,474	114,739	118,925	123,039	127,085	131,068	134,991	138,858	142,672	146,436	150,151	153,822	157,449	161,035	164,581	168,09	171,562	174,999	178,403	181,775	185,116
2000	109,818	114,317	118,73	123,062	127,319	131,506	135,627	139,687	143,689	147,635	151,53	155,375	159,173	162,926	166,637	170,306	173,937	177,53	181,087	184,609	188,099	191,556
2100	113,449	118,097	122,655	127,131	131,528	135,854	140,111	144,305	148,439	152,516	156,539	160,512	164,435	168,313	172,146	175,937	179,687	183,399	187,074	190,713	194,317	197,889
2200	117,022	121,817	126,519	131,135	135,671	140,133	144,525	148,851	153,115	157,32	161,47	165,568	169,615	173,614	177,568	181,479	185,347	189,176	192,967	196,72	200,438	204,122
2300	120,542	125,481	130,324	135,079	139,752	144,348	148,872	153,328	157,72	162,052	166,327	170,548	174,717	178,836	182,909	186,937	190,922	194,866	198,771	202,637	206,467	210,262
2400	124,011	129,092	134,075	138,967	143,774	148,502	153,156	157,741	162,259	166,716	171,114	175,456	179,745	183,983	188,173	192,317	196,417	200,474	204,491	208,469	212,409	216,313
2500	127,433	132,654	137,774	142,801	147,741	152,599	157,382	162,093	166,736	171,315	175,835	180,296	184,704	189,059	193,365	197,623	201,836	206,005	210,133	214,22	218,269	222,281
2600	130,809	136,168	141,424	146,584	151,655	156,642	161,551	166,387	171,153	175,854	180,493	185,073	189,597	194,068	198,487	202,858	207,183	211,463	215,7	219,895	224,051	228,169
2700	134,141	139,637	145,027	150,319	155,519	160,633	165,667	170,626	175,514	180,335	185,092	189,788	194,428	199,012	203,545	208,027	212,462	216,851	221,196	225,498	229,76	233,983
2800	137,433	143,064	148,586	154,008	159,335	164,575	169,733	174,814	179,821	184,76	189,634	194,446	199,199	203,896	208,54	213,132	217,676	222,172	226,624	231,032	235,399	239,725
2900	140,687	146,451	152,103	157,653	163,107	168,471	173,751	178,951	184,078	189,134	194,123	199,049	203,914	208,723	213,476	218,177	222,828	227,431	231,988	236,501	240,971	245,399
3000	143,902	149,798	155,58	161,257	166,835	172,322	177,722	183,042	188,285	193,457	198,56	203,599	208,575	213,494	218,356	223,164	227,922	232,63	237,291	241,907	246,479	251,009

σmax	180 Mpa	E	210 Gpa	Vx-x	20,86 cm^3	θ	22,5 °	T	10 s

$$\sigma_x = \frac{\dfrac{W}{2}\left(g\cdot\sin\theta + \left(2\dfrac{\pi}{T}\right)^2\cdot\dfrac{\theta}{180}\pi\cdot Z\right)l_x}{4\cdot V_{x-x}}$$

Resulting stress < σmax
Resulting stress > σmax
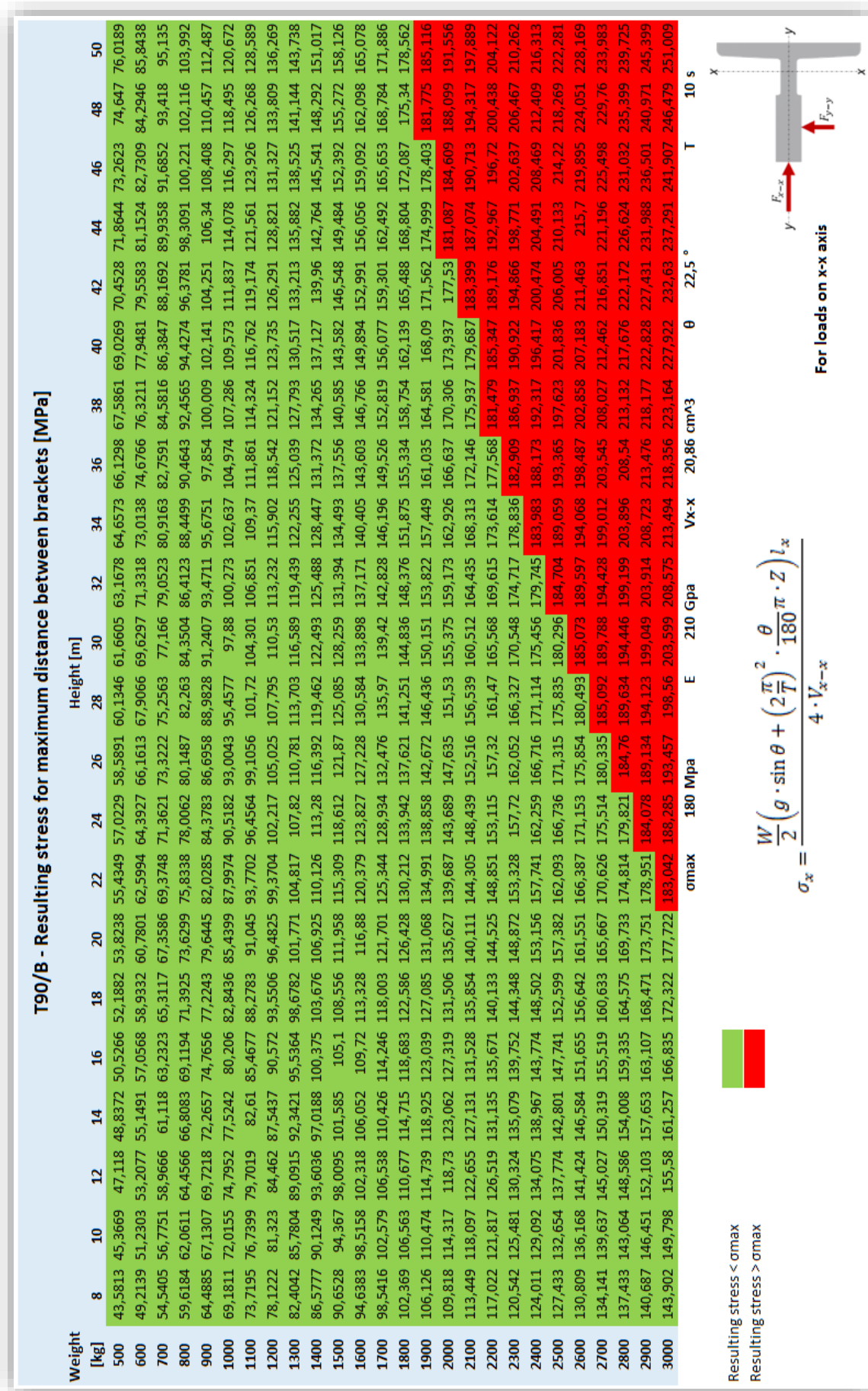
For loads on x-x axis

Figure 33 *Resulting stress from maximum bracket distance*

By combining these methods and applying them for the various rail dimensions and orientations, the optimal solution for the sizing of guide rails can be established for any project within the range of application.

For the next stage in optimizing the evaluation process, a common denominator for the worst-case scenarios should be determined. The values retrieved form the worst-case will always be the determining factor in an evaluation process and in the pursuit of creating an efficient and user friendly system, a minimum amount of required input is desired.

Regardless of the project or area for use, the requirements for roll in stowed conditions are without exceptions the most conservative scenario for sizing of guiderails. This is a result of the strict specifications set by the notifying body for this condition. Because of this, only the loads caused by the ship rotation around the longitudinal axis of the hull is considered in the atomized solution. However, the user should still be able to determine the orientation of the guides, as this has a great impact on the load distribution on the rails. In stowed conditions, the weight is considered as only the component weight on rope, since the elevator is assumed to be parked in these circumstances. Even though the elevator system is not performing any personnel travel this case, it must be taken into account whether the construction supported by the EGS is intended to carry passengers or not. In line with the topic of passenger activity discussed in section *2.3.1,* rail dimensions smaller than T90/B should not be applied in the support of passenger cabins. The user must therefore be able to choose between applications for either passenger cabins or counterweights and service lifts. In doing so, the program can eliminate unfit dimensions, even if calculations identifies the guide as suitable for the application. While keeping the worst-case in mind, the mass center shall be considered at its maximum height in the shaft for every evaluation process. This length represents the difference in height from the rotation line of the hull to the center of mass acting on the guide rail and is determined using *Function 5* and the specified parameters provided by the customer. In *Figure 34* the support of both car and counterweight is illustrated in opposite orientations compared to the hull coordinate system.
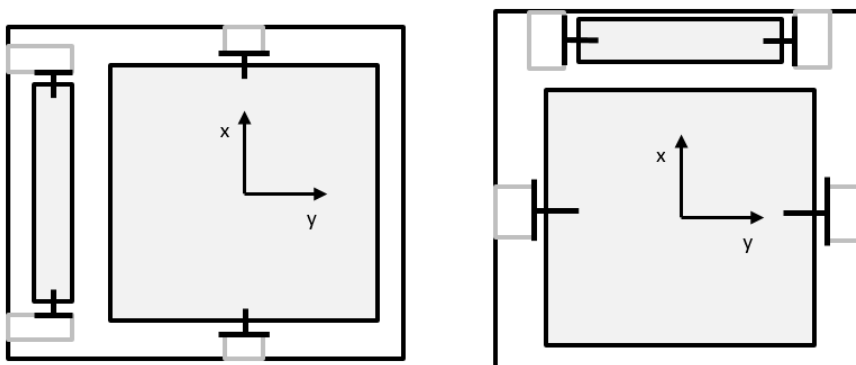
Figure 34 *Elevator components in shaft oriented in opposite direction*

Based on these qualities, a calculation tool for automatic sizing of guide rails is developed, where only four input specifications are needed in order to provide the optimal solution for any project within the range of application. The tool interface is illustrated in *Figure 35* on the next page, where a typical example is applied.
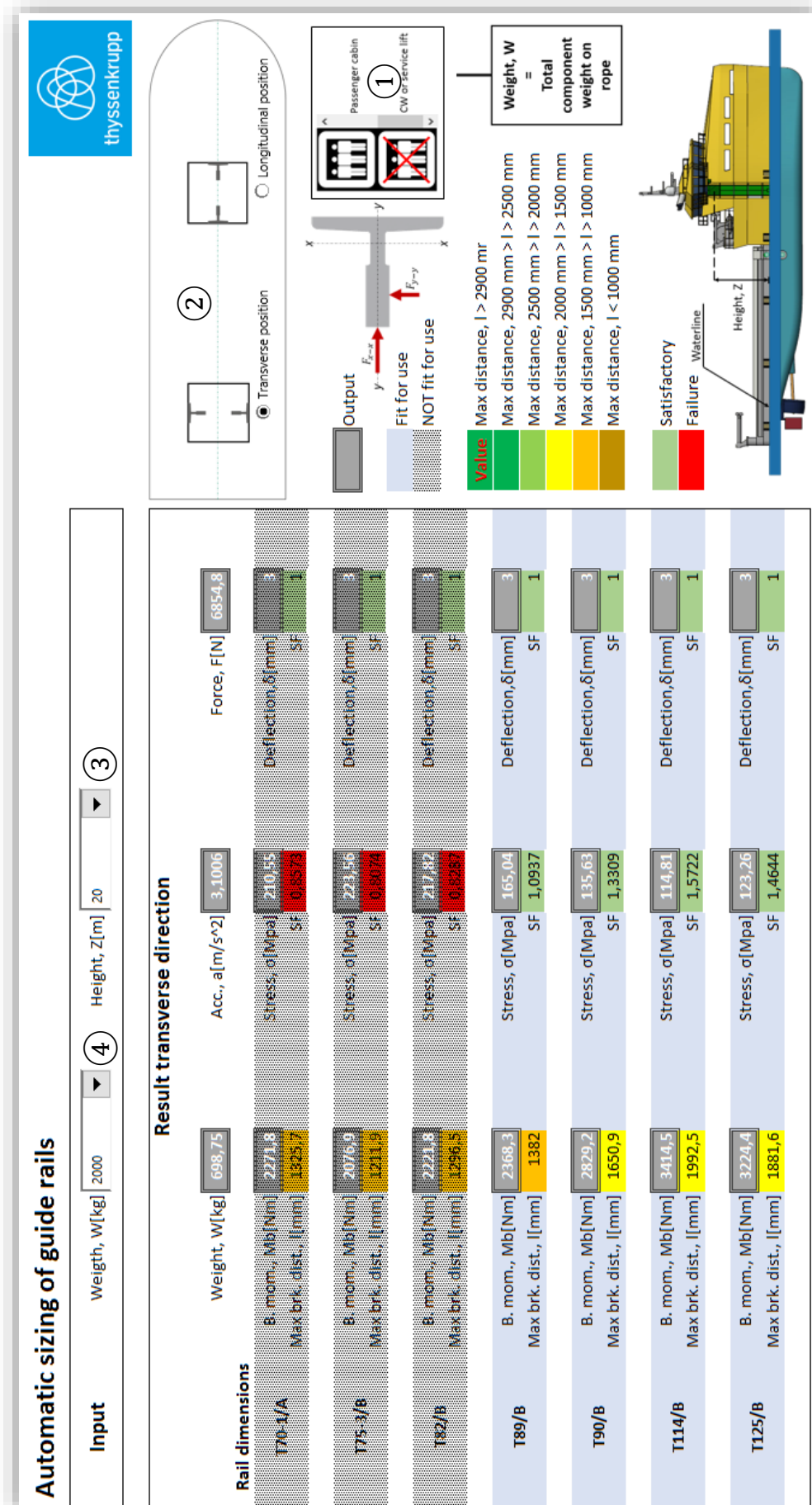
Figure 35 *Interface of calculation tool for automatic sizing of guide rails*

The tool is built with Excel as platform and is hyper coupled to different applications in order to produce the necessary information. The user inputs on the interface are clickable, but the rest of the sheet is locked for changes. The input specifications in this example are indicated in the figure with numbering from 1 to 4 and can be changed only by the click of the mouse.

1) *Number 1* indicates whether the system is supporting components intended for passenger travel or not. By clicking on the passenger cabin, all rail dimensions prior to T90/B is automatically marked as NOT fit for use according to the mark explanation. In this example, the evaluation is set to apply for a counterweight or service lift and all rail dimensions are potential components as long as the requirements are fulfilled.

2) *Number 2* allows the user to determine the guide rail orientation in relation to the ship hull. In the automatic sizing, rolling conditions apply and by clicking on the longitudinal position the resulting loads related to the y-y axis of the rail are considered in accordance with *Function 15*. In this example the transverse position is selected, which means that the determining load is applied on the x-x axis of just the one guide rail and *Function 16* is used to determine the force.

3) *Number 3* determines the height, which is defined according to the figure provided in the bottom corner of the interface. By clicking on the associated arrow, a scrollable array with multiple choices appears. The chosen value will correspond to the height indicated in the matrices for both maximal bracket distance and resulting stress. In this example the height is set to 20 meters and the values for this height is activated in all matrices related to the transverse operation.

Figure 36 *Height options*

4) *Number 4* determines the total component weight on rope. The value is selected in the similar mater as for the height and the matrix values for this weight is activated. For the specified orientation, the matrix value corresponding to both the selected weight and height is returned in the result for all rail dimensions. In this example, the selected weight is set to 2000 kg.

Figure 37 *Weight options*

The returned value for the bracket distance also determines the bending moment for the rail and the returned stress determines the corresponding safety factor. These are all specific values for each individual rail dimensions, whereas the resulting weight, acceleration and force is common parameters determined by the defined load condition. It is important to note that the safety factor for deflection is equal to *one* for each rail in the automatic sizing. This is because the tool returns the optimal solution for the system, where the requirement for maximum deflection is constantly pushed to the limit of *three* millimeters.

The result in this example indicates that the T89/B guide will be certified and may be applied in the system. However, it also indicates that the maximum bracket distance is below 1500 mm, which means that the T90/B might be the preferred choice in this case.

3.2.2 *Validation of brackets*

Even though the guide rail selected for an EGS is certified for the applied conditions, it is still necessary to establish whether the supporting brackets in the EGS are able to fulfill their purpose or not. There are no standard specifications as to how the supplier should connect the guide rails to the trunk wall or how the solution is validated. Because of this and the variating trunk interior, it exists a vast variety of bracket solutions, both mas produced and custom made. The evaluation for each solution may differ, but in order to get the entire EGS certified, the supplier must provide valid proof that the bracket solution can withstand the absolute load conditions in which the guides are validated for.

In this research, a structural analysis is conducted for the two bracket solutions considered for the EGS. The main potential impact may vary according to the direction and positioning of the load and in order to ensure the bracket capability, the solution must be tested against what is assumed to be the worst-case scenario in relation to the various loads. Suitable models were created using Autodesk Inventor and the necessary geometric relationships were constructed before imported to ANSYS, where the appropriate boundary conditions were applied for the structural finite element analysis. A total of five load cases were conducted for each bracket solution and the boundary conditions were carefully determined in order to create an environment as realistic as possible. The impact is considered as the loads acting on the guide rail trough the resulting force that is applied on the guide shoe.

Load cases

In the first load case, it is assumed that the load is acting directly on the bracket and that the impact creates a pressure between the rail and the trunk wall. The applied force is defined as F_{x-x} in *Figure 38* and in order to create a realistic environment, three brackets are included to provide the proper restrictive contribution in the load case. In this case, the system is illustrated with the adjustable bracket, but the principle boundary conditions applies to bout solutions, where the faces that are welded to the trunk wall is considered to have a fixed constrain, whereas all other components are mated. The force is applied on the respective guide shoe face, providing a pressure on the rail equal to a realistic situation. The simplifications made for the environmental setup results in faster simulation and are considered as reasonable assumptions. For instance, a similar model with five brackets was tested and returned the same values for the bracket in question, which indicates that the chosen model is suitable for the load case.

For the second load case, the same model and environmental setup is used, but the applied force represent the load acting on the y-y axis of the guide and is defined as F_{y-y} in the figure. This impact is assumed to create an extensive twisting load on the bracket, as influenced guide shoe face is in direct height with the components.
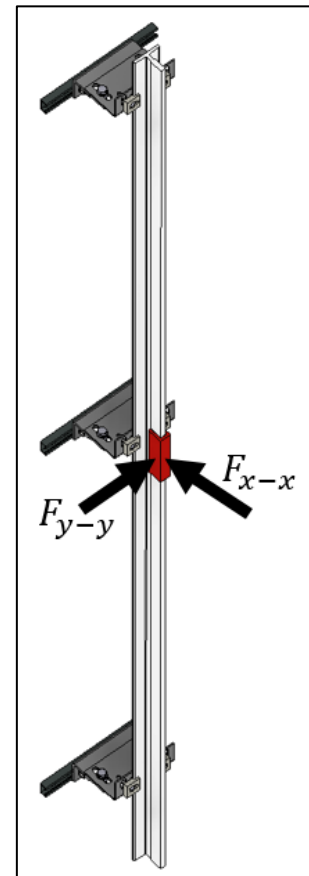

Figure 38 Load case 1 and 2

In load case three, the impact is considered in the middle between two brackets, as when determining the worst-case for sizing of guide rails. This condition is assumed to cause for a bending of the rail around the connected supports and result in corresponding bending stress for the brackets. The model used for this load case is constructed by the same principle as the previous, but consists of four brackets in order to provide an evenly distributed resistance to the load. The illustration of a model used for adjustable brackets are shown on the left side in *Figure 39*, where the applied force is indicated as F_{x-x}. The bending stress is expected to be large for the brackets closest to the impact, but severely drop in magnitude for the next.

Load case four is identical to the previous case, except that the force is set to be acting according to F_{x-x} in the figure. This impact will result in both twisting and bending of the brackets, but on the other hand the magnitude of the applied force is divided by tow compared to the force applied on the x-x axis.
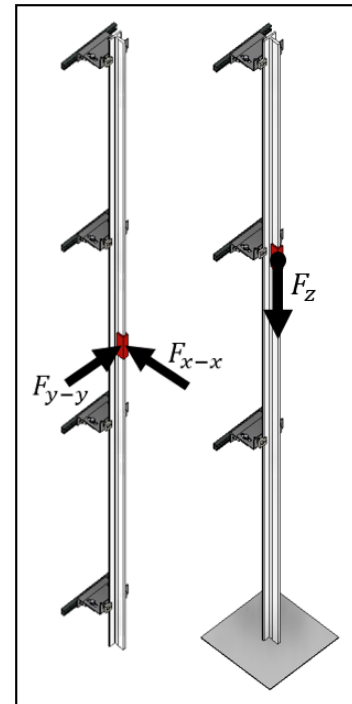
Figure 39 Load case 3, 4 and 5

The fifth and last load case differs from the other cases, as the load is acting in the vertical direction simulating a dragging force representing the activation of a safety gear with a captive roller. The impact point is set parallel to the bracket in question, as illustrated on the right side in the above figure. For the FEM-analysis of this load case, the boundary conditions are altered in order to let the guide rail slip between the rail clips at the specific force, as discussed in section *2.2.3* for rail clips. According to regular procedures for construction steel, the constraints between the guide rail and the connecting components are defined with a coefficient of friction equal to 0.2. In addition, the bottom face of the rail is fixed in order to create the required buckling effect. Since the boundary conditions allows the rail to slip and because most of the impact is picked up in the guide, large stresses are not expected to occur in the brackets. However, the load case is included in the evaluation process, as it is a common factor in the evaluation of land based systems.

The geometric models developed in Autodesk Inventor are constructed using the dimensions of a T90/B for the guide rails to provide a realistic reaction on the brackets. In relation to the impact, this middle class dimension is assumed to be a suitable representation for the system, as the stiffness of a larger dimensions will compensate for a larger potential load and the smaller dimensions with lower stiffness is subjected to smaller loads. Also, future trends indicates an increased use of the T90/B guide rails. As a generalization made for the analysis of the load cases, the bracket distance is set to 1500 mm in the models.

Component mesh for FEM-analysis

After the model geometry is imported to ANSYS and the specific boundary conditions are applied, a proper mesh must be created for the components in order to conduct a valid simulation. The fineness of the grid determines how precise the software will compute the algorithms for solving the simulation. Component elements that are too large will return bad

results, but element sizes that are too small may complicate the commutation to a certain extend were the system crashes or don't produce a result at all. The accuracy of the solution will eventually stagnate at a certain mesh size and a further size reduction is redundant. Also, when looking at a specific part of a multi body construction, it is not necessary to provide a significantly fine grid for the surrounding components. In the process of determining an appropriate mesh for the analysis in this research, the element size for the components of interest were set to *four mm,* equal to the smallest geometric dimension. In doing so, the risk of errors are reduced as the element fits inside the area and the complexity of the automatic mesh is reduced. When running the simulation with an element size of *three mm,* the resulting difference proved insignificant and the suggested sized were considered as sufficient. The grid information for all components included in the FEM analysis is listed in *Table 9* and the mesh for the welded and adjustable bracket solutions are illustrated in *Figure 40* and*Figure* **41**, respectively. When analyzing the resulting stresses, it is important to consider the potential effect of singularity, where the loads tend to be concentrated in a small element area. This phenomenon should be defined as a local non-destructive impact and the stresses in the immediate vicinity is to be considered as the real loads.

Table 9 *Component mesh*

Component	Mesh type	Element size	Nodes	Elements
Top brackets	*Element size*	*4 mm*	*41658*	*22428*
Welded bracket	*Element size*	*4 mm*	*123955*	*74103*
Adjustable bracket	*Element size*	*4 mm*	*72150*	*44984*
Rail clips	*Element size*	*4 mm*	*5402*	*3162*
Halfen rail	*Element size*	*5 mm*	*16710*	*29710*
Guide rail T90/B	*Element size*	*25 mm*	*-*	*-*
Rail shoe	*Quad/tri*	*-*	*2461*	*557*
Remaining components	*Element size*	*10 mm*	*-*	*-*
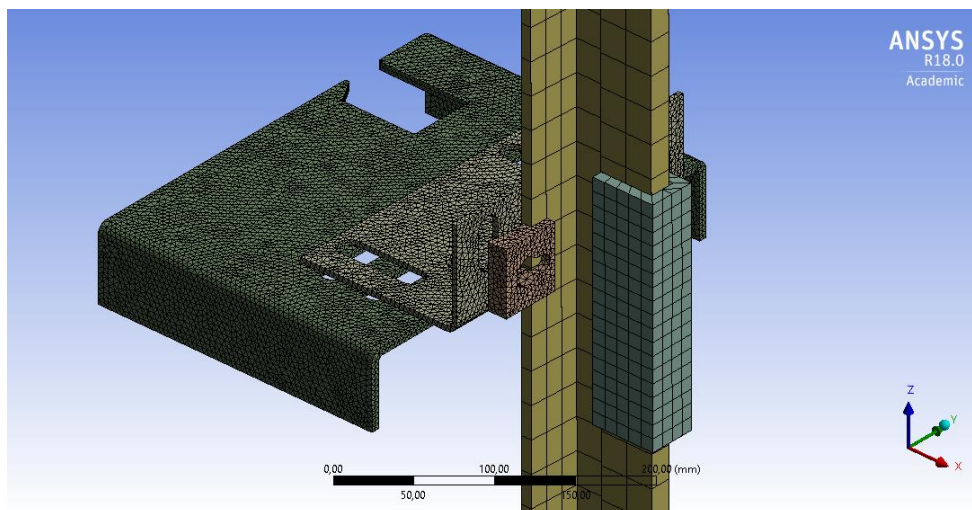
Figure 40 *Component mesh for the welded bracket solution*
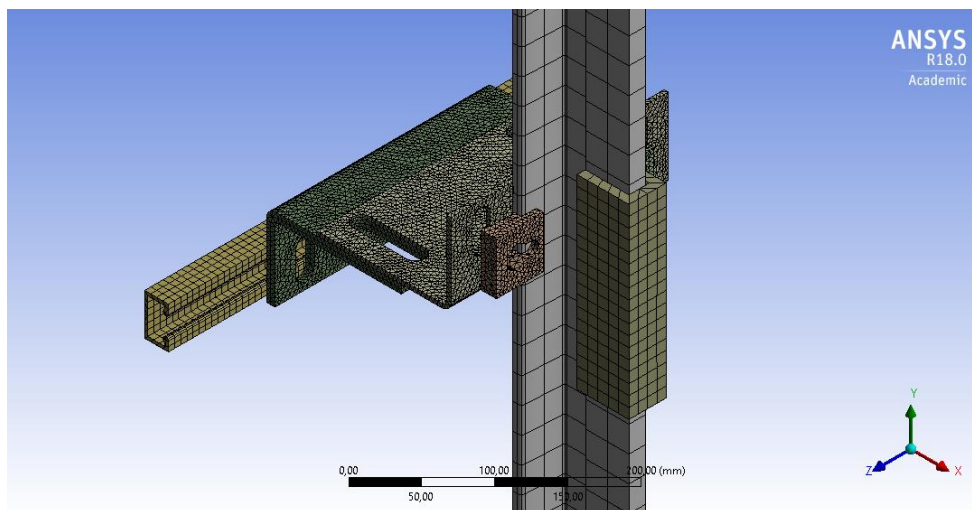
Figure 41 *Component mesh for the adjustable bracket solution*

Applied forces

The applied forces in the various load cases are based on the tolerance area in which the guide rail can be utilized in the system. For impact in the horizontal direction, the forces are determined according to the matrix for maximum bracket distance and the resulting worst-case-loads produced when bracket distance is above 1500 mm. The measurements from the various combinations of height and weight are plotted in *Figure 42* for loads acting on both the x-x and y-y axis of the T90/B guide rail.
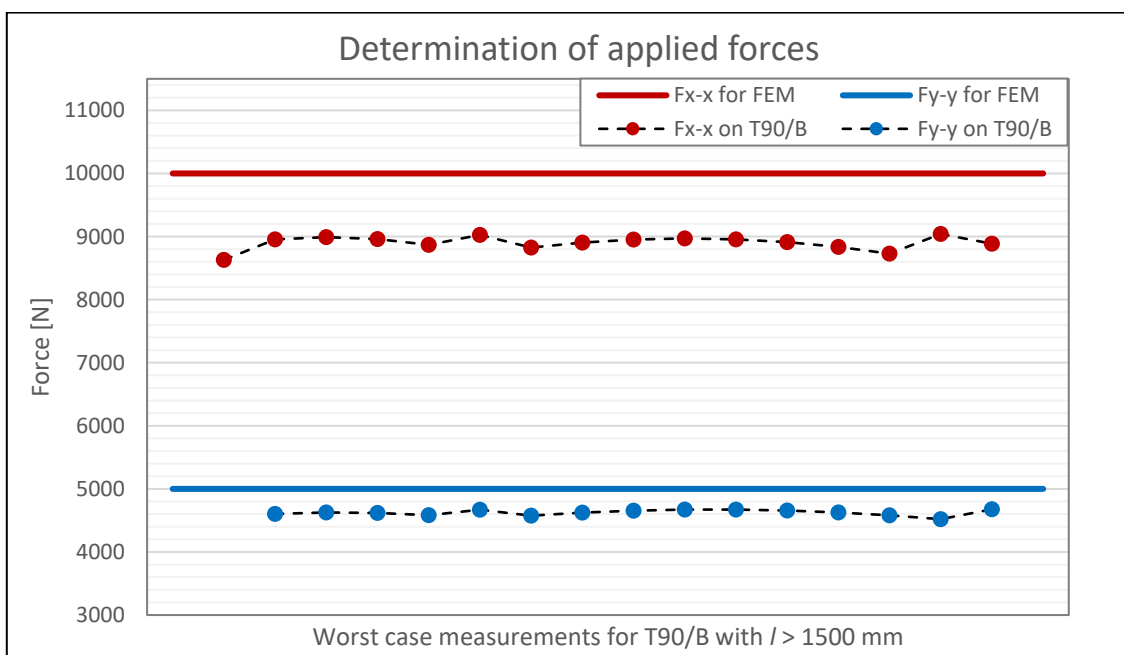
Figure 42 *Forces determined for FEM-analyses based on the worst-case measurements*

The loads determined in the above graph is considered as the worst-case scenario and impacts greater than this is not expected to occur in on the system. However, in an attempt to investigate the integrity of the individual bracket solutions, an additional analyses is conducted, where the horizontal worst-case-loads are multiplied with 1.5. These applied forces are referred to as extreme loads.

For the applied force in *load case five*, a safety gear with a captive roller is assumed to be activated for a mass with a net weight of 3000 kg. This net weight is doubled for the extreme analysis. In applying *Function 1*, the resulting forces are determined for the vertical drag and listed in *Table 10* together with the other forces applied in the structural analysis.

Table 10 *Forces applied for both a worst-case and an extreme scenario*

Applied force	Worst-case	Extreme
F_{x-x}	*10 kN*	*15 kN*
F_{y-y}	*5 kN*	*7.5 kN*
F_z	*45 kN*	*90 kN*

3.3 Potential savings

With Case 1, *Traditional Welded* as the base cases, a real current project is set under review in order to provide a realistic estimate of the potential savings thyssenkrupp could achieve by considering one of the other concepts for the EGS-installation on this ship. The marine project in question is a medium sized cruise vessel built by Vard Langsten and contains the total of six elevator shafts. The desired specifications regarding the position, orientation and weight of the elevator components that are to be installed are illustrated in the simplified sketch provided in *Figure 43.* A full list of the ship specifications related to the elevator installation is provided in *Appendix G* and used for establishing the scope of the project. For thyssenkrupp this is a typical projects and the company is currently undertaking several project with the similar scope. The two main aspects to consider when comparing the EGS-concepts are the guide rails needed and the estimated installation time. When compared to the results obtained for the base case, the main EGS-savings may be assumed for the concepts in relation to both weight and expenses. The ship is to be given the name *Sunshine,* but is currently known to as Vard PNO1967.
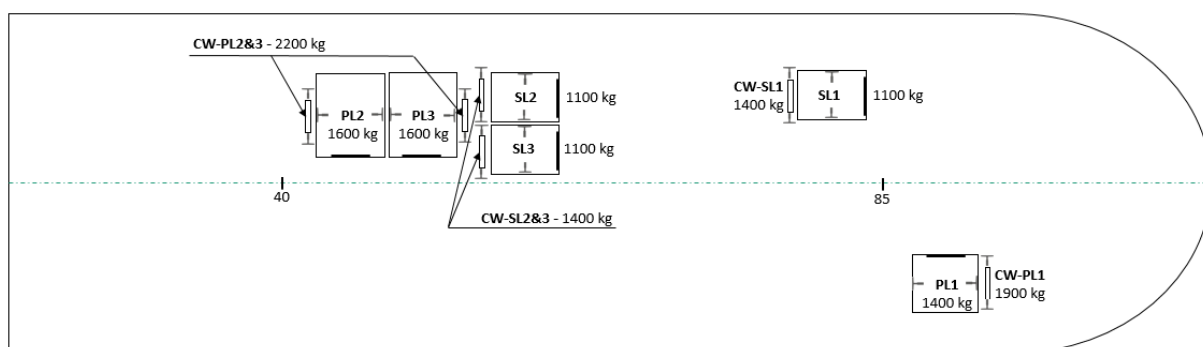
Figure 43 *Simplified sketch of the elevator components for the Sunshine project*

3.3.1 Type and amount of guide rails

The guide rails are the main component of the EGS and will determine the scope of both material cost and weight, depending on the type and amount needed for the project. Whit regards to the guide rails, the concepts distinguishes between the traditional and optimized

sizing when deciding on which dimension should be applied for the support of the different elevator components. For this project, Vard is asking for six traction lifts to be installed, tree passenger lifts and three service lifts, where the four input specifications are retrieved from the attached specifications and listed in *Table 11.* The traditional sizing is determined based historical and current practices in thyssenkrupp, where T127/B is applied for the cabins and T90/B is applied for the counterweight, regardless, as long as validated. The traditional sizing for this project can be seen in context with the attachment in *Appendix C* that provides a similar project evaluation. In addition to the component height and weight, the orientation and application area of the guide rail is computed in the calculation tool for optimized sizing according to the table specification below.

Table 11 Traditional and optimized sizing for PNO1967 based on project specifications

Elevator/CW	Guide orientation	Weight W[kg]	Height Z[m]	Traditional sizing	Optimized sizing
PL1	*Longitudinal*	*1400*	*18.6*	*T127/B*	*T90/B*
PL2	*Longitudinal*	*1600*	*21.6*	*T127/B*	*T90/B*
PL3	*Longitudinal*	*1600*	*21.6*	*T127/B*	*T90/B*
CW - PL1	*Transverse*	*1900*	*18.6*	*T90/B*	*T90/B*
CW - PL2	*Transverse*	*2200*	*21.6*	*T90/B*	*T90/B*
CW - PL3	*Transverse*	*2200*	*21.6*	*T90/B*	*T90/B*
SL1	*Transverse*	*1100*	*15.8*	*T127/B*	*T90/B*
SL2	*Transverse*	*1100*	*18.6*	*T127/B*	*T90/B*
SL3	*Transverse*	*1100*	*18.6*	*T127/B*	*T90/B*
CW - SL1	*Transverse*	*1400*	*15.8*	*T90/B*	*T70-1/A*
CW - SL2	*Transverse*	*1400*	*18.6*	*T90/B*	*T70-1/A*
CW - SL3	*Transverse*	*1400*	*18,6*	*T90/B*	*T70-1/A*

Based on the specific elevator travel heights provided by the shipyard and stated in the attached specifications for PNO1967, the amount of the five meter guide rail products that must be ordered from the manufacturer is estimated and listed in *Table 12* for both methods of sizing. The total amount is the same for both methods, but the total difference in material cost and weight may be severely influenced on the account of the different dimensions.

Table 12 Number of five meter guide rails needed for PNO1967

	T70-1/A	T90/B	T127/B
Traditional sizing		*48*	*47*
Optimized sizing	*23*	*72*	

3.3.2 Estimation of installation time

Statements from the management in the thyssenkrupp marine department indicates that the installation cost related to the EGS could be reduced considerably, mainly depending on the choice of bracket solutions. The hourly rate for the technicians are quite high and the time spent on each elevator shaft is therefore of grate significance in relation to the total EGS-expenses.

In order to make a reasonable assumption of the potential savings related to the EGS-installation, a simplified generalization for the PNO1967 project was established and reviewed in cooperation with the area manager and service manager for the department. The assumptions made are based on the generalized specifications of a single shaft listed in *Table 13*. According to the experienced representations from thyssenkrupp, the main issue is related to the bracket solutions used in the different concepts, but the different specifications on rail dimensions and bracket distance are also considered. With the traditional welded case as the base case, the time needed for installing an EGS supporting the car in a 20 meter high shaft is estimated. The assessment resulted in an estimated time of approximately one and a half week, or 50 hours, for the base case and a reduction of at least 15 hours when switching to the adjustable solution. For the cases where the optimized sizing is applied, the installation time is reduced accordingly, but the expected advantages of the adjustable solutions indicates that the installation time for Case 2 is shorter than Case 3 even when traditionally sized. The essence of this estimation is not the actual time, but the time difference and since the estimation represents the time difference for a single shaft, it is considered reasonable for generalized assumptions of shafts with similar specifications.

Table 13 Estimate of EGS-installation schedule pr. shaft for PNO1967

EGS-installation specification and schedule for Vard PNO1967 "Sunshine"					
Indication		**Concept 1** Traditional Welded	**Concept 2** Traditional Adjustable	**Concept 3** Optimized Welded	**Concept 4** Optimized Adjustable
Specifications:					
Shaft height	*m*	*20*	*20*	*20*	*20*
Nr. of guides	*pr. shaft*	*8*	*8*	*8*	*8*
Rail dimension	*type*	*T127/B*	*T127/B*	*T90/B*	*T90/B*
Rail weight	*kg*	*116*	*116*	*68*	*68*
Bracket dist.	*m*	*1.5*	*1.5*	*1.8*	*1.8*
Nr. of brackets	*pr. shaft*	*26*	*26*	*20*	*20*
Bracket type	*type*	*WELDED*	*ADJUSTABLE*	*WELDED*	*ADJUSTABLE*
Schedule pr. shaft:					
Hours	*h*	*50*	*35*	*44*	*30*
Workers	*people*	*2*	*2*	*2*	*2*
Work hours	*h*	*100*	*70*	*88*	*60*

4. Analytic results

In this chapter, some analytic results for the implementations discussed in the structural methodology are presented. These results are determined by the specifications previous stated in this report.

4.1 Standardization of guide rail dimensions

As a result of the matrices developed for the optimization of the guide rail sizing, a standardized limitation line can be drawn across the various load combinations for each rail dimension. The limit is defined for bracket distances larger than 1500 mm and for both transverse and longitudinal applications individually, as the conditions differ for the two. The guide rails have their area of application to the right and above the drawn lines in relation to the height and weight, which essentially are the corresponding values for each bottom cell in the yellow field for each matrix indicating bracket distance above 1500 mm. The standardized results for the transverse and longitudinal oriented guide rails are presented in *Figure 44* and *Figure* **45**, respectively. In accordance with the method of automatic sizing, the requirements for stowed condition during rolling of the hull are considered as the worst-case and determining factors in the application.
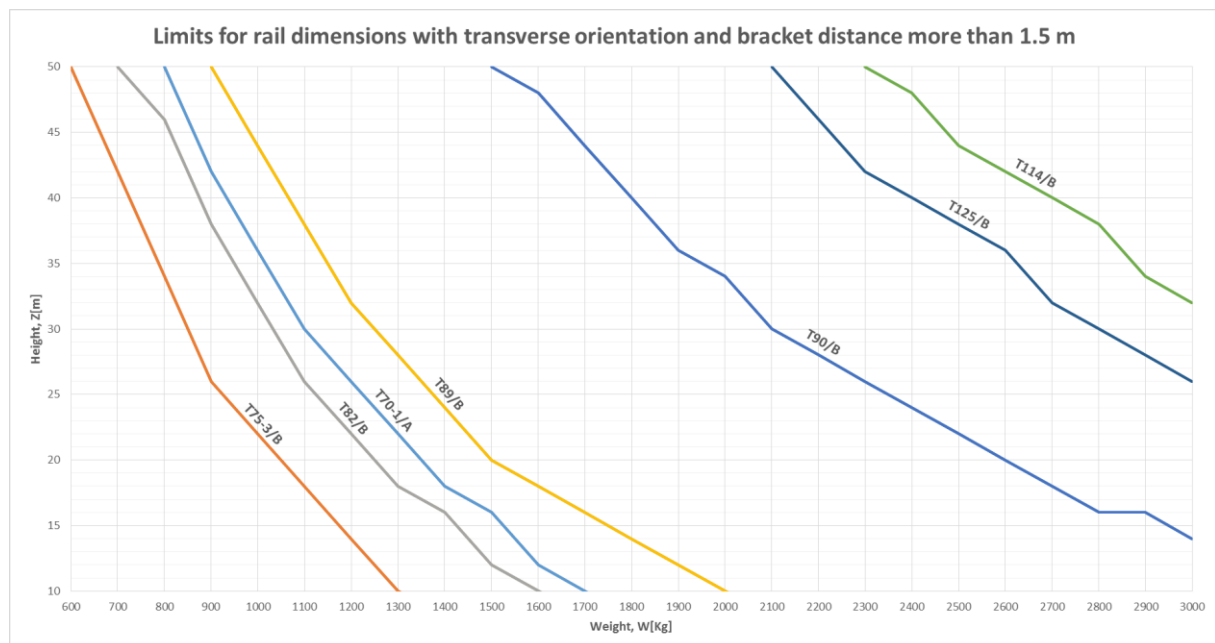
Figure 44 *Limits for transverse guide rails*

For guide rails oriented in the transverse direction, there is a distinctive difference in performance of the rail dimensions both larger and smaller than the T90/B guide rail. The performance of this dimension should prove sufficient in most of the projects that thyssenkrupp is currently undertaking, but it is important to be vigilant in case the limitation line should be exceeded. On the other hand, the opportunity to go down a size if possible should not be overlooked with regards to the potential savings. For guides with this orientation, the entire impact is concentrated on just the one component when the worst-case occurs.
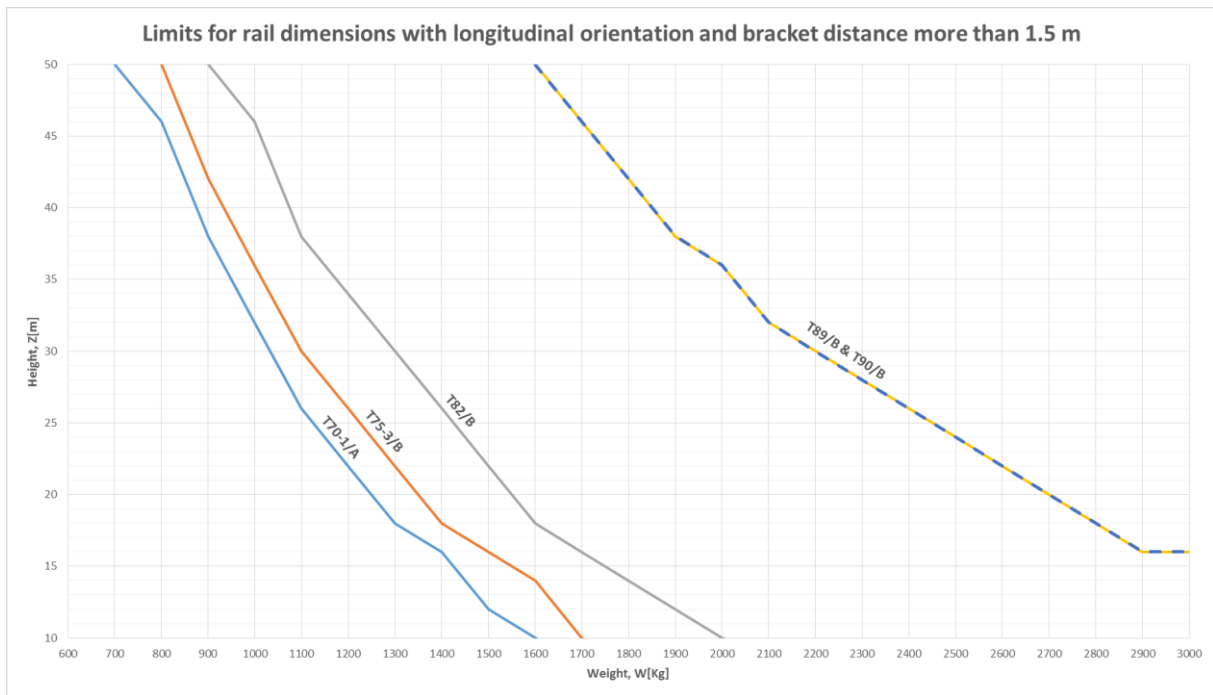
Figure 45 *Limits for longitudinal guide rails*

For the guide rails oriented in the longitudinal direction, there is a distinctive difference in performance which corresponds to the definition provided for the rail sizes. The light guide rails show a more or less similar performance at the lower range of the graph, the medium sized T89/B and T90/B show identical performance at a higher range, whiles the heavy guides have a performance beyond the defined area of load combinations when oriented in the longitudinal direction. For guides with this orientation, the impact is divided between the two components and the resulting strain is reduced when the worst-case occur.

The standardized limitation lines for the guide rails can function as an effective aid when dealing with customers and making fast evaluation of different projects. Because of the effect the orientation has on the system, it should be considered in the early phase of the elevator provisions.

Figure 46 *Hurtigruten is a typical examples of projects thyssenkrupp is undertaking [13]*

4.2 Structural analysis of brackets

The bracket solutions considered in this research are validated by performing a structural analysis of the various load cases presented in section *3.2.2* using the FEM software ANSYS. The five different load cases are conducted for both solutions and with two different loads, one considered as the worst-case and the other as an extreme load. The worst-case reveals the determining value, whereas the extreme load indicates the further performance of the solution. To avoid evaluation based on the effect of singularity for the solutions, the real stresses are considered as the tension in the area of immediate proximity to the maximum value. However, the maximum value is included in the result and referred to as a non-destructive local stress. The FEM-simulation returns the total deformation in *mm* and the Von-Mises stress in *MPa.* In order to demonstrate the effect of the impact, the resulting deflections are enlarged for visibility. Further documentation of the analysis is provided in *Appendix H*, where the deflection results from the FEM-analyses are visualized.
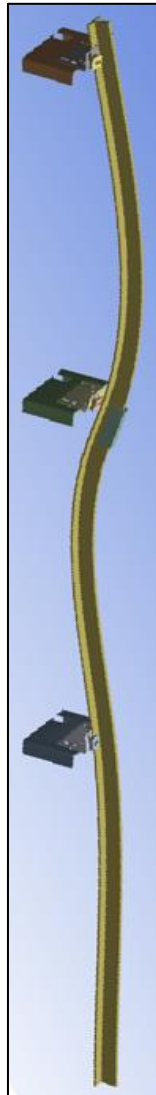
Figure 47 *Illustration of an EGS with applied load in ANSYS*

4.2.1 Load case 1: Direct load on x-x

The force is applied directly on the system with impact on the x-x axis of the guide rail.

Welded bracket solution

Figure 48 *Load case 1 on welded system*

Figure 49 *Load case 1 for welded bracket: Simulated worst-case stress result*

Figure 50 *Load case 1 for welded bracket: Simulated extreme stress result*

Pressure causes maximum stresses to occur centered on the upper bracket component and on both the front and back side. The reason for this is that the welded bracket is so massive.

Table 14 *Load case 1 for welded bracket: Values from simulation results*

Applied force		Real stress	Non-destructive local stress	Maximum bracket deflection
Worst-case	F_{x-x} = 10 kN	*85 MPa*	*106.8 MPa*	*0.052 mm*
Extreme	F_{x-x} = 15 kN	*130 MPa*	*160.21 MPa*	*0.078 mm*

Adjustable bracket solution
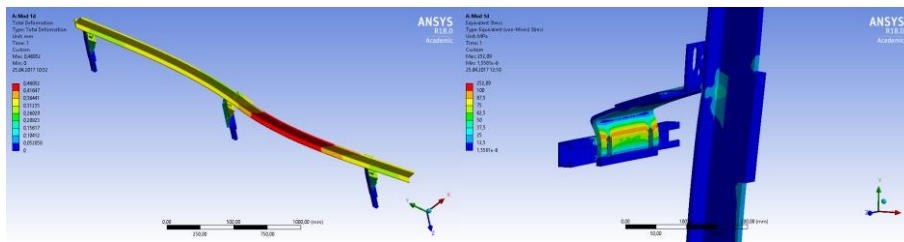
Figure 51 *Load case 1 on Adjustable system*

Figure 52 *Load case 1 for adjustable bracket: Simulated worst-case stress result*

Figure 53 *Load case 1 for adjustable bracket: Simulated extreme stress result*

On the account of the geometry, the pressure causes the brackets to bend upwards and around the Halfen rail. As a result, the maximum stresses are found here.

Table 15 *Load case 1 for adjustable bracket: Values from simulation results*

Applied force		Real stress	Non-destructive stress	Maximum bracket deflection
Worst-case	F_{x-x} = 10 kN	*100 MPa*	*131.93 MPa*	*0.353 mm*
Extreme	F_{x-x} = 15 kN	*150 MPa*	*194.16 MPa*	*0.529 mm*

4.2.2 Load case 2: Direct load on y-y

The force is applied directly on the system with impact on the y-y axis of the guide rail.

Welded bracket solution
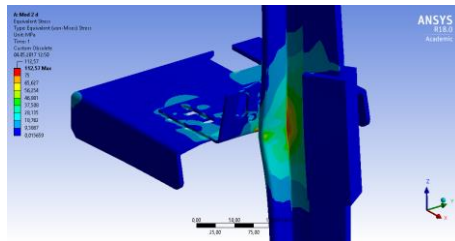
Figure 54 Load case 2 on welded system
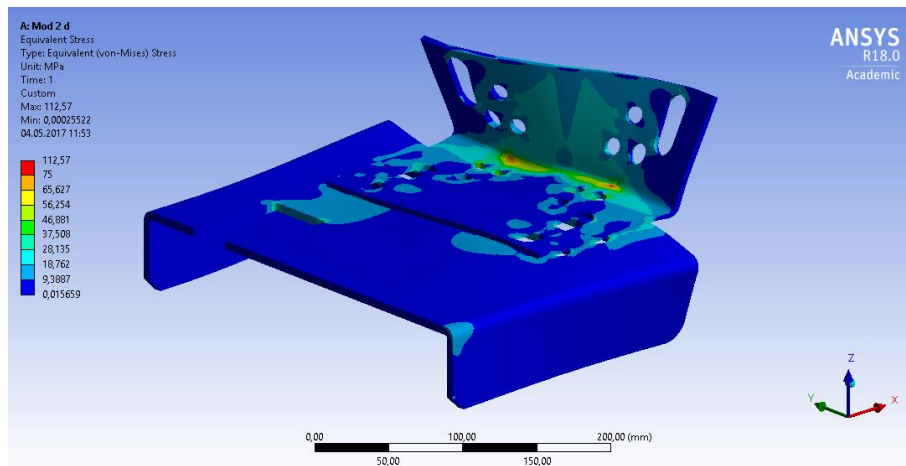
Figure 55 Load case 2 for welded bracket: Simulated worst-case stress result
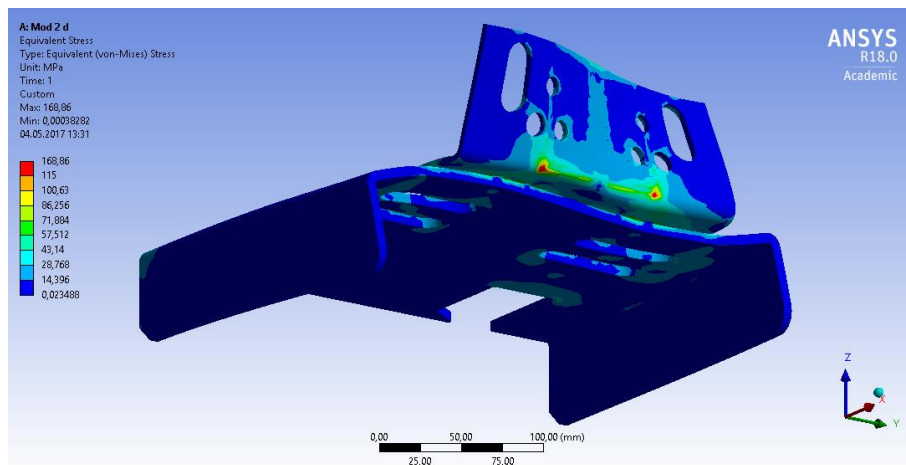
Figure 56 Load case 2 for welded bracket: Simulated extreme stress result

A twisting motion causes maximum stresses to occur on the edges of where the guide rail is in contact with the lower part of the bracket. The welded bracket is less effected.

Table 16 Load case 2 for welded bracket: Values from simulation results

Applied force		Real stress	Non-destructive local stress	Maximum bracket deflection
Worst-case	F_{y-y} = 5 kN	75 MPa	112.57 MPa	0.079 mm
Extreme	F_{y-y} = 7.5 kN	115 MPa	168.86MPa	0.118 mm

Adjustable bracket solution
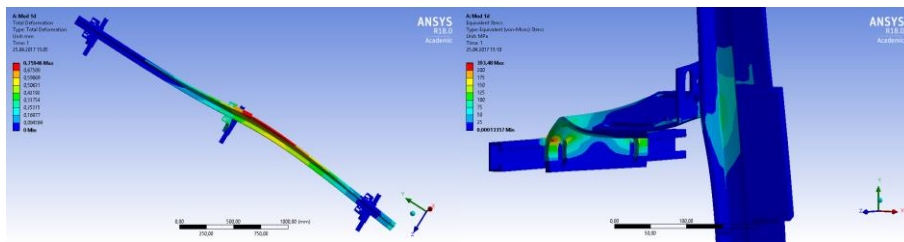
Figure 57 *Load case 2 on Adjustable system*
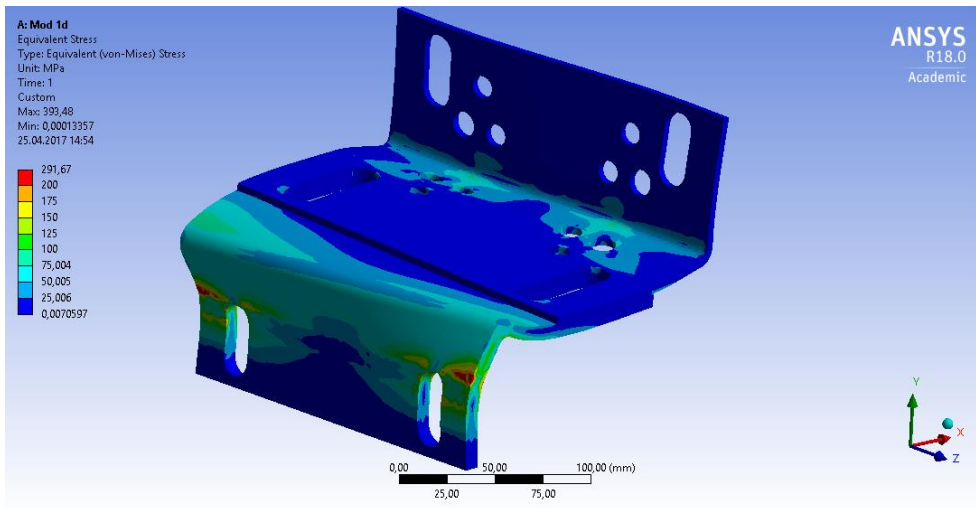
Figure 58 *Load case 2 for adjustable bracket: Simulated worst-case stress result*

Figure 59 *Load case 2 for adjustable bracket: Simulated extreme stress result*

The twisting generated by the guide rail travels through the brackets and causes the maximum stresses to occur on the edges of where the bracket is in contact with the Halfen rail.

Table 17 *Load case 2 for adjustable bracket: Values from simulation results*

Applied force		Real stress	Non-destructive stress	Maximum bracket deflection
Worst-case	F_{y-y} = 5 kN	*200 MPa*	*291.67 MPa*	*0.361 mm*
Extreme	F_{y-y} = 7.5 kN	*295 MPa*	*437.5 MPa*	*0.541 mm*

4.2.3 Load case 3: Centered load on x-x

The force is centered between two brackets with impact on the x-x axis of the guide rail.
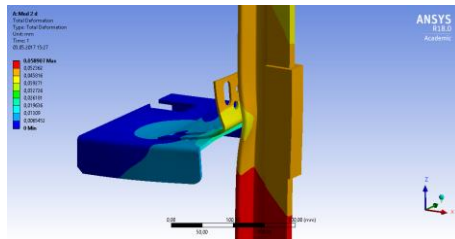
Welded bracket solution
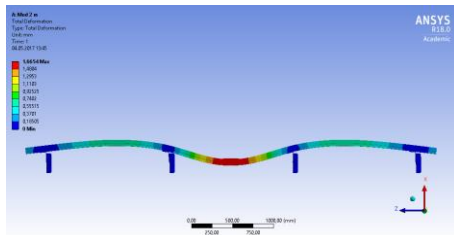
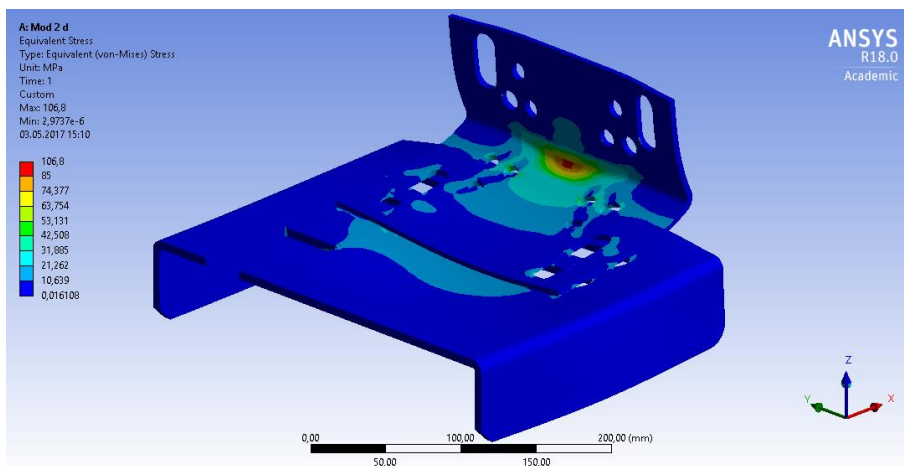*Figure 60* Load case 3 on welded system
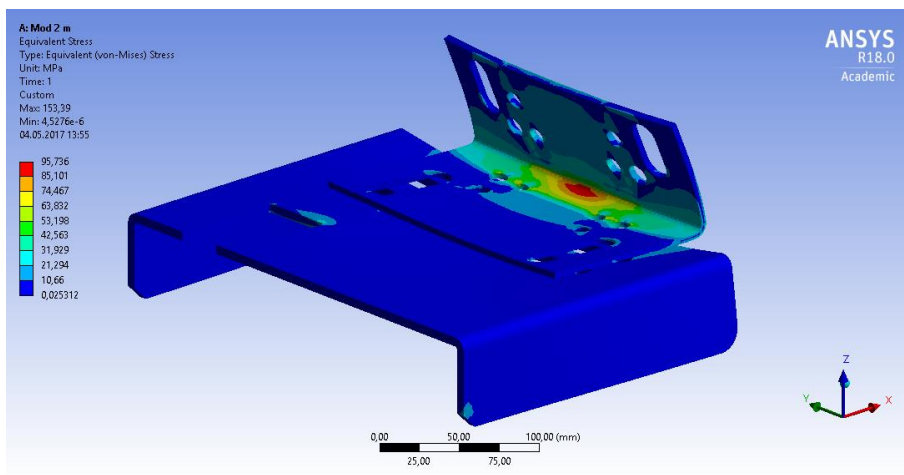
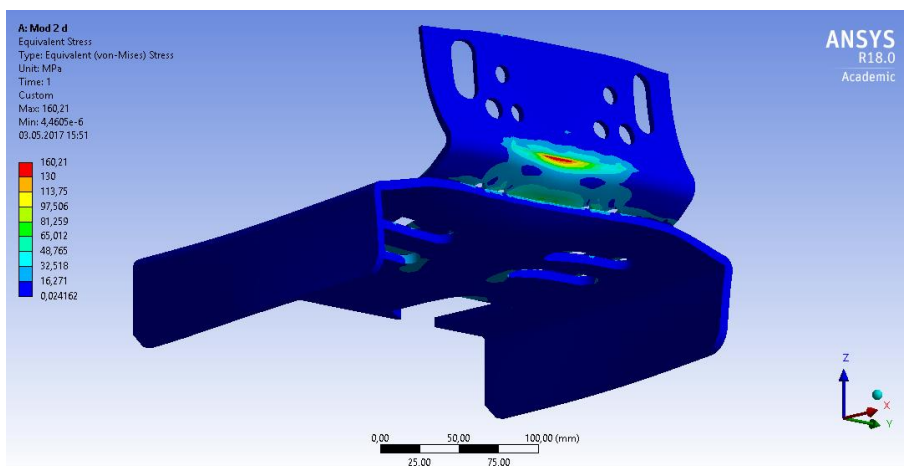*Figure 61* Load case 3 for welded bracket: Simulated worst-case stress result
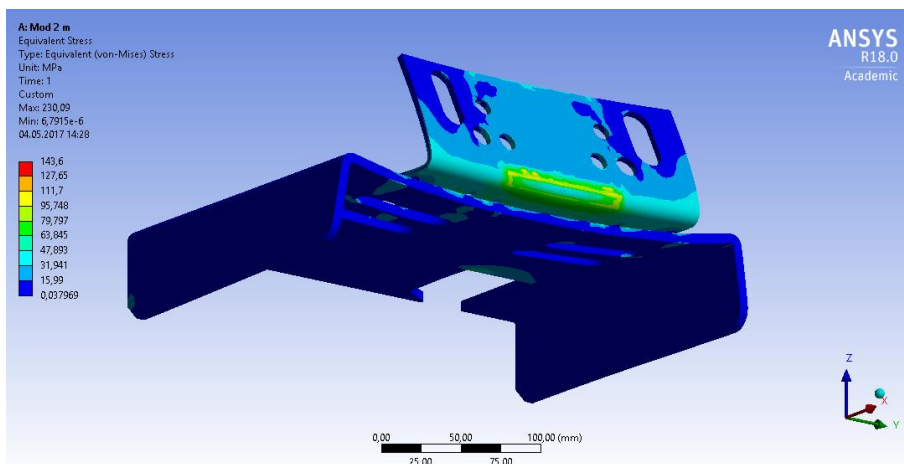
Figure 62 Load case 3 for welded bracket: Simulated extreme stress result

The maximum stresses are found in the bracket directly below the point of impact and are a result of the bending of the smaller bracket part. The stress is concentrated in the back center.

Table 18 Load case 3 for welded bracket: Values from simulation results

| Applied force		Real stress	Non-destructive local stress	Maximum bracket deflection
Worst-case	F_{x-x} = 10 kN	*85 MPa*	*95.376 MPa*	*0.227 mm*
Extreme	F_{x-x} = 15 kN	*128 MPa*	*143.6 MPa*	*0.341 mm*

Adjustable bracket solution
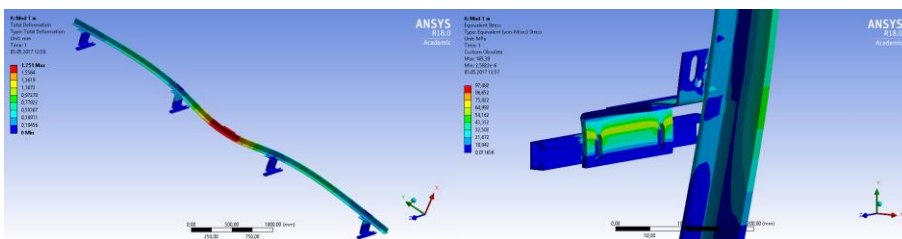
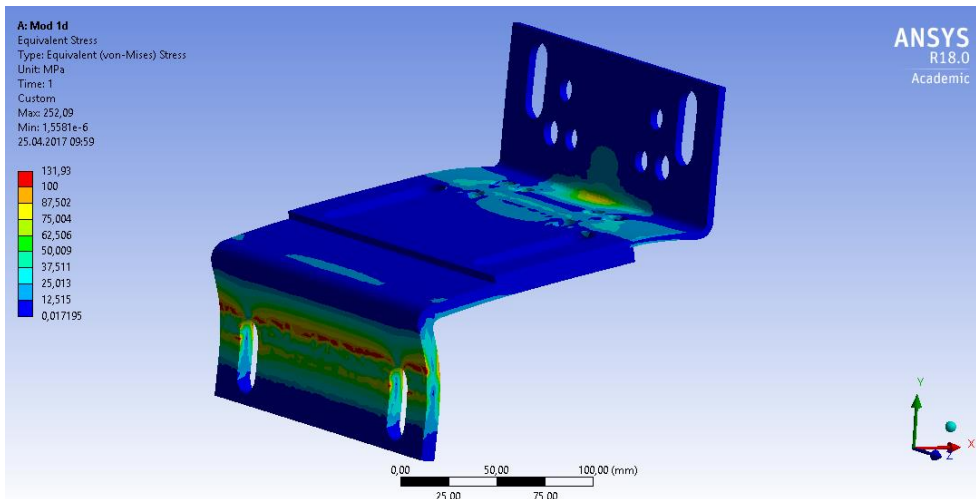*Figure 63 Load case 3 on Adjustable system*
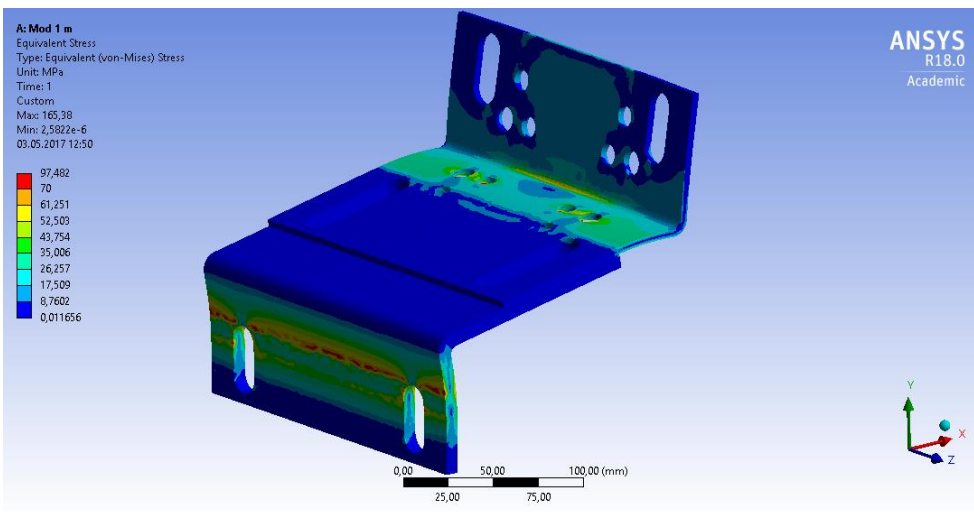
Figure 64 Load case 3 for adjustable bracket: Simulated worst-case stress result
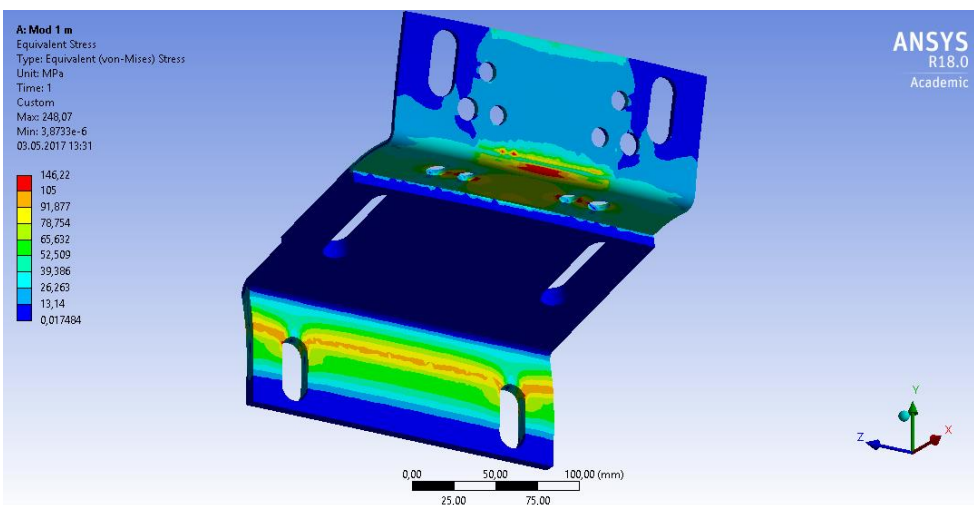
Figure 65 Load case3 for adjustable bracket: Simulated extreme stress result

The maximum stresses are found in the bracket directly above the point of impact and are concentrated in the area of where the bracket bends around the Halfen rail and in the center of where the guide rail is acting on the system.

Table 19 Load case 3 for adjustable bracket: Values from simulation results

Applied force		Real stress	Non-destructive stress	Maximum bracket deflection
Worst-case	F_{x-x} = 10 kN	*70 MPa*	*97.482 MPa*	*0.342 mm*
Extreme	F_{x-x} = 15 kN	*105 MPa*	*146.22 MPa*	*0.513 mm*

4.2.4 Load case 4: Centered load on y-y

The force is centered between two brackets with impact on the y-y axis of the guide rail.

Welded bracket solution
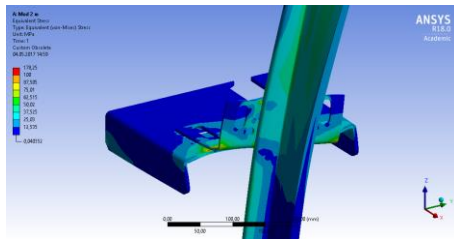
Figure 66 *Load case 4 on welded system*
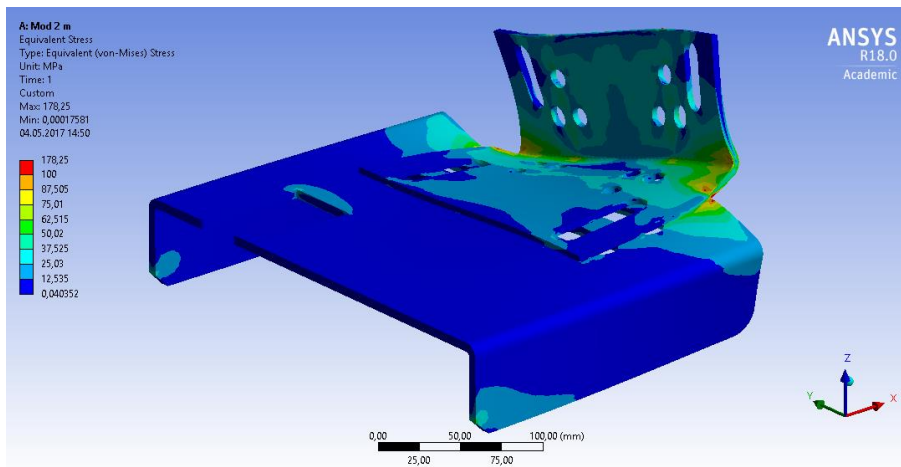
Figure 67 *Load case 4 for welded bracket: Simulated worst-case stress result*
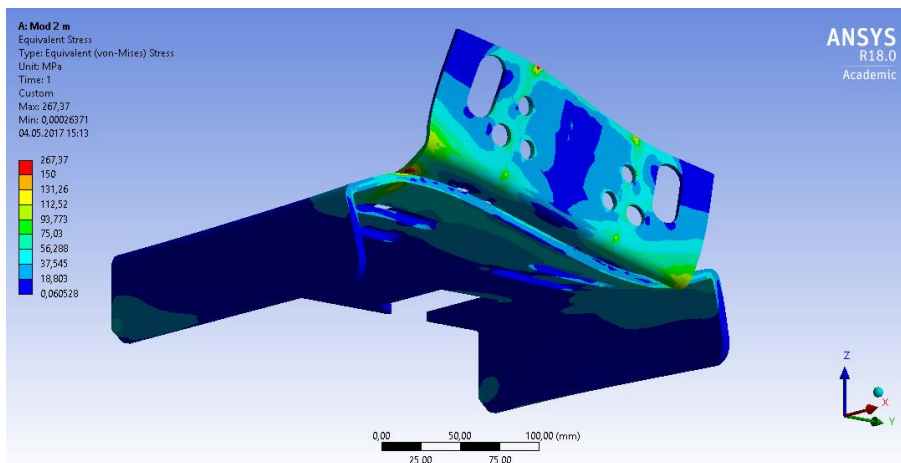
Figure 68 *Load case 4 for welded bracket: Simulated extreme stress result*

The maximum stresses are found in the bracket directly below the point of impact and causes a twisting tension. The largest values are located in the where the components are connected.

Table 20 *Load case 4 for welded bracket: Values from simulation results*

Applied force		Real stress	Non-destructive local stress	Maximum bracket deflection
Worst-case	F_{x-x} = 10 kN	*100 MPa*	*178.25 MPa*	*0.309 mm*
Extreme	F_{x-x} = 15 kN	*150 MPa*	*267.37 MPa*	*0.464 mm*

Adjustable bracket solution
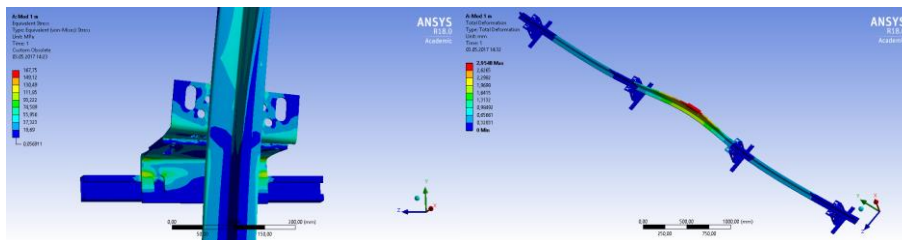
Figure 69 *Load case 4 on Adjustable system*
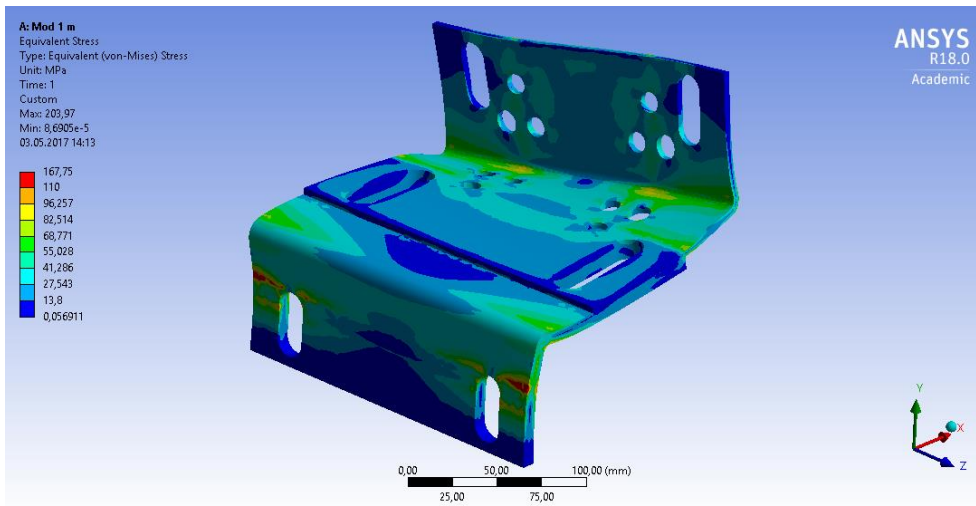
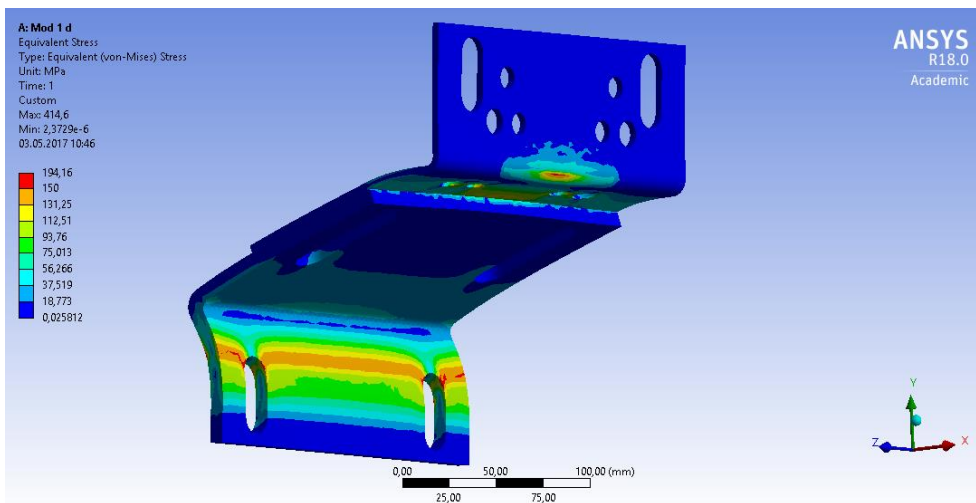*Figure 70* *Load case 4 for adjustable bracket: Simulated worst-case stress result*
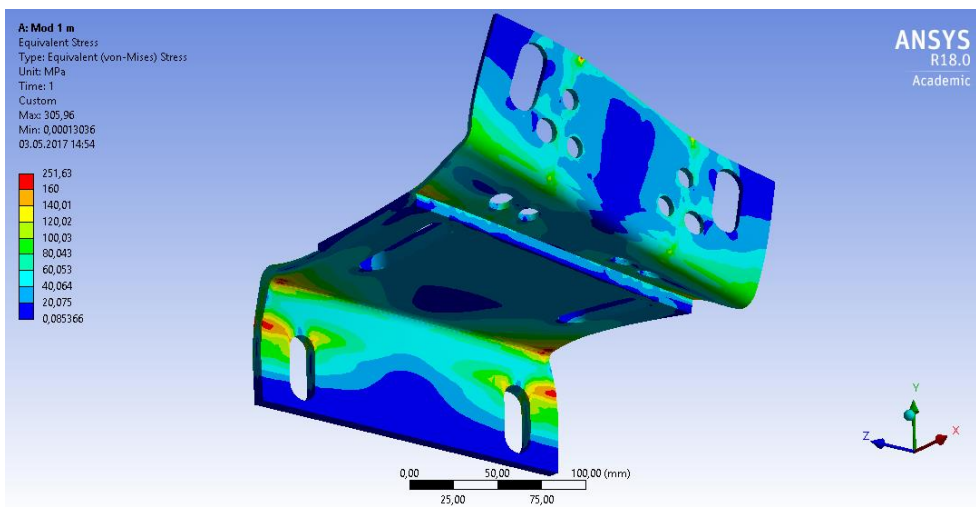
Figure 71 *Load case 4 for adjustable bracket: Simulated extreme stress result*

The maximum stresses are found in the bracket directly below the point of impact and causes a twisting tension. The largest values are located in the edges of where the bracket are connected to the Halfen rail.

Table 21 *Load case 4 for adjustable bracket: Values from simulation results*

Applied force		Real stress	Non-destructive stress	Maximum bracket deflection
Worst-case	F_{x-x} = 10 kN	110 MPa	167.75 MPa	0.479 mm
Extreme	F_{x-x} = 15 kN	160 MPa	251.63	0.718 mm

4.2.5　Load case 5: Vertical drag with slip

The force is vertically applied, dragging the guide between the rail clips with a friction slip.

Welded bracket solution
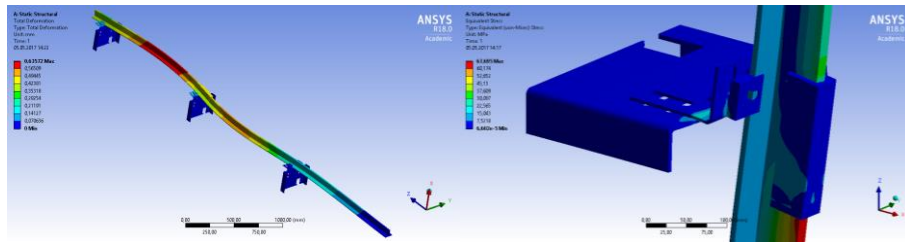
Figure 72 *Load case 5 on welded system*
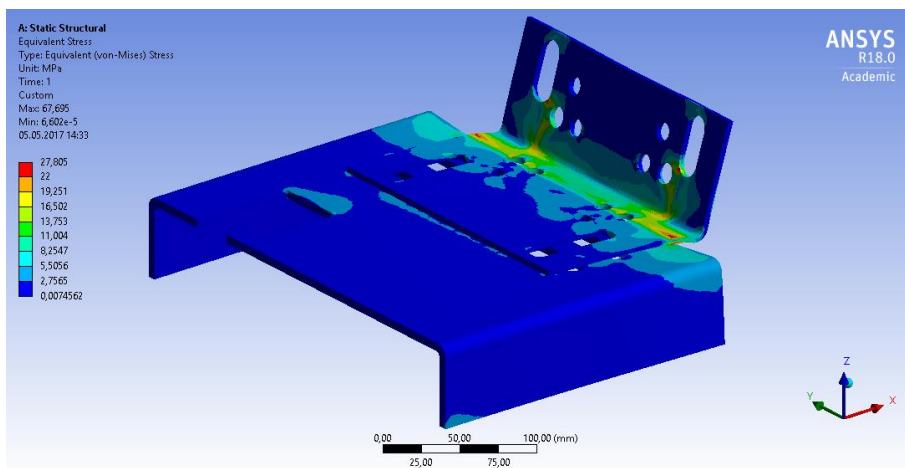
Figure 73 *Load case 5 for welded bracket: Simulated heavy load stress result*
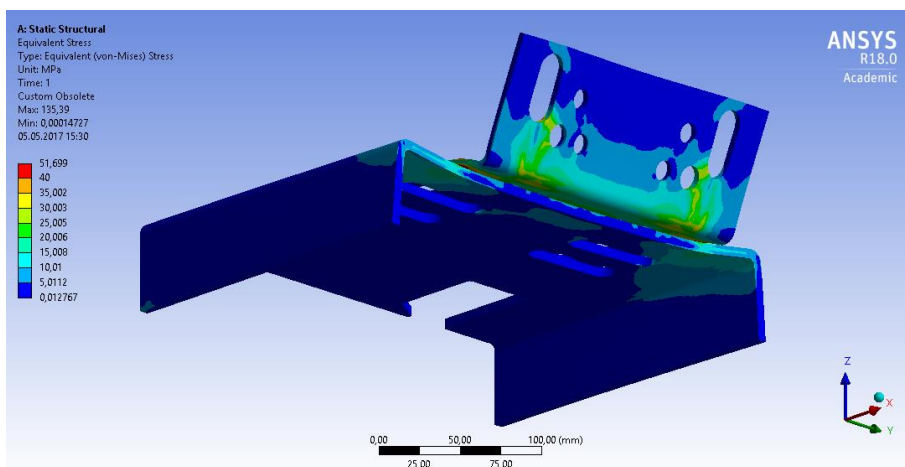
Figure 74 *Load case 5 for welded bracket: Simulated extreme stress result*

The friction force produced cause for a minor bending of the brackets. The largest stresses are found on top of the upper bracket in the area it bends around the welded component.

Table 22 *Load case 5 for welded bracket: Values from simulation results*

Applied force		Real stress	Non-destructive local stress	Maximum bracket deflection
Heavy load	F_{x-x} = 10 kN	*22 MPa*	*27.805 MPa*	*0.136 mm*
Extreme	F_{x-x} = 15 kN	*40 MPa*	*51.699 MPa*	*0.259 mm*

Adjustable bracket solution
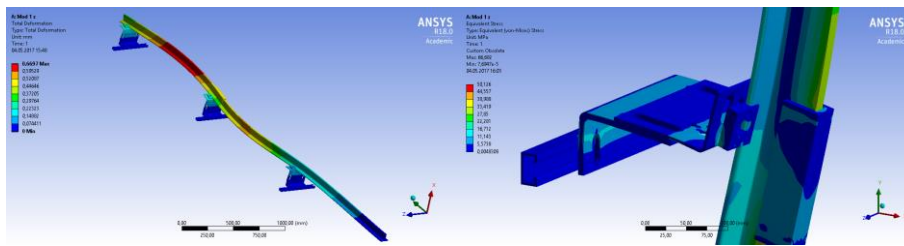
*Figure 75* *Load case 5 on Adjustable system*

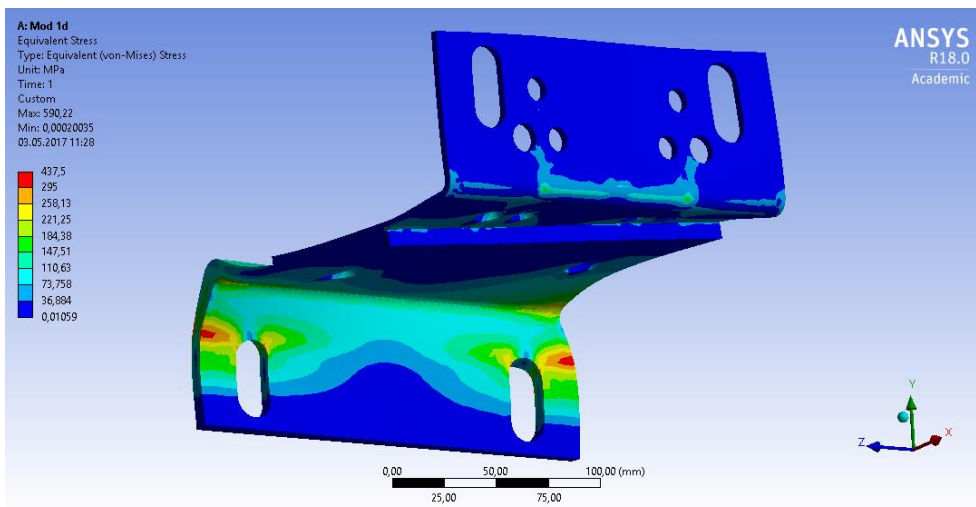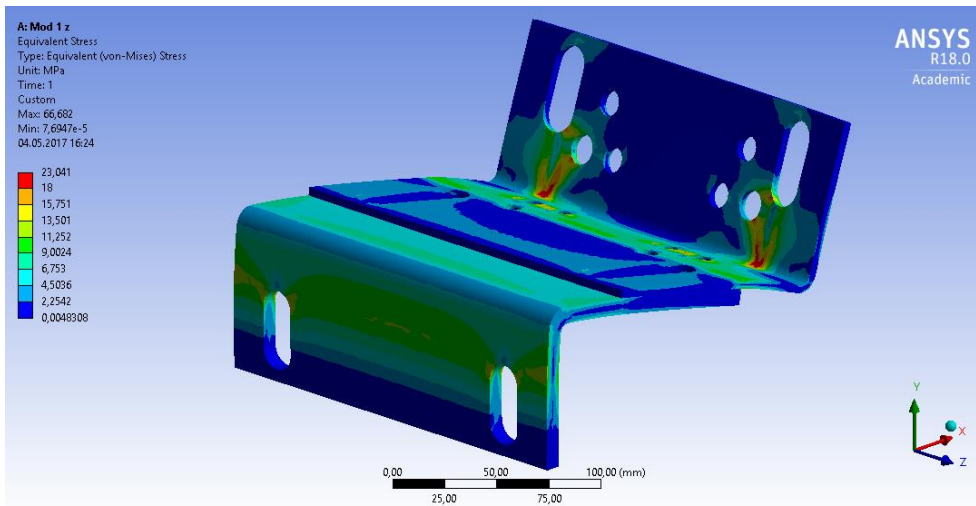*Figure 76* *Load case 5 for adjustable bracket: Simulated heavy load stress result*
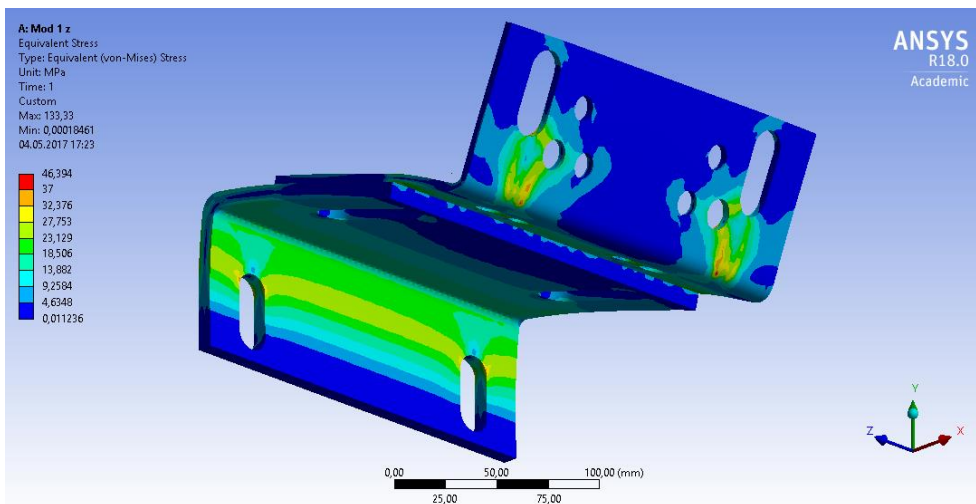
Figure 77 *Load case 5 for adjustable bracket: Simulated extreme stress result*

The friction force produced cause for a minor bending of the brackets. The largest stresses are found in the area of which the rail clips are connected to the bracket.

Table 23 *Load case 5 for adjustable bracket: Values from simulation results*

Applied force		Real stress	Non-destructive stress	Maximum bracket deflection
Worst-case	$F_{x-x} = 10$ kN	18 MPa	23.041 MPa	0.250 mm
Extreme	$F_{x-x} = 15$ kN	37 MPa	46.394 MPa	0.533 mm

4.2.6 Overall bracket stress results

Table 24 *Compete list of simulated bracket stress results*

STRESS RESULTS					
LOAD CASE		**LOADS**			
Direct		Worst-case		Extreme	
		Real	Non-destructive	Real	Non-destructive
1 x-x	*Welded*	*85 MPa*	*107 MPa*	*120 MPa*	*160 MPa*
	Adjustable	*100 MPa*	*131 MPa*	*150 MPa*	*194 MPa*
2 y-y	*Welded*	*75 MPa*	*113 MPa*	*115 MPa*	*167 MPa*
	Adjustable	*200 MPa*	*292 MPa*	*295 MPa*	*438 MPa*
Centered		Worst-case		Extreme	
		Real	Non-destructive	Real	Non-destructive
3 x-x	*Welded*	*85 MPa*	*96 MPa*	*128 MPa*	*144 MPa*
	Adjustable	*70 MPa*	*98 MPa*	*105 MPa*	*146 MPa*
4 y-y	*Welded*	*100 MPa*	*178 MPa*	*150 MPa*	*267 MPa*
	Adjustable	*110 MPa*	*168 MPa*	*160 MPa*	*252 MPa*
Vertical		Heavy load		Extreme	
		Real	Non-destructive	Real	Non-destructive
5 z	*Welded*	*22 MPa*	*28 MPa*	*40 MPa*	*52 MPa*
	Adjustable	*18 MPa*	*23 MPa*	*37 MPa*	*46 MPa*

The simulated stress results from the structural analyses of the brackets are sorted and presented in *Table 24*. For both bracket solution, the obtained result from each load case contains four values that provides an identification on how the two solutions are performing in the different conditions. Even though the actual validation of the brackets are determined by the values in the left stress row only, the combined results contributes to create a transparent impression of the bracket characteristics.

A more analytical presentation of the stress results are presented in *Figure 78* Figure *79*, where the brackets are reviewed separately and the values are measured against a limitation line set equal to the material yield stress. Form this graphic composition, the performance of the welded bracket solution proves to be quite steady, whereas the presentation of the adjustable bracket performance is more variable, depending on the direction of the applied force. Even though the determination line in both graphs provides validation for the application of the solutions, it also indicates a vulnerability for loads acting sideways on the adjustable bracket, especially when the impact is applied directly on the system. In this case, all other readings exceeds the limitation line, indicating that the absolute performance of this solution is at its utmost. As expected, the resulting stresses from the vertical drag proved insignificant.
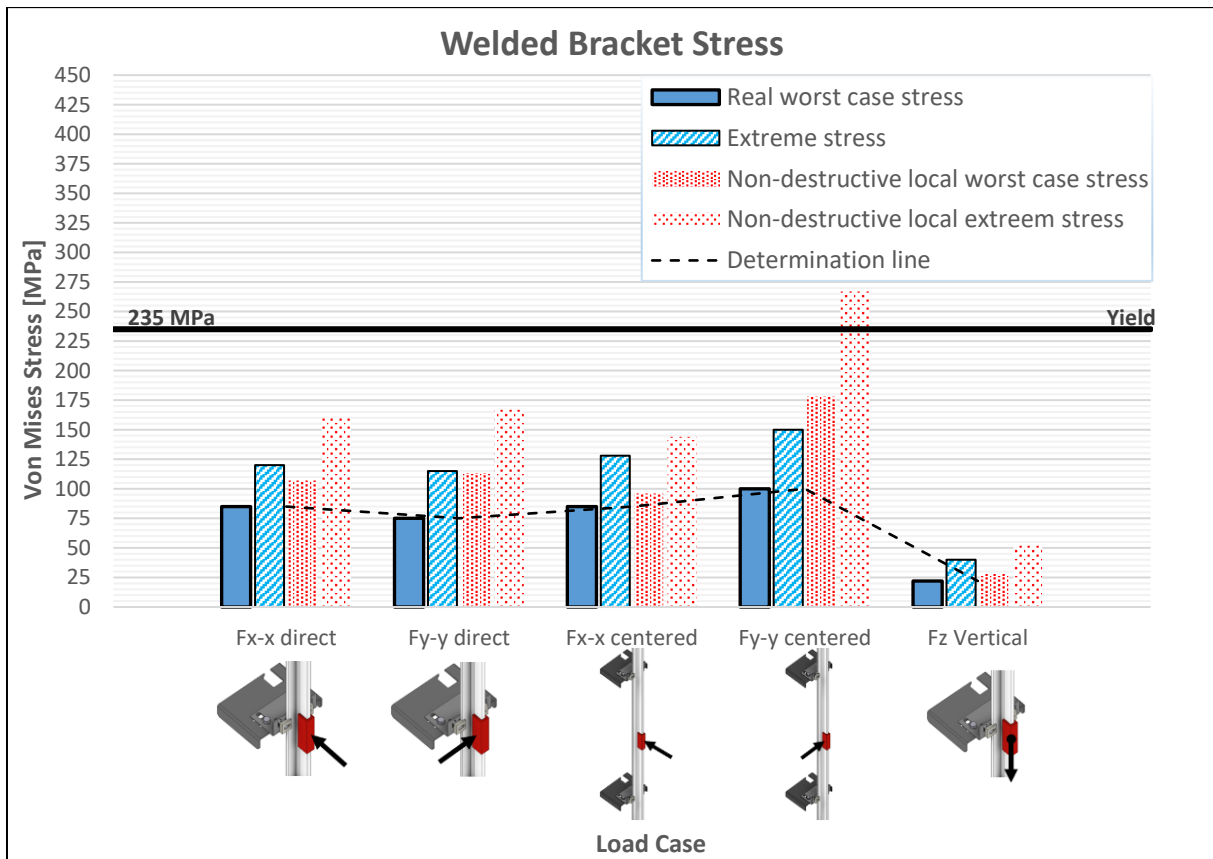
Figure 78 *Welded bracket stress results from structural analysis*
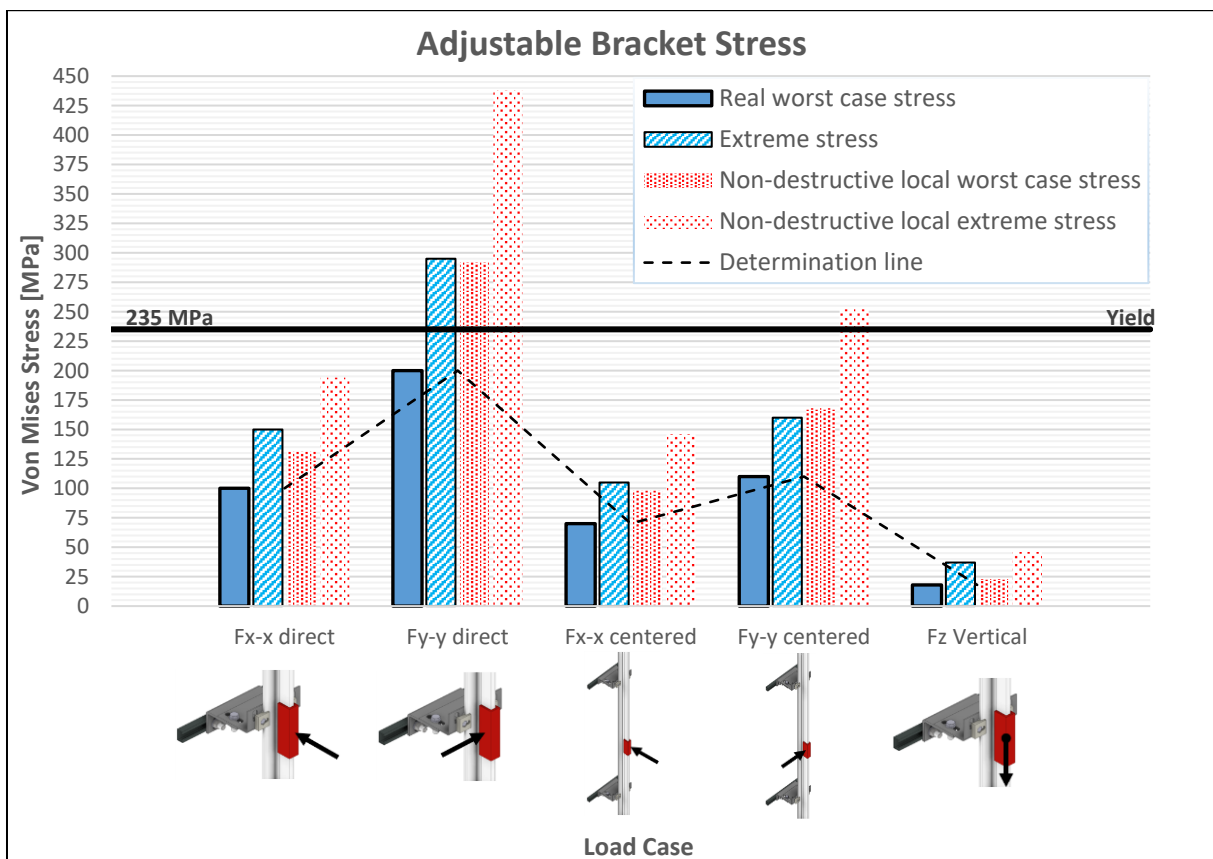
Figure 79 *Adjustable bracket stress results from structural analysis*

4.3 Estimated savings

By combining the information provided for the installation and product specifications in section *2.4* and the estimations performed for the potential savings in section *3.3,* a fairly precise and objective approximation can be accomplished with regards to the concept differences in relation to both component weight and overall expenses. In order to carry out a realistic estimation, a practical example is reviewed, where the specifications are obtained from the current project Vard PNO1967. The main aspects considered for the execution are the guide rail material cost and weight and the approximate amount of working hours spent performing the EGS-installation in a generalized elevator shaft.

4.3.1 Material cost and weight

The product price and weight are retrieved from *Table 6* Cost and weight for spesific guide rail products à 5 m and the type and amount of guide rails for the different methods of sizing are taken from *Table 12*.

Table 25 Material cost and weight for the guide rails needed in the six ellevator shafts

Component info			Traditional sizing			Optimized sizing		
Dimension	Price [€]	Weight [kg]	Amount [pcs]	Cost [€]	Weight [kg]	Amount [pcs]	Cost [€]	Weight [kg]
T127	257	116	47	12058	5447	0	0	0
T90	154	68	48	7399	3252	72	11098	4878
T70	68	44	0	0	0	23	1564	1015
Sum			*95 pcs:*	**19457 €**	**8699 kg**	*95 pcs:*	**12662 €**	**5893 kg**
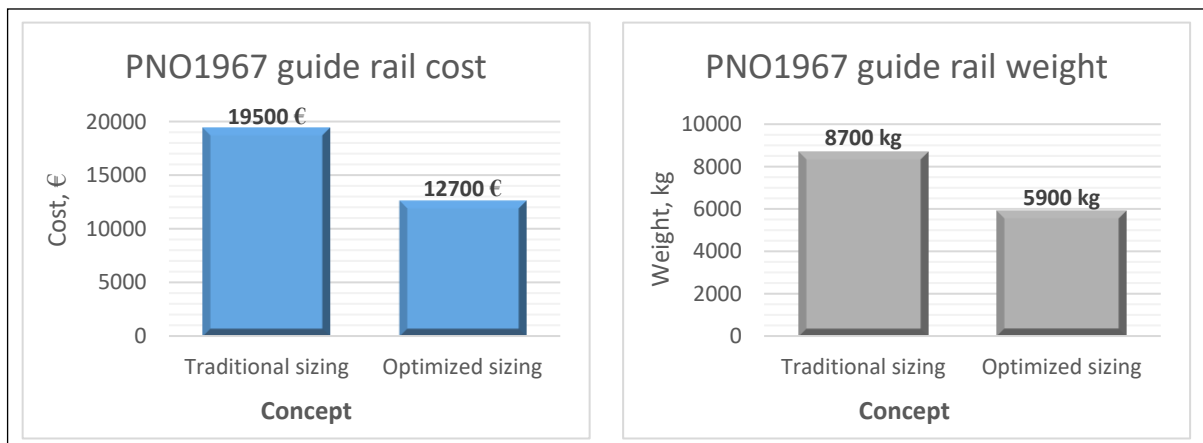
Figure 80 *Guide rail cost and weight rounded off to the nearest hundred*

The results from *Table 25* are rounded off to the nearest hundred and presented in *Figure 80*, where the distinctive differences for the methods of sizing are visualized. Since the results are based on the total of six elevator shafts with more or less the same characteristics, it is considered reasonable to make a generalization for the potential savings per shaft and use this in the estimations for similar projects. The potential guide rail material savings from using the optimized method of sizing is presented in *Table 26* for both the project and per shaft.

Table 26 *Potential material savings when applying the optimized method for sizing*

Guide rail material savings				
Scope	Cost		Weight	
Vard PNO1967	6795 €	34.9 %	2806 kg	32,3 %
Approximate pr. shaft	1132 €		468 kg	

4.3.2 EGS-installation cost

When combining the estimated amount of work hours needed for installing the EGS in a generalized elevator shaft, found in Table 13, with the hourly rate for technicians provided in *Table 7*, the approximate EGS-installation cost is estimated for the different concepts and presented in *Table 27*.

Table 27 *Estimated EGS-installation cost*

Approximate EGS-installation cost					
Indication		**Concept 1:** Traditional Welded	**Concept 2:** Traditional Adjustable	**Concept 3:** Optimized Welded	**Concept 4:** Optimized Adjustable
Specifications:					
Hourly rate	*€/h*	*75*	*75*	*75*	*75*
Work hours	*h/shaft*	*100*	*70*	*88*	*60*
Cost pr. shaft	*€*	*7500*	*5250*	*6600*	*4500*
Vard PNO1967	*€*	*45000*	*31500*	*39600*	*27000*
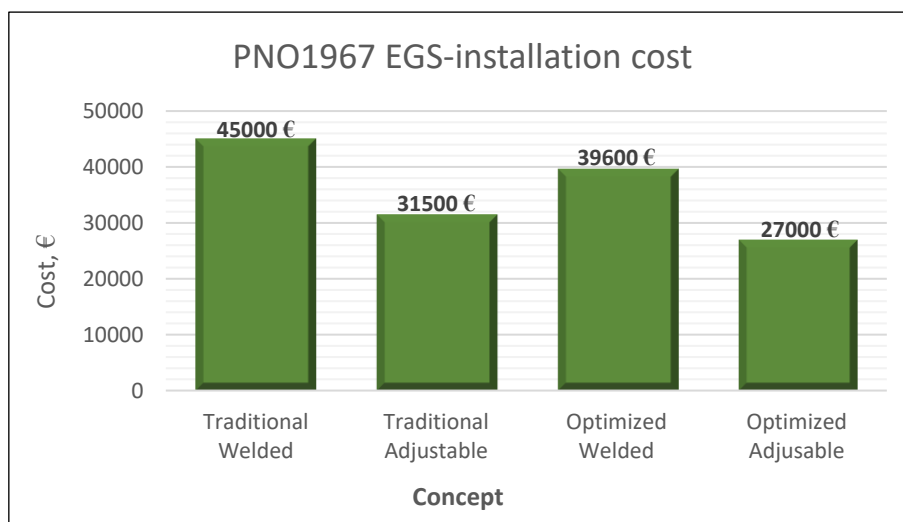
Figure 81 *Estimated concept EGS-installation cost for PNO1967*

The potential savings for the different concepts of EGS-installation are estimated from the traditional welded concept as the base case and presented in *Table 28*, indicating the reduction for both the project and per shaft.

Table 28 *EGS-installation cost reduction for the various concepts*

	Concept	Vard PNO1967	Approximate pr. shaft	Percent
EGS-installation cost reduction				
1	Traditional welded	*(45000 €)*	*(7500 €)*	*(100 %)*
2	Traditional adjustable	*-13500 €*	*-2250 €*	*-30.0 %*
3	Optimized welded	*-5400 €*	*-900 €*	*-12.0 %*
4	Optimized adjustable	*-18000 €*	*-3000 €*	*-40.0 %*

4.3.3 Overall reduction potential of EGS-expenses

Based on the approximations and assumptions made throughout section *4.3,* an overall estimation is made in relation to the EGS-expenses. The overall estimated expenses for Vard PNO1967 are listed in *Table 29* and presented in *Figure 82.*

Table 29 *Estimated overall EGS-expenses for PNO1967*

Concept	Material cost	Installation cost	Overall expenses
Estimated EGS-expenses for PNO1967			
1	*19500 €*	*45000 €*	***64500 €***
2		*31500 €*	***51000 €***
3	*12700 €*	*39600 €*	***52300 €***
4		*27000 €*	***39700 €***
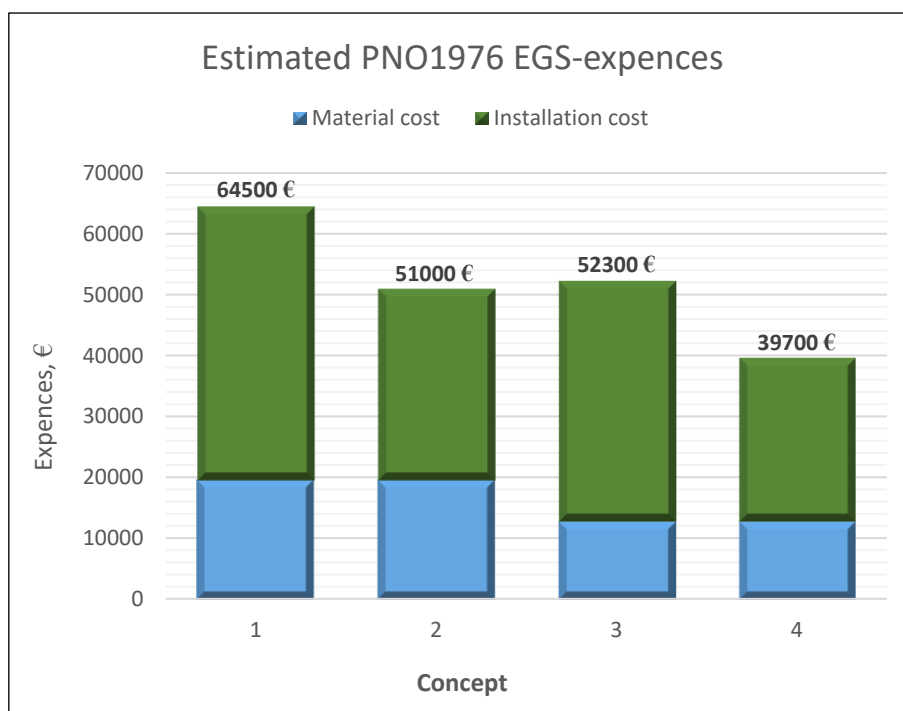
Figure 82 *Estimated overall EGS-expenses for PNO1976*

The estimation of the different expenses for the various concept indicates a considerable variation in the overall EGS-expenditures. In *Table 31*, the potential overall cost reductions are listed for the concepts in relation to the base case. The *cost* reduction is presented with respect to the EGS-expenses for both a single elevator shaft and for the reviewed project. In addition, based on the collection provided in *Table 30,* an estimation is included for all current potential projects thyssenkrupp is involved with.

Table 30 *Current potential projects and elevator shafts*

Current potential projects			
Project	Nr. of vessels	Lifts pr. ship	Nr. of elevators pr. project
Hurtigruten	4	8	32
Hapaq Lloyd	2	5	10
Collor Line	1	9	9
Sunshine	1	6	6
Ponant	4	6	24
Total amount of potential elevator shafts			81

*Subjected to changes

Table 31 *Estimated reduction potential for overall EGS-expenses*

Estimated overall reduction of EGS-expenses				
Concept	Per shaft	Vard PNO1967	Current potential projects	Percent
1	*(10750 €)*	*(64500 €)*	*(870750 €)*	*(100 %)*
2	*-2247 €*	*-13500 €*	*-181987 €*	*-20.9 %*
3	*-2032 €*	*-12200 €*	*-164572 €*	*-18.9 %*
4	*-4128 €*	*-24800 €*	*-334368 €*	*-38.4 %*

5. Discussion

The discussions in this chapter consists of two parts; one where the reviewed concepts are assessed against a weighted screening method in order to make an objective statement regarding their individual potential and the other where the general aspects of the research are discussed in greater detail.

5.1 Assessment

The concepts are assessed based on the three screening principles complexity, risk and cost, as discussed in section *3.1* and rated on a scale from *one* to *four* depending on the corresponding qualities identified in this research. A score of one suggests a poor performance in relation to the screening principle in question, whereas a score of four indicates excellent potential. The score will point out the characteristics of the concept, either positive or negative, but must be considered in context with the final weighted rating in order to identify the concept applicability. A score of two and three suggests acceptable and good performance, respectively.

Principle rating

POOR ← | **1** | **2** | **3** | **4** | → **EXCELLENT**

Since the screening principle related to the concept expenses is a more concise and measurable criteria, the concept rating with respect to cost is given based on the potential savings in accordance to the below scale.

Reduced cost rating

	1	2	3	4	
POOR ←	>10%	<10%	<20%	<30%	→ EXCELLENT
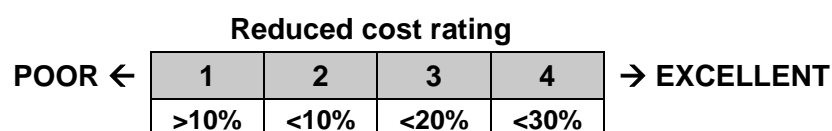
5.1.1 Concept 1: Traditional welded

In this concept, the guide rails are determined from the traditional sizing method, which in most cases results in over-engineering and the application of massive dimensions. This could complicate the situation with regards to the shipyards wishes to keep the component weight to a minimum within the elevator shaft and reduce the quality of the finished product. However, the massive dimensions will provide structural abilities way beyond the requirements for certification set by DNV. Because of this, the concept is considered as excellent with respect to potential risks and given the highest score for this criteria. Even though the component weight might cause complications, the application of the welded bracket solution eliminates the complexity tied to altering potential stiffeners inside the trunk and the implementation of this concept is therefore *not* considered as complex. The welded bracket is however considered as a poor solution in relation to the installation time and resulting cost. In addition, the material cost is considered quite high for the massive guide rail dimensions applied in this concept which is expected to have the highest EGS-expenses. Because of this, the traditional welded concept is defined as the base case in relation to the overall cost and is therefore at a

zero percent cost reduction. The rated score in relation to the screening principles for this concept is presented in *Table 32* below.

Table 32 *Concept 1: Rated score*

Complexity	Risk	Cost
3	4	1

5.1.2 Concept 2: Traditional adjustable

For the second concept, the guide rails are sized using the same method as for the base case, which results in high component weights inside the elevator trunk. In this case, the adjustable bracket solution is considered for the EGS. Because this solution requires a smooth trunk surface in the area for the associated Halfen rail, this could complicate the applicability of the concept if the issue is not addressed in early dialog with the shipyard and the stiffeners are placed on the inside the trunk. As a result of these potential complications, this concept is rated poorly against complexity. The structural abilities for the guide rail is the same as for the base case, whereas the bracket solution proves to be more variable depending on the direction of impact. However, the solution is within the requirements and verified against the conservative worst-case loads and is therefore considered to perform well in relation to potential risks. As a result of applying the adjustable brackets, the estimated EGS-installation time for this concept is reduced and the overall potential savings are 20.9 % compared to the base case and therefore given the score of *three* for cost.

Table 33 *Concept 2: Rated score*

Complexity	Risk	Cost
1	3	3

5.1.3 Concept 3: Optimized welded

In this concept, the optimized method for sizing of guide rails are applied and the potential risk of over-engineering against the requirements for validation is eliminated. This method is combined with the welded bracket solution and the concept can be applied without regards to any stiffeners. As a result of this and the reduced component weight, the concept abilities are considered as excellent in relation to the complexity. This is also the case with regards to potential risks, as then structural abilities of the EGS-components are validated and performes at a stable level. The potential savings are reduced as a result of the optimized sizing of the guide rail, but the resulting installation time for applying the welded bracket solution keeps the potential cost reduction below 20 %.

Table 34 *Concept 3: Rated score*

Complexity	Risk	Cost
4	4	2

5.1.4 Concept 4: Optimized adjustable

The fourth concept reviewed in this research is generally considered as the most promising alternative for future projects. However, there are aspects related to the concept that could complicate the implementation and limit the application. Even though the component weights are reduced, the complication related to the possible trunk stiffeners is an issue that needs to be addressed for the concept to be feasible. Also, the variation in bracket performance might cause for some concern if the system should ever be exposed to lodes exceeding the area for validation. Still, the concept abilities are considered good against potential risks. In relation to the expenses, the potential cost reduction for both the material and installation time amounts to a total of 38.4 % compared to the base case, which is considered as excellent.

Table 35 *Concept 4: Rated score*

Complexity	Risk	Cost
2	*3*	*4*

5.1.5 Weighted screening

The weighted screening is a system developed for evaluating the concept applicability as a whole. By multiplying the rated score given for each screening principle with the weighted score of the principle itself, a score is given to reflect the magnitude of this. Combining the results, a total score is used to find the normalized rating, placing the concept within the defined range.

Min score	<25%	<50%	<75%	Max score
	Scrapped	Not recommended	Recommended	Highly recommended
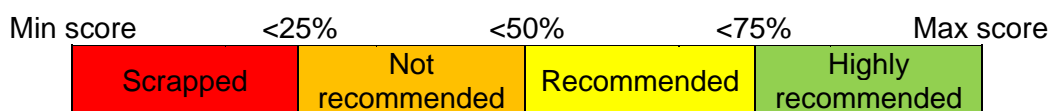
A color code will provide an indication for the assessment of the concepts accordingly to the above scale. The screening principles are weighted relatively to the impact they might have on the project based on the criteria previously discussed in section *3.1*. The weighting is scaled from one to five, where one is insignificant, two is subordinate, three is important, four is essential and five is vital.

Weighted rating

INSIGNIFICANT ← | 1 | 2 | 3 | 4 | 5 | → VITAL
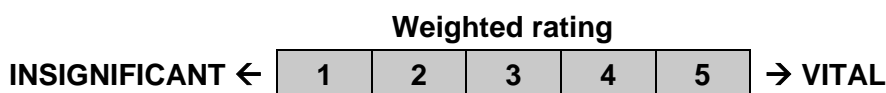
Complexity   [2]

The main issues considered in relation to the complexity are the component weight inside the trunk and the feasibility related to the possible stiffeners. Even though a potential reduction of the material weight might be considered as an advantage with respect to the quality of the product, it is considered negligible in relation to the bigger picture. More severe is the issue related to the trunk stiffeners. However, the management for the marine department in thyssenkrupp clams that this issue can be resolved by conducting a transparent dialog with

the shipyard in the early phases of a project and state the areas of the trunk that should be smooth for the bracket positioning. Because of this, the complexity as a screening principle is considered to be of subordinate impact for the concept.

Risk   [1]

The risk aspect related to the marine operations are initially of vital importance when considering the assessment of project that are to be executed. However, all concepts considered in this research is validated against the worst-case conditions and should therefore be regarded as safe. As a result of this, the impact of the weighted screening for risk is defined as insignificant.

Cost   [5]

For the supplier the project will always be cost driven where the overall expenses can determine whether a concept is a profitable solution for an application and whether it should be recommended for a project or not. Therefore this screening criterion is weighted to have a vital impact on the assessment.

Table 36 Weighted screening for objective assessment of concepts

Screening principle	Weight	TRADITIONAL WELDED	TRADITIONAL ADJUSTABLE	OPTIMIZED WELDED	OPTIMIZED ADJUSTABLE
		Score			
Complexity	2	3	1	4	2
Risk	1	4	3	4	3
Cost	5	1	3	2	4
Min/Max score	8/32	Total score			
		15	20	22	27
		Normalized score			
		29%	50%	58%	79%
		Not recommended	Not recommended	Recommended	Highly recommended

5.2 General

For land based elevators installed in normal conditions, the performance of the EGS is usually not considered to be of noteworthy importance and little attention is payed to the sizing of the components as long as they are within reason. However, for installations on ships, the elevators are exposed to the maritime conditions and the ship motion generates another specter of load cases on the EGS. The soul propose of the system is mainly to provide guidance for the vertical travel of the elevator components, but must also provide a sufficient amount of support against loads acting in the horizontal direction when installed on ships. Because of the unpredictable movements, strict requirements are established for the marine elevates, where the role of the EGS is of vital importance and defined as the main aspect for certification of an installation with regards to the structural abilities.

As a respectable supplier of ship elevators, the marine department of thyssenkrupp have been looking for opportunities to improve the operation. As a result of strong suspicions of over-engineering of the components applied for the marine EGS, an attempt to optimize the system was determined and an extensive research on the topic was initiated.

In order to fulfill the intentions, the main objective for the study was set to develop optimization methods for avoiding over-engineering, reducing both cost and weight for the main components. In doing so, proper validation of the necessary solutions was implied. Because the requirements for certification primarily concerns the guide rails in the EGS, a system was developed to conduct the conservative sizing based on the exact specifications set by the notifying body. The mathematical approach were developed according to the DNV requirement and validated by DNV representatives through the attached mail correspondence.

In a further development of the manual sizing method, an automatic sizing tool was created for the guide rails. One of the major issue with thyssenkrupp`s traditional method of sizing is related to a misinterpretation regarding the requirements for operating and stowed conditions and the method could have the potential to improve if corrected. However, instead of suggesting a solution for validation, the automatic method is constructed to return the optimal solution for a specific project using only four input specifications. Basically, this tool provides a highly efficient method for evaluating projects based on the best possible solution that is guaranteed to be approved by DNV. Since the automatic method determined the optimal solution, the calculations are based on the worst-case scenario of roll during stowed conditions only. However, the user can still access the manual sizing in the calculation tool and be free to apply whichever load case desired. Because the optimized method produce solutions validated by the DNV, there are no reason for applying the traditional methods and the assessed concepts *one* and *two* should therefore be eliminated as alternatives for future project evaluations. Since the orientation of the guide rails have proven to influence the EGS performance based on the worst-case, it is something that should be discussed with the customer at an early stage in case this could result in the application of a guide rail with a smaller dimension, reducing both cost and weight even further.

Another issue that should be addressed in the early phase of a project, is the decision on where to place the brackets within the elevator trunk and arrange with the shipyard to have them provide a smooth surface for the designated areas. In doing so, the adjustable brackets may be applied, resulting in a substantial reduction in terms of installation costs. Even though the adjustable bracket shows a venerability against sideways impacts directly on the system, both bracket solutions are validated against the worst-case scenario and should therefore be treated at fully applicable components. The fact that the structural analysis performed in this study indicates that the adjustable bracket is closer to the indicated limitation line, suggests a better utilization of the material compared to the welded bracket solution in terms of engineering.

The estimation of the potential savings was carried out with comparisons to concept *one* as the base case in order to make an approximate suggestion on the main differences of the various aspects regarding the EGS as an isolated system. This because there are several other aspects related to the entire elevator installation that are not considered in this research. Therefore, when assessing the concept expenditures, the potential cost reduction is the only factor of interest and *not* the actual expense. The practical example chosen for the estimation is a typical project according to the portfolio of thyssenkrupp and can therefore be used as a fairly good generalization when passing judgement on the potential project savings. The estimated cost reduction for the current potential projects combined may not provide an accurate amount, but in terms of estimation illustrates the severity of the potential scope.

In the event of conducting furfure research on this topic, the applications stated in DNV GL Classification of Ships could be considered for determining the ship motion on a specific vessel. Implementing this method could in some cases result in a slightly better result in relation to the guide rail sizing. However, this is a complex method which cannot be standardized to the extent of the method from DNV GL Rules for Lifts on Ships. Also, the results are seldom noteworthy improved, if any at all, and the method is not jet approved for validation of the EGS.

6. Conclusion

For elevators installed on ships, the EGS is considered the main issue for certification against structural abilities. The validation of this system is determined by the requirements set by DNV GL and the associated components should be engineered based on the empirical specifications required. Regardless of any motions caused by hydro dynamic forces for a specific vessel or the positioning of the elevator trunk within the ship, the performed evaluation method is considered quite conservative and provides a sufficient proof of validation in the format most preferred by the notifying body.

The calculation tool developed in this research provides an optimized method for sizing of the guide rails and since the method has been validated by DNV, it should immediately be implemented in the evaluation process for current and future projects. In doing so, the potential reduction in both material weight and cost is quite significant.

Structural analysis trough FEM-simulations indicates that both bracket solutions revived in this research are within the limitations for the worst-case scenario and fit for use in the applications. The welded bracket solution provides a steady performance across all load cases and with a great distance from the limitation line, whereas the performance of the adjustable solution is more variable and closer to the limit, in particularly for sideways impacts directly on the system. In terms of sizing, the adjustable bracket utilizes its potential to a greater extend and when implemented in the system, the installation cost is expected to drop drastically compared to the welded bracket, on the account of reduced amount of work hours needed for the application.

The overall reduction potential of the EGS-expenses estimated for the defined concepts in this study is of substantial magnitude and illustrates the severity of the scope. The main expenditures related to EGS are considered as a result of the material cost and installation time. The potential savings are therefore based on the combination of the method for guide rail sizing conducted and the applied solution for bracket support.

The assessments carried out in this study suggests that concept *one* and *two* should *not* be recommended for future projects and it is concluded to consider the optimized concepts exclusively. The only factor separating these two concepts is the applied bracket solution, where the preferred solution requires a smooth trunk surface to be applicable. There is a large difference in potential savings for these concepts with respect to the installation cost and the supplier should always tribe to achieve the implementation of the adjustable bracket solution.

It is recommended to establish a customer relationship that opens up for transparent communication and allows for dialog and discussions regarding the installation related to the elevator specifications. In doing so, it should be possible to conduct certain arrangements so that the adjustable bracket can be applied and the orientation of the guide rails set to the most appropriate position. This will make it feasible to implement the best possible solution for each individual project.

7. References

[1]   *Digi Tech Elevators , "Machine room traction elevators," 2017. [Online]. Available: http://digitechelevators.com/?page_id=414.*

[2]   *ISO 630, Structural steels - Plates, wide flats, bars, sections and profiles, International Standard, 2011.*

[3]   *BONLY, "Elevator Guide rail," 2013. [Online]. Available: https://www.youtube.com/watch?v=v9VYlZDluzE&t=11s.*

[4]   *ISO 7465, Passenger lifts and service lifts - Guide rails for lift cars and counterweights - T-type, International Standard, 2007.*

[5]   *Monteferrio, Product and Service, Monteferro, 2015.*

[6]   *DNV GL, Rules for Certification of Lifts in Ships, Mobile Offshore Units and Offshore Installations 2008, Det Norske Veritas GL, 2008.*

[7]   *Getxo Ship, "Ship`s motions at sea," 2014. [Online]. Available: http://getxoship.blogspot.no/2014/01/shipsmotions-at-sea-vesselunder-sea-has.html.*

[8]   *ISO 8383, Lifts on Ships - Specific requirements, International Standard, 1991.*

[9]   *ABS, Guide for Certification of Lifting Appliances, New York: American Bureau of Shipping, 2014.*

[10]   *LR, Code for Lifting Appliances in a Marine Environment, Loyds Register, 2014.*

[11]   *EN 81-20, Safety rules for the construction and installation of lifts - Lifts for the transport of persons and goods - Part 20: Passenger and goods passenger lifts, European committee for Standardization, 2011.*

[12]   *Sky Elevator, "Products," 2015. [Online]. Available: http://www.sky-elevator.com/index.php?sayfa=alt_urunler&dil=eng&kategori=34.*

[13]   *Banett, "Hurtigruten bygger fire nye skip," 2016. [Online]. Available: http://www.banett.no/nyheter/2016/04/21/Hurtigruten-bygger-fire-nye-skip-12632008.ece.*

8. List of appendices

70

RULES FOR CERTIFICATION OF LIFTS

Table 2 Buckling factor ω as a function of λ for steel of 370 N/mm² grade

λ	0	1	2	3	4	5	6	7	8	9	λ
20	1.04	1.04	1.04	1.05	1.05	1.06	1.06	1.07	1.07	1.08	20
30	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.13	1.13	30
40	1.14	1.14	1.15	1.16	1.16	1.17	1.18	1.19	1.19	1.20	40
50	1.21	1.22	1.23	1.23	1.24	1.25	1.26	1.27	1.28	1.29	50
60	1.30	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.39	1.40	60
70	1.41	1.42	1.44	1.45	1.46	1.48	1.49	1.50	1.52	1.53	70
80	1.55	1.56	1.58	1.59	1.61	1.62	1.64	1.66	1.68	1.69	80
90	1.71	1.73	1.74	1.76	1.78	1.80	1.82	1.84	1.86	1.88	90
100	1.90	1.92	1.94	1.96	1.98	2.00	2.02	2.05	2.07	2.09	100
110	2.11	2.14	2.16	2.18	2.21	2.23	2.27	2.31	2.35	2.39	110
120	2.43	2.47	2.51	2.55	2.60	2.64	2.68	2.72	2.77	2.81	120
130	2.85	2.90	2.94	2.99	3.03	3.08	3.12	3.17	3.22	3.26	130
140	3.31	3.36	3.41	3.45	3.50	3.55	3.60	3.65	3.70	3.75	140
150	3.80	3.85	3.90	3.95	4.00	4.06	4.11	4.16	4.22	4.27	150
160	4.32	4.38	4.43	4.49	4.54	4.60	4.65	4.71	4.77	4.82	160
170	4.88	4.94	5.00	5.05	5.11	5.17	5.23	5.29	5.35	5.41	170
180	5.47	5.53	5.59	5.66	5.72	5.78	5.84	5.91	5.97	6.03	180
190	6.10	6.16	6.23	6.29	6.36	6.42	6.49	6.55	6.62	6.69	190
200	6.75	6.82	6.89	6.96	7.03	7.10	7.17	7.24	7.31	7.38	200
210	7.45	7.52	7.59	7.66	7.73	7.81	7.88	7.95	8.03	8.10	210
220	8.17	8.25	8.32	8.40	8.47	8.55	8.63	8.70	8.78	8.86	220
230	8.93	9.01	9.09	9.17	9.25	9.33	9.41	9.49	9.57	9.65	230
240	9.73	9.81	9.89	9.97	10.05	10.14	10.22	10.30	10.39	10.47	240
250	10.55										

For steel qualities with intermediate strengths, determine the value of the ω by linear interpolation

Table 3 Buckling factor ω as a function of λ for steel of 520 N/mm² grade

λ	0	1	2	3	4	5	6	7	8	9	λ
20	1.06	1.06	1.07	1.07	1.08	1.08	1.09	1.09	1.10	1.11	20
30	1.11	1.12	1.12	1.13	1.14	1.15	1.15	1.16	1.17	1.18	30
40	1.19	1.19	1.20	1.21	1.22	1.23	1.24	1.25	1.26	1.27	40
50	1.28	1.30	1.31	1.32	1.33	1.35	1.36	1.37	1.39	1.40	50
60	1.41	1.43	1.44	1.46	1.48	1.49	1.51	1.53	1.54	1.56	60
70	1.58	1.60	1.62	1.64	1.66	1.68	1.70	1.72	1.74	1.77	70
80	1.79	1.81	1.83	1.86	1.88	1.91	1.93	1.95	1.98	2.01	80
90	2.05	2.10	2.14	2.19	2.24	2.29	2.33	2.38	2.43	2.48	90
100	2.53	2.58	2.64	2.69	2.74	2.79	2.85	2.90	2.95	3.01	100
110	3.06	3.12	3.18	3.23	3.29	3.35	3.41	3.47	3.53	3.59	110
120	3.65	3.71	3.77	3.83	3.89	3.96	4.02	4.09	4.15	4.22	120
130	4.28	4.35	4.41	4.48	4.55	4.62	4.69	4.75	4.82	4.89	130
140	4.96	5.04	5.11	5.18	5.25	5.33	5.40	5.47	5.55	5.62	140
150	5.70	5.78	5.85	5.93	6.01	6.09	6.16	6.24	6.32	6.40	150
160	6.48	6.57	6.65	6.73	6.81	6.90	6.98	7.06	7.15	7.23	160
170	7.32	7.41	7.49	7.58	7.67	7.76	7.85	7.94	8.03	8.12	170
180	8.21	8.30	8.39	8.48	8.58	8.67	8.76	8.86	8.95	9.05	180
190	9.14	9.24	9.34	9.44	9.53	9.63	9.73	9.83	9.93	10.03	190
200	10.13	10.23	10.34	10.44	10.54	10.65	10.75	10.85	10.96	11.06	200
210	11.17	11.28	11.38	11.49	11.60	11.71	11.82	11.93	12.04	12.15	210
220	12.26	12.37	12.48	12.60	12.71	12.82	12.94	13.05	13.17	13.28	220
230	13.40	13.52	13.63	13.75	13.87	13.99	14.11	14.23	14.35	14.47	230
240	14.59	14.71	14.83	14.69	15.08	15.20	15.33	15.45	15.58	15.71	240
250	15.83										

For steel qualities with intermediary strengths, determine the value of ω by linear interpolation.
NOTE. Read values of λ vertically in tens and horizontally units
Example. λ = 73   ω = 1.45 (table 2)

Det Norske Veritas

41
RULES FOR CERTIFICATION OF LIFTS

Table 1

Rated load (mass) kg	Maximum available car area (see note) m²	Maximum number of passengers	Rated load (mass) kg	Maximum available car area (see note) m²	Maximum number of passengers
100	0.40	1	975	2.35	13
180	0,50	2	1 000	2,40	13
225	0,70	3	1 050	2,50	14
300	0,90	4	1 125	2,65	15
375	1,10	5	1 200	2,80	16
400	1.17	5	1 250	2.90	16
450	1.30	6	1 275	2.95	17
525	1.45	7	1 350	3.10	18

Rated load (mass) kg	Maximum available car area (see note) m²	Maximum number of passengers	Rated load (mass) kg	Maximum available car area (see note) m²	Maximum number of passengers
600	1.60	8	1 425	3.25	19
630	1.66	8	1 500	3.40	20
675	1.75	9	1 600	3.65	21
750	1.90	10	1 800	3.88	24
800	2.00	10	2 100	4.36	28
825	2.05	11	2 500	5.00	33
900	2.20	12			

Det Norske Veritas

Adrián Alejandro Elizondo   23.06.2016

CALCULATION OF THE STRENGHT OF GUIDE RAIL

thyssenkrupp

Job Name	Kleven 370	Order Nr.	330216029

PARAMETERS

Total weight of Car	1100	kg
Capacity (Rated load)	585	kg
Total working weight (W_1)	1685	kg
CWT weight (W_2)	1135	kg
Distance to gravity center (Z_c)	25	m
Distance to gravity center (Z_w)	24,2	m
Rolling	22,5	°
Rolling period	10	s
Pitching	7,5	°
Pitching period	7	s
Bracket distance of Car (ℓ_1)	150	cm
Bracket distance of CWT (ℓ_2)	150	cm
Guide rail car	T 127-2/B	
Guide rail CWT	T 90/B	

MODIFY

CAR

Rolling

F_x	655,27	kg
Max. Bending Moment	24572,62	kg*cm
Stress	795,23	kg/cm² ✓
Max. Deflection	1,11	mm ✓

Pitching

F_y	168,20	kg
Max. Bending Moment	6307,56	kg*cm
Stress	174,24	kg/cm² ✓
Max. Deflection	0,24	mm ✓

COUNTER WEIGHT

Rolling

F_x	434,21	kg
Max. Bending Moment	16282,83	kg*cm
Stress	780,20	kg/cm² ✓
Max. Deflection	1,43	mm ✓

Pitching

F_y	110,86	kg
Max. Bending Moment	4157,20	kq*cm
Stress	352,30	kg/cm² ✓
Max. Deflection	0,70	mm ✓

1. Guide rail description

Total weight of Car	:	1100	kg
Capacity (Rated load)	:	585	kg
Total working weight (W_1)	:	1685	kg
CWT weight (W_2)	:	1135	kg

Distance from ship's metacenter to gravity center of:

1) Car in Top
   - Transverse Y_c :
   - Vertical Z_c :   ABT.   25   m
   - Longitudinal X_c :

2) CWT in Top
   - Transverse Y_w :
   - Vertical Z_w :   ABT.   24,2   m
   - Longitudinal X_w :

2. Mode of Operation

Passenger lifts, their associated machinery and structure are to be designed to operate at sea with respect to the following conditions:

a)	Rolling	:	±	10 °	,with 10 second perdiod (LR,DNV,ABS,BV,GL,NK,KR)
b)	Pitching	:	±	5 °	,with 10 second perdiod (DNV,ABS,BV,GL,NK,KR)
	Pitching	:	±	7,5 °	,with 10 second perdiod (LR)

In addition to the operational conditions the lifts, associated machinery and structure are to be designed to withstand the forces resulting from consideration of the following conditions when in its stowed conditions:

a) Roll   :   ±   22,5°   , with 10 second period
    Pitch   :   ±   7,5   °   , with 7 second period

3. Calculation of car guide rail (Car)
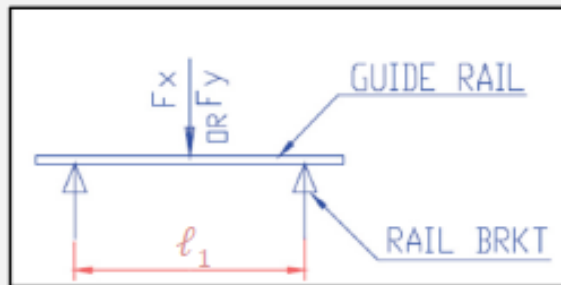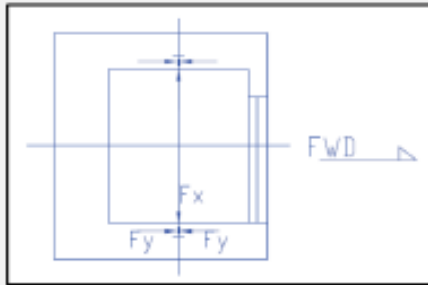
a) <u>Rolling</u>   :   ±   22,5°   , with 10 second period

$$F_x = \frac{W_1}{2}\{sin\theta + \frac{1}{g} * (\frac{2\pi}{T})^2 * \frac{\theta}{180} * \pi * Z_c\}$$

$W_1 =$	1685,00	kg
$\theta =$	22,50	°
$T =$	10,00	s
$Z_c =$	25,00	m

$F_x =$	**655,27**	kg

- Max. Bending Moment (Mb max)

$$Mb_{max} = \frac{\ell_1}{4} * F_x$$

$F_x =$	655,27	kg
$\ell_1 =$	150	cm

$Mb_{max} =$	**24572,62**	kg·cm

- Stress (σ)

$$\sigma = \frac{Mb_{max}}{Z_x}$$

$Mb_{max} =$	24572,62	kg·cm
$Z_x =$	30,90	cm³

$\sigma =$	**795,23**	kg/cm²

$\sigma \leq 1840 \, kg/cm^2$ → OK!

- Max. Deflection (δ max)

$$\delta_{max} = \frac{F_x * \ell_1^{\ 3}}{48E * I_x}$$

$$
\begin{aligned}
E &= & 210000,0 \quad & \text{kg/cm}^2 \\
I_x &= & 198,40 \quad & \text{cm}^4
\end{aligned}
$$

$$
\boxed{\delta_{max} \quad = \qquad 0,24 \qquad} \text{mm}
$$
$$\delta_{max} \quad \leq \quad 3\ \text{mm} \qquad \rightarrow \quad \text{OK!}$$

b)   Pitching   :   ±   7,5°   , with 7 second period

$$F_y = \frac{W_1}{4}\{sin\theta + \frac{1}{g}*(\frac{2\pi}{T})^2 * \frac{\theta}{180}*\pi*Z_c\}$$

$$
\begin{aligned}
W_1 &= & 1685,00 \quad & \text{kg} \\
\theta &= & 7,50 \quad & ° \\
T &= & 7,00 \quad & \text{s} \\
Z_c &= & 25,00 \quad & \text{m}
\end{aligned}
$$

$$
\boxed{F_y \quad = \qquad 168,20 \qquad} \text{kg}
$$

- Max. Bending Moment (Mb max)

$$Mb_{max} = \frac{\ell_1}{4}*F_y$$

$$
\begin{aligned}
F_y &= & 168,20 \quad & \text{kg} \\
\ell_1 &= & 150,00 \quad & \text{cm}
\end{aligned}
$$

$$
\boxed{Mb_{max} \quad = \qquad 6307,56 \qquad} \text{kg·cm}
$$

- Stress (σ)

$$\sigma = \frac{Mb_{max}}{Z_y}$$

$$
\begin{aligned}
Mb_{max} &= & 6307,56 \quad & \text{kg·cm} \\
Z_y &= & 36,20 \quad & \text{cm}^3
\end{aligned}
$$

$$
\boxed{\sigma \quad = \qquad 174,24 \qquad} \text{kg/cm}^2
$$
$$\sigma \quad \leq \quad 1840\ kg/cm^2 \quad \rightarrow \quad \text{OK!}$$

- Max. Deflection (δ max)

$$\delta_{max} = \frac{F_y * \ell_1^{\ 3}}{48E * I_y}$$

$$
\begin{aligned}
E &= & 210000,0 \quad & \text{kg/cm}^2 \\
I_y &= & 230,00 \quad & \text{cm}^4
\end{aligned}
$$

$$
\boxed{\delta_{max} \quad = \qquad 0,24 \qquad} \text{mm}
$$
$$\delta_{max} \quad \leq \quad 3\ \text{mm} \qquad \rightarrow \quad \text{OK!}$$

4. Calculation of car guide rail (CWT)
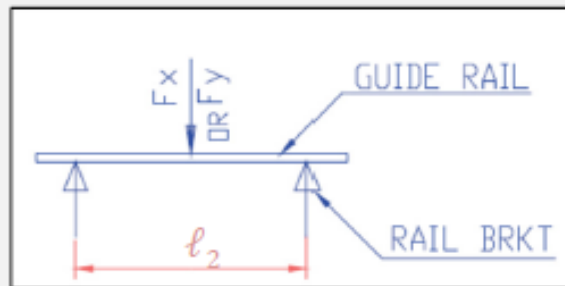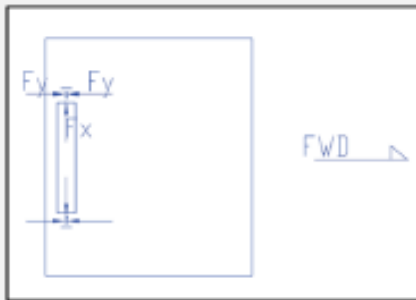
a) <u>Rolling</u> : ± 22,5 ° , with 10 second period

$$F_x = \frac{W_2}{2}\left\{\sin\theta + \frac{1}{g} * \left(\frac{2\pi}{T}\right)^2 * \frac{\theta}{180} * \pi * Z_w\right\}$$

$W_2 =$	1135,00	kg
$\theta =$	22,50	°
$T =$	10,00	s
$Z_w =$	24,20	m

$F_x =$	**434,21**	kg

- Max. Bending Moment (Mb max)

$$Mb_{max} = \frac{\ell_2}{4} * F_x$$

$F_x =$	434,21	kg
$\ell_2 =$	150,00	cm

$Mb_{max} =$	**16282,83**	kg·cm

- Stress (σ)

$$\sigma = \frac{Mb_{max}}{Z_x}$$

$Mb_{max} =$	16282,83	kg·cm
$Z_x =$	20,87	cm³

σ =	**780,20**	kg/cm²

σ ≤ 1840 kg/cm² → OK!

- Max. Deflection (δ max)

$$\delta_{max} = \frac{F_x * \ell_2{}^3}{48E * I_x}$$

$E =$	210000,0	kg/cm²
$I_x =$	102,00	cm⁴

$\delta_{max} =$	**1,43**	mm

$\delta_{max} ≤$ 3 mm → OK!

b) <u>Pitching</u>   :   ± 7,5°   , with 7 second period

$$F_y = \frac{W_2}{4}\{sin\theta + \frac{1}{g} * (\frac{2\pi}{T})^2 * \frac{\theta}{180} * \pi * Z_w\}$$

$W_2 =$	1135,00	kg
$\theta =$	7,50	°
$T =$	7,00	s
$Z_w =$	24,20	m

$F_y =$ **110,86**   kg

- Max. Bending Moment (Mb max)

$$Mb_{max} = \frac{\ell_2}{4} * F_y$$

$F_y =$	110,86	kg
$\ell_2 =$	150,00	cm

$Mb_{max} =$ **4157,20**   kg·cm

- Stress (σ)

$$\sigma = \frac{Mb_{max}}{Z_y}$$

$Mb_{max} =$	4157,20	kg·cm
$Z_y =$	11,80	cm³

$\sigma =$ **352,30**   kg/cm²

$\sigma \leq 1840\,kg/cm^2 \rightarrow$ OK!

- Max. Deflection (δ max)

$$\delta_{max} = \frac{F_y * \ell_2^3}{48E * I_y}$$

$E =$	210000,0	kg/cm²
$I_y =$	53,00	cm⁴

$\delta_{max} =$ **0,70**   mm

$\delta_{max} \leq 3\,mm \rightarrow$ OK!

*Allowable stress of guide rail
$\sigma_a = F * \sigma$

Where, σ_a = Allowable stress, in kg/cm² $\sigma = 1.0\,\sigma_y$

F = Stress factor, 0.8 σ_y = Yield stress, 2300 kg/cm²

σ = Failure stress, in kg/cm² $\therefore \sigma_a = 0.8 * 2300 = 1840\,kg/cm^2$

*Allowable deflection of guide rail $\delta_{max} \leq 3\,mm$ Adrián Alejandro Elizondo

$E := 210 \; GPa$

$\sigma_{max} := 180.5 \; MPa$

$\delta_{max} := 3 \; mm$

Column 127

$Z_{x\_127} := 31.17 \; cm^3$

$I_{x\_127} := 201.7 \; cm^4$

$W_x := \dfrac{W_1}{2}\left[(\sin(\theta_x)) + \left(\dfrac{1}{g}\right) \cdot \left(2 \cdot \dfrac{\pi}{T_x}\right)^2 \cdot \left(\dfrac{\theta_x}{180°}\right) \cdot \pi \cdot Z_c\right]$

$\sigma_{x\_127} := \dfrac{Mb_x}{Z_{x\_127}}$

$SF_{\sigma x\_127} := \dfrac{\sigma_{max}}{\sigma_{x\_127}}$

$\delta_{x\_127} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_127}}$

$SF_{\delta x\_127} := \dfrac{\delta_{max}}{\delta_{x\_127}}$

$Z_{y\_127} := 36.2 \; cm^3$

$I_{y\_127} := 229.9 \; cm^4$

$W_y := \dfrac{W_1}{4}\left[(\sin(\theta_y)) + \left(\dfrac{1}{g}\right) \cdot \left(2 \cdot \dfrac{\pi}{T_y}\right)^2 \cdot \left(\dfrac{\theta_y}{180°}\right) \cdot \pi \cdot Z_c\right]$

$\sigma_{y\_127} := \dfrac{Mb_y}{Z_{y\_127}}$

$SF_{\sigma y\_127} := \dfrac{\sigma_{max}}{\sigma_{y\_127}}$

$\delta_{y\_127} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_127}}$

$SF_{\delta y\_127} := \dfrac{\delta_{max}}{\delta_{y\_127}}$

Column 127_1

$Z_{x\_127\_1} := 30.65 \; cm^3$

$I_{x\_127\_1} := 187.9 \; cm^4$

$a_x := \left(2 \cdot \dfrac{\pi}{T_x}\right)^2 \cdot \left(\dfrac{\theta_x}{180°}\right) \cdot \pi \cdot Z_c$

$\sigma_{x\_127\_1} := \dfrac{Mb_x}{Z_{x\_127\_1}}$

$SF_{\sigma x\_127\_1} := \dfrac{\sigma_{max}}{\sigma_{x\_127\_1}}$

$\delta_{x\_127\_1} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_127\_1}}$

$SF_{\delta x\_127\_1} := \dfrac{\delta_{max}}{\delta_{x\_127\_1}}$

$Z_{y\_127\_1} := 23.61 \; cm^3$

$I_{y\_127\_1} := 149.9 \; cm^4$

$a_y := \left(2 \cdot \dfrac{\pi}{T_y}\right)^2 \cdot \left(\dfrac{\theta_y}{180°}\right) \cdot \pi \cdot Z_c$

$\sigma_{y\_127\_1} := \dfrac{Mb_y}{Z_{y\_127\_1}}$

$SF_{\sigma y\_127\_1} := \dfrac{\sigma_{max}}{\sigma_{y\_127\_1}}$

$\delta_{y\_127\_1} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_127\_1}}$

$SF_{\delta y\_127\_1} := \dfrac{\delta_{max}}{\delta_{y\_127\_1}}$

Column 125

$Z_{x\_125} := 26.16 \; cm^3$

$I_{x\_125} := 151 \; cm^4$

$\sigma_{x\_125} := \dfrac{Mb_x}{Z_{x\_125}}$

$SF_{\sigma x\_125} := \dfrac{\sigma_{max}}{\sigma_{x\_125}}$

$\delta_{x\_125} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_125}}$

$SF_{\delta x\_125} := \dfrac{\delta_{max}}{\delta_{x\_125}}$

$Z_{y\_125} := 25.46 \; cm^3$

$I_{y\_125} := 159.1 \; cm^4$

$\sigma_{y\_125} := \dfrac{Mb_y}{Z_{y\_125}}$

$SF_{\sigma y\_125} := \dfrac{\sigma_{max}}{\sigma_{y\_125}}$

$\delta_{y\_125} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_125}}$

$SF_{\delta y\_125} := \dfrac{\delta_{max}}{\delta_{y\_125}}$

Column 114

$Z_{x\_114} := 29.74 \; cm^3$

$I_{x\_114} := 179.3 \; cm^4$

$a_x := \left(2 \cdot \dfrac{\pi}{T_x}\right)^2 \cdot \left(\dfrac{\theta_x}{180°}\right) \cdot \pi \cdot Z_c$

$\sigma_{x\_114} := \dfrac{Mb_x}{Z_{x\_114}}$

$SF_{\sigma x\_114} := \dfrac{\sigma_{max}}{\sigma_{x\_114}}$

$\delta_{x\_114} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_114}}$

$SF_{\delta x\_114} := \dfrac{\delta_{max}}{\delta_{x\_114}}$

$Z_{y\_114} := 19.05 \; cm^3$

$I_{y\_114} := 108.6 \; cm^4$

$a_y := \left(2 \cdot \dfrac{\pi}{T_y}\right)^2 \cdot \left(\dfrac{\theta_y}{180°}\right) \cdot \pi \cdot Z_c \qquad F_y := W_y \cdot g$

$\sigma_{y\_114} := \dfrac{Mb_y}{Z_{y\_114}}$

$SF_{\sigma y\_114} := \dfrac{\sigma_{max}}{\sigma_{y\_114}}$

$\delta_{y\_114} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_114}}$

$SF_{\delta y\_114} := \dfrac{\delta_{max}}{\delta_{y\_114}}$

Column 90

$Z_{x\_90} := 20.86 \; cm^3$

$I_{x\_90} := 102 \; cm^4$

$F_x := W_z \cdot g$

$\sigma_{x\_90} := \dfrac{Mb_x}{Z_{x\_90}}$

$SF_{\sigma x\_90} := \dfrac{\sigma_{max}}{\sigma_{x\_90}}$

$\delta_{x\_90} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_90}}$

$SF_{\delta x\_90} := \dfrac{\delta_{max}}{\delta_{x\_90}}$

$Z_{y\_90} := 11.66 \; cm^3$

$I_{y\_90} := 52.48 \; cm^4$

$Mb_y := \dfrac{l_B}{4} F_y$

$\sigma_{y\_90} := \dfrac{Mb_y}{Z_{y\_90}}$

$SF_{\sigma y\_90} := \dfrac{\sigma_{max}}{\sigma_{y\_90}}$

$\delta_{y\_90} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_90}}$

$SF_{\delta y\_90} := \dfrac{\delta_{max}}{\delta_{y\_90}}$

Column 89

$Z_{x\_89} := 14.35 \; cm^3$

$I_{x\_89} := 59.83 \; cm^4$

$Mb_x := \dfrac{l_B}{4} F_x$

$\sigma_{x\_89} := \dfrac{Mb_x}{Z_{x\_89}}$

$SF_{\sigma x\_89} := \dfrac{\sigma_{max}}{\sigma_{x\_89}}$

$\delta_{x\_89} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_89}}$

$SF_{\delta x\_89} := \dfrac{\delta_{max}}{\delta_{x\_89}}$

$Z_{y\_89} := 11.78 \; cm^3$

$I_{y\_89} := 52.41 \; cm^4$

$\sigma_{y\_89} := \dfrac{Mb_y}{Z_{y\_89}}$

$SF_{\sigma y\_89} := \dfrac{\sigma_{max}}{\sigma_{y\_89}}$

$\delta_{y\_89} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_89}}$

$SF_{\delta y\_89} := \dfrac{\delta_{max}}{\delta_{y\_89}}$

Column 70

$Z_{x\_70} := 10.79 \; cm^3$

$I_{x\_70} := 52.81 \; cm^4$

$\sigma_{x\_70} := \dfrac{Mb_x}{Z_{x\_70}}$

$SF_{\sigma x\_70} := \dfrac{\sigma_{max}}{\sigma_{x\_70}}$

$\delta_{x\_70} := \dfrac{F_x \cdot l_B{}^3}{48 \cdot E \cdot I_{x\_70}}$

$SF_{\delta x\_70} := \dfrac{\delta_{max}}{\delta_{x\_70}}$

$Z_{y\_70} := 7.03 \; cm^3$

$I_{y\_70} := 24.62 \; cm^4$

$\sigma_{y\_70} := \dfrac{Mb_y}{Z_{y\_70}}$

$SF_{\sigma y\_70} := \dfrac{\sigma_{max}}{\sigma_{y\_70}}$

$\delta_{y\_70} := \dfrac{F_y \cdot l_B{}^3}{48 \cdot E \cdot I_{y\_70}}$

$SF_{\delta y\_70} := \dfrac{\delta_{max}}{\delta_{y\_70}}$

M Gmail   Finn Inge Røsholm <f.roesholm@gmail.com>

Fwd: FW: Beregning av heisføring installert i skip. Thyssenkrupp Elevator

Geir Marius Øie <geirmoie@gmail.com>   23. mai 2017 kl. 14:49
Til: "Bauer, Samuel" <Samuel.Bauer@thyssenkrupp.com>, "Bostrand, Geir" <Geir.Bostrand@thyssenkrupp.com>,
f.roesholm@gmail.com

———— Videresendt e-post ————
Fra: **Jensen, Harald** <Harald.Jensen@dnvgl.com>
Dato: 23. mai 2017 kl. 14:40
Emne: RE: FW: Beregning av heisføring installert i skip. Thyssenkrupp Elevator
Til: Geir Marius Øie <geirmoie@gmail.com>

Calculation as described beneath will be accepted by our section.

However we also wants from customer calculations of stress in the guiding beams from forces acting in operating
conditions.

Best regards

for DNV GL AS

Harald Jensen

Senior Engineer, Lifting Appliances

E-mail harald.jensen@dnvgl.com
Mobile +47 95154157 | Direct +47 67 57 81 50

www.dnvgl.com | LinkedIn

DNV·GL

DNV and GL have merged to form DNV GL – Read more here: www.dnvgl.com/merger
[Legal requirements go here]

From: Geir Marius Øie [mailto:geirmoie@gmail.com]
Sent: 23. mai 2017 14:24
To: Jensen, Harald <Harald.Jensen@dnvgl.com>
Subject: Re: FW: Beregning av heisføring installert i skip. Thyssenkrupp Elevator

Hei, Harald.

Gitt at thyssenkrupp Elevator følger prosedyrene og reglene som du oppgir i mailen, vil da dokumentasjonen bli godkjent?

Mvh, Geir M. Øie

3. mai 2017 kl. 10:25 skrev Jensen, Harald <Harald.Jensen@dnvgl.com>:

Jeg har så langt ikke fått tilbakemelding fra min sjef om jeg kan sette av tid til dette.

Da disse skinneinnfestingene i praksis ikke er et kritisk punkt, regner vi ikke på disse, kunne på spenninger, utbøyninger og på knekkfare i skinnene.

Den informasjonen jeg kan komme med om den måten vi regner krefter på skinnene er som følgende:

Maksimale bevegelser er som følgende (se vår heisstandard):

- Continuous vibrations: 2 mm double amplitude of frequency 0 to 25 Hz
- Rolling: ± 10°, period 10 s
- Pitching: ± 5°, period 7 s
- Heave: Amplitude = 0.0125 L with 10 seconds period, L being the length of the ship as defined by the current Rules for Steel Ships.

1.4.2.2 Stowed conditions
In addition to the operational conditions the lift, associated machinery and structures are to be able to withstand the forces resulting from following conditions when the lift is stowed:

- Rolling: ± 22° 30'
- Pitching: ± 7° 30'

I praksis regner vi kunn på «Stowed condition» da der er her de største belastningene oppstår. For «Stowed condition» må vi forutsette at det ikke er personer i heisstolen.

Vi forutsetter at maks «Roll» og «Pich» ikke oppstår på samme tid.

Vi må vurdere, ut fra heisstolens og motvektens plassering i skipet om lasten opptas av en eller to «styrings-sko»

Så beregnes lasten ut fra vanlige «pendelberegninger»

Se eksempel under:

Heis nummer: 15-6005

Avstand mellom fester　　　　　$l := 1500 \cdot mm$

Nyttelast i stol　　　　　　　　$R_{car} := 1400 \cdot kg$

Egenvekt av stol　　　　　　　$m_{car} := 1755 \cdot kg$

$MPa \equiv \dfrac{newton}{mm^2}$

$kN \equiv 1000 \cdot newton$

$E \equiv 210000 \cdot MPa$

$Nm \equiv newton \cdot m$

$T := 10 \cdot s$

$\theta := 22.5 \cdot deg$

$\omega := \dfrac{1}{T}$　　　　　$\omega = 0.1 \, \dfrac{1}{s}$

$R := 22 \cdot m$　　　　　oppgitt av leverandør:

antar svingeform:

$s_1(t) := A \cdot \cos(\omega \cdot 2 \cdot \pi \cdot t)$　　　$v(t) := -2 \cdot A \cdot \sin(2 \cdot \omega \cdot \pi \cdot t) \cdot \omega \cdot \pi \;\Leftarrow$

$a(t) := -4 \cdot A \cdot \cos(2 \cdot \omega \cdot \pi \cdot t) \cdot \omega^2 \cdot \pi^2 \;\Leftarrow\; A := R \cdot \theta$

max kraft på skinnene for rullingen:

$P_{rull.1} := \left(A \cdot \omega^2 \cdot 4 \cdot \pi^2\right) \cdot m_{car} + \sin(\theta) \cdot m_{car} \cdot g$　　　　　$P_{rull.1} = 12.6 \; kN$
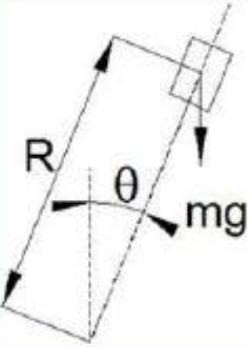
Denne kondisjonen er ikke beskrevet i reglene (perioden er ikke gitt, men det vil være naturlig å forutsette at den er større enn 10 s).

Vi regner på krefter både fra heis-stol og fra motvekt. Motvekt gir normalt de største lastene.

Jeg anntar dette skulle være tilstrekkelig til å beregne kreftene i skinnenes innfestingspunkter.

Når det gjelder beregning av spenninger i skinnenen kan jeg og nevne litt om det, selv om det sikkert er kjent stoff for deg.

Vi må vurdere, ut fra heisstolens og motvektens plassering i skipet om lasten opptas av en eller to «styrings-sko». Størst last får vi om stolen vipper «sideveis» slik at den ene skinnen må stå imot alle kreftene.

Vi sier da at 2 styrings-sko tar lasten, ellers blir det alle 4.

Vi regner på spenninger i skinnen for både heis stol og motvekt.

Da blir speningeberegningene som vist i eksemplet under.

7.6.2017   Gmail - Fwd: FW: Beregning av heisføring installert i skip. Thyssenkrupp Elevator

Last på skinne

Antall innfestinger som tar last fra heisstol under rulling $n_j := 2$

Skinne profil: Guidene er T125B $W_{x,l} = 26.200 \cdot cm^3$ $W_{y,l} = 25.400 \cdot cm^3$

Motstandmoment profil:

$W_l := \text{if}(n_l > 2, W_{y,l}, W_{x,l})$ $W_l = 26.2 \ cm^3$

merk: dette er beregning for
"stowed condition" og da er vel
ikke stolen full lastet.

$p_l := \dfrac{P_{tot,l}}{n_l}$ ← $p_l = 6286 \ N$

bøyning av bjelkene: modell fritt lagret bjelke, avstand $l = 1.5 \ m$

$\sigma_{b,l} := \dfrac{p_l \cdot l \cdot \frac{1}{4}}{W_l}$ $\sigma_{b,l} = 90 \ MPa$

Når det gjelder maksimal utbøyning så har vi ingen konkrete krav i vår standard annet en at funksjonaliteten ska opprettholdes.

Vi velger imidlertid å benytte ISO8383 sine krav som en veileder – det vil si maks 3 mm.

Skinne profil:

$J_{x,l} := 159.0 \cdot cm^4$ $J_{y,l} := 151. \cdot cm^4$ $J_l := \text{if}(n_l > 2, J_{y,l}, J_{x,l})$ $J_l = (1.6 \cdot 10^6) \ mm^4$

$f := \dfrac{p_l \cdot l^3}{E \cdot J_l \cdot 48}$ $f = 0.909 \ mm$ < 3 mm

Når vi har avsluttet beregninger etter laster fra «Roll» gjør vi nye beregninger etter laster fra «Pitch»

Vi regner og på vertikale laster som gir knekk i skinnen. Dette er laster som oppstår når fangapparatet evt. trer i funksjon.

Lastgen vil være avhenging av typen fang-appar.

Se eksempel under:

If safety gear is of type Instaneous, let Sgt:20

If safety gear is of type captive roller, let Sgt:15

If safety gear is of type progressive, let Sgt:10

$Sgt := 10$

Weight of empty car: $P_1 := 4400 \cdot kg$

Load in the car: $Q_1 := 6500 \cdot kg$

Load from safety gear on each guide: $F_1 := Sgt \cdot (P_1 + Q_1) \cdot \dfrac{N}{kg}$ $F_1 = (1.09 \cdot 10^5) \, N$

Car guide rail: T140-2/B

Cross section area: $A = 4344 \cdot mm^2$

Radius of gyration: $I = 32.4 \cdot mm$

Max dist. between bracets: $l_k := 1800 \cdot mm$ $\lambda := \dfrac{l_k}{I}$ $\lambda = 55.556$

Buckling load factor (see next page): $\omega := 1.25$

Calculated buckling stress: $\sigma_k := \dfrac{(F_1 \cdot \omega)}{A}$ $\sigma_k = ? \, \dfrac{N}{mm^2}$

Max. allowable buckling stress
For Steel of 370: 140 mPa
For Steel of 520: 210 mPa

Jeg håper ovennvente kan være til nytte. Skulle det være interesse for mer informasjon, vennlist gi beskjed.

Lykke til med oppgaven

Best regards

for DNV GL AS

Harald Jensen

Senior Engineer, Lifting Appliances

E-mail harald.jensen@dnvgl.com
Mobile +47 95154157 | Direct +47 67 57 81 50

www.dnvgl.com | LinkedIn

Flip page!

Maximum distance between brackets for brackets for loads on x-x axis

T70-1/A - Maximum distance between brackets [mm]

Weight W[kg]	Height, Z[m] 8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	2338,6	2292,1	2249,1	2209,2	2171,9	2137,1	2104,4	2073,6	2044,5	2017	1990,9	1966,1	1942,5	1920	1898,5	1877,9	1858,2	1839,3	1821,2	1803,7	1786,9	1770,7
600	2200,7	2157	2116,5	2078,9	2043,9	2011,1	1980,3	1951,3	1923,9	1898	1873,5	1850,2	1828	1806,8	1786,6	1767,2	1748,7	1730,9	1713,8	1697,4	1681,5	1666,3
700	2090,5	2048,9	2010,5	1974,8	1941,5	1910,4	1881,1	1853,6	1827,6	1803	1779,7	1757,5	1736,4	1716,3	1697,1	1678,7	1661,1	1644,2	1628	1612,4	1597,3	1582,8
800	1999,5	1959,7	1923	1888,8	1857	1827,2	1799,2	1772,9	1748	1724,5	1702,2	1681	1660,8	1641,6	1623,2	1605,6	1588,8	1572,6	1557,1	1542,2	1527,8	1513,9
900	1922,5	1884,3	1848,9	1816,1	1785,5	1756,8	1729,9	1704,6	1680,7	1658,1	1636,7	1616,3	1596,9	1578,4	1560,7	1543,8	1527,6	1512,1	1497,1	1482,8	1469	1455,7
1000	1856,2	1819,3	1785,1	1753,4	1723,9	1696,2	1670,2	1645,8	1622,7	1600,9	1580,2	1560,5	1541,8	1523,9	1506,8	1490,5	1474,9	1459,9	1445,5			
1100	1798,1	1762,4	1729,3	1698,6	1670	1643,2	1618	1594,3	1572	1550,8	1530,8	1511,7	1493,6	1476,2	1459,7	1443,9						
1200	1746,7	1712	1679,9	1650	1622,2	1596,2	1571,8	1548,7	1527	1506,5	1487	1468,5	1450,9	1434								
1300	1700,7	1666,9	1635,7	1606,6	1579,5	1554,2	1530,4	1508	1486,8	1466,8	1447,8											
1400	1659,2	1626,2	1595,7	1567,4	1541	1516,2	1493	1471,2	1450,5													
1500	1621,5	1589,3	1559,5	1531,8	1505,9	1481,8	1459,1	1437,7														
1600	1587	1555,5	1526,3	1499,2	1473,9	1450,2																
1700	1555,2	1524,3	1495,7	1469,2	1444,4																	
1800	1525,9	1495,6	1467,5	1441,5																		
1900	1498,6	1468,9	1441,3																			
2000	1473,2	1444																				
2100	1449,5																					
2200																						
2300																						
2400																						
2500																						
2600																						
2700																						
2800																						
2900																						
3000																						

δmax	3 mm	E 210000 Mpa	Ix 52,81 cm^4	θy 22,5 °	Ty 10 s

$$l_x = \sqrt[3]{\dfrac{\delta_{max} \cdot 48 E I_{x-x}}{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right)}}$$

*Maximum allowable distance between brackets is 2900 mm

Value

Max distance, l > 2900 mm
Max distance, 2900 mm > l > 2500 mm
Max distance, 2500 mm > l > 2000 mm
Max distance, 2000 mm > l > 1500 mm
Max distance, 1500 mm > l > 1000 mm
Max distance, l < 1000 mm
Exceeds maximum allowable stress

For loads on x-x axis

T70-1/A - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	Height [m] 8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	67,655	70,427	73,145	75,814	78,436	81,016	83,555	86,056	88,521	90,953	93,352	95,721	98,06	100,37	102,66	104,92	107,16	109,37	111,56	113,73	115,88	118,01
600	76,399	79,529	82,599	85,612	88,574	91,487	94,354	97,178	99,962	102,71	105,42	108,09	110,73	113,35	115,93	118,48	121,01	123,5	125,98	128,43	130,86	133,26
700	84,668	88,137	91,539	94,878	98,161	101,39	104,57	107,7	110,78	113,82	116,83	119,79	122,72	125,61	128,47	131,3	134,1	136,87	139,61	142,33	145,02	147,69
800	92,55	96,342	100,06	103,71	107,3	110,83	114,3	117,72	121,1	124,42	127,7	130,94	134,14	137,31	140,43	143,53	146,59	149,62	152,61	155,58	158,52	161,44
900	100,11	104,21	108,23	112,18	116,06	119,88	123,64	127,34	130,99	134,58	138,14	141,64	145,1	148,52	151,91	155,25	158,56	161,84	165,08	168,29	171,47	174,62
1000	107,4	111,8	116,11	120,35	124,51	128,6	132,64	136,61	140,52	144,38	148,19	151,95	155,66	159,33	162,96	166,55	170,1	173,61	177,09	180,54	183,95	187,33
1100	114,44	119,13	123,73	128,24	132,68	137,04	141,34	145,57	149,74	153,85	157,91	161,92	165,87	169,78	173,65	177,48	181,26	185	188,71	192,38	196,02	199,62
1200	121,28	126,24	131,12	135,9	140,6	145,23	149,78	154,26	158,68	163,04	167,34	171,59	175,78	179,92	184,02	188,07	192,08	196,05	199,98	203,87	207,72	211,54
1300	127,92	133,16	138,3	143,35	148,31	153,19	157,99	162,72	167,38	171,97	176,51	180,99	185,41	189,79	194,11	198,38	202,61	206,8	210,94	215,04	219,11	223,14
1400	134,4	139,91	145,31	150,61	155,82	160,94	165,99	170,96	175,85	180,68	185,45	190,16	194,8	199,4	203,94	208,43	212,87	217,27	221,62	225,94	230,21	234,44
1500	140,73	146,49	152,15	157,7	163,15	168,52	173,8	179	184,13	189,19	194,18	199,11	203,97	208,78	213,54	218,24	222,89	227,5	232,06	236,57	241,04	245,47
1600	146,91	152,93	158,84	164,63	170,33	175,93	181,44	186,87	192,23	197,51	202,72	207,86	212,94	217,96	222,93	227,84	232,69	237,5	242,26	246,97	251,64	256,26
1700	152,97	159,24	165,39	171,42	177,35	183,18	188,93	194,58	200,16	205,65	211,08	216,43	221,72	226,95	232,12	237,23	242,29	247,3	252,25	257,16	262,02	266,83
1800	158,92	165,43	171,81	178,08	184,24	190,3	196,26	202,14	207,93	213,64	219,28	224,84	230,34	235,77	241,14	246,45	251,7	256,9	262,05	267,14	272,19	277,2
1900	164,75	171,5	178,12	184,62	191	197,28	203,47	209,56	215,56	221,48	227,32	233,09	238,79	244,42	249,99	255,49	260,94	266,33	271,67	276,95	282,18	287,37
2000	170,48	177,46	184,31	191,04	197,65	204,15	210,55	216,85	223,06	229,19	235,23	241,2	247,1	252,92	258,68	264,38	270,02	275,59	281,12	286,58	292	297,37
2100	176,12	183,33	190,41	197,36	204,18	210,9	217,51	224,02	230,43	236,76	243,01	249,18	255,27	261,29	267,24	273,12	278,94	284,71	290,41	296,06	301,65	307,2
2200	181,66	189,11	196,41	203,57	210,61	217,54	224,36	231,07	237,69	244,22	250,66	257,02	263,31	269,52	275,65	281,72	287,73	293,67	299,56	305,38	311,16	316,88
2300	187,13	194,79	202,31	209,69	216,95	224,08	231,11	238,02	244,84	251,57	258,2	264,75	271,23	277,62	283,94	290,2	296,38	302,51	308,57	314,57	320,52	326,41
2400	192,51	200,4	208,14	215,73	223,19	230,53	237,76	244,87	251,89	258,81	265,63	272,37	279,03	285,61	292,12	298,55	304,91	311,21	317,45	323,62	329,74	335,8
2500	197,82	205,93	213,88	221,68	229,35	236,89	244,32	251,63	258,84	265,95	272,96	279,89	286,73	293,49	300,18	306,79	313,33	319,8	326,21	332,55	338,84	345,06
2600	203,06	211,38	219,54	227,55	235,43	243,17	250,79	258,3	265,69	272,99	280,19	287,3	294,33	301,27	308,13	314,91	321,63	328,27	334,85	341,36	347,81	354,21
2700	208,24	216,77	225,14	233,35	241,42	249,36	257,18	264,88	272,46	279,95	287,33	294,62	301,83	308,94	315,98	322,94	329,82	336,63	343,38	350,06	356,68	363,23
2800	213,35	222,09	230,66	239,08	247,35	255,48	263,49	271,38	279,15	286,82	294,38	301,85	309,23	316,52	323,73	330,86	337,92	344,9	351,81	358,65	365,43	372,14
2900	218,4	227,35	236,12	244,74	253,2	261,53	269,73	277,8	285,76	293,61	301,35	309	316,55	324,02	331,4	338,69	345,91	353,06	360,13	367,14	374,08	380,95
3000	223,39	232,54	241,52	250,33	258,99	267,51	275,89	284,15	292,29	300,32	308,24	316,06	323,79	331,42	338,97	346,44	353,82	361,13	368,37	375,53	382,63	389,66

σmax	180 Mpa	180 Mpa	E 210000 Mpa	Zx 10,79 cm^3	θy 22,5 °	Ty 10 s

Resulting stress < σmax

Resulting stress > σmax

$$\sigma_x = \frac{\dfrac{W}{2}\left(g\cdot\sin\theta + \left(2\dfrac{\pi}{T}\right)^2\cdot\dfrac{\theta}{180}\pi\cdot Z\right)l_x}{4\cdot V_{x-x}}$$

For loads on x-x axis

T75-3/B - Maximum distance between brackets [mm]

Weight [kg]	Height [m]																					
	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	2138	2095,5	2056,2	2019,7	1985,6	1953,7	1923,8	1895,7	1869,1	1843,9	1820,1	1797,4	1775,8	1755,3	1735,6	1716,8	1698,8	1681,5	1664,9	1649	1633,6	1618,8
600	2011,9	1971,9	1934,9	1900,6	1868,5	1838,5	1810,4	1783,9	1758,9	1735,2	1712,8	1691,4	1671,1	1651,8	1633,3	1615,6	1598,6	1582,4	1566,8	1551,7	1537,3	1523,3
700	1911,1	1873,2	1838	1805,4	1774,9	1746,4	1719,7	1694,5	1670,8	1648,3	1627	1606,7	1587,4	1569	1551,5	1534,7	1518,6	1503,1	1488,3	1474	1460,3	1447
800	1827,9	1791,6	1758	1726,8	1697,7	1670,4	1644,8	1620,8	1598	1576,5	1556,1	1536,8	1518,3	1500,7	1483,9	1467,9	1452,5	1437,7	1423,5	1409,8	1396,7	1384
900	1757,6	1722,6	1690,3	1660,3	1632,3	1606,1	1581,5	1558,4	1536,5	1515,8	1496,2	1477,6	1459,9	1443	1426,8	1411,3	1396,5	1382,3	1368,7	1355,6		
1000	1696,9	1663,2	1632	1603	1576	1550,7	1526,9	1504,6	1483,5	1463,5	1444,6	1426,6	1409,5	1393,2	1377,6	1362,6						
1100	1643,8	1611,2	1580,9	1552,9	1526,7	1502,2	1479,2	1457,5	1437,1	1417,8	1399,4	1382	1365,4									
1200	1596,9	1565,1	1535,8	1508,5	1483	1459,2	1436,9	1415,9	1396	1377,2	1359,4											
1300	1554,8	1523,9	1495,3	1468,8	1444	1420,8	1399,1	1378,6	1359,3													
1400	1516,9	1486,7	1458,8	1432,9	1408,8	1386,2	1364,9															
1500	1482,4	1452,9	1425,7	1400,3	1376,7	1354,6																
1600	1450,8	1422	1395,3	1370,5																		
1700	1421,8	1393,5	1367,4																			
1800	1395	1367,2																				
1900	1370,1																					
2000																						
2100																						
2200																						
2300																						
2400																						
2500																						
2600																						
2700																						
2800																						
2900																						
3000																						

| δmax | 3 mm | E 210000 Mpa | Ix 40,35 cm^4 | θy 22,5 ° | Ty | 10 s |

$$l_x = \sqrt[3]{\dfrac{\delta_{max} \cdot 48 E I_{x-x}}{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2\right) \cdot \dfrac{\theta}{180}\,\pi \cdot Z}}$$

*Maximum allowable distance between brackets is 2900 mm

For loads on x-x axis

Value	
	Max distance, l > 2900 mm
	Max distance, 2900 mm > l > 2500 mm
	Max distance, 2500 mm > l > 2000 mm
	Max distance, 2000 mm > l > 1500 mm
	Max distance, 1500 mm > l > 1000 mm
	Max distance, l < 1000 mm
	Exceeds maximum allowable stress

T75-3/B - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	Height [m] 8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	71,837	74,78	77,666	80,5	83,285	86,024	88,72	91,375	93,993	96,575	99,122	101,64	104,12	106,58	109	111,4	113,78	116,13	118,46	120,76	123,04	125,3
600	81,121	84,445	87,704	90,904	94,049	97,142	100,19	103,19	106,14	109,06	111,93	114,77	117,58	120,35	123,09	125,8	128,48	131,14	133,77	136,37	138,95	141,5
700	89,901	93,585	97,197	100,74	104,23	107,66	111,03	114,35	117,63	120,86	124,05	127,2	130,3	133,38	136,42	139,42	142,39	145,33	148,24	151,13	153,98	156,81
800	98,271	102,3	106,25	110,12	113,93	117,68	121,37	125	128,58	132,11	135,6	139,04	142,44	145,8	149,12	152,4	155,65	158,86	162,05	165,2	168,32	171,41
900	106,3	110,65	114,93	119,12	123,24	127,29	131,28	135,21	139,08	142,9	146,67	150,4	154,07	157,7	161,3	164,85	168,36	171,84	175,28	178,69	182,07	185,42
1000	114,03	118,71	123,29	127,79	132,21	136,55	140,83	145,05	149,2	153,3	157,35	161,34	165,28	169,18	173,03	176,84	180,61	184,34	188,04	191,7	195,32	198,91
1100	121,51	126,49	131,38	136,17	140,88	145,51	150,07	154,57	158,99	163,36	167,67	171,92	176,13	180,28	184,38	188,45	192,46	196,44	200,37	204,27	208,13	211,96
1200	128,77	134,05	139,22	144,3	149,29	154,2	159,04	163,8	168,49	173,12	177,68	182,19	186,64	191,05	195,4	199,7	203,96	208,17	212,34	216,47	220,56	224,62
1300	135,83	141,4	146,85	152,21	157,48	162,66	167,75	172,77	177,72	182,6	187,42	192,18	196,88	201,52	206,11	210,65	215,14	219,58	223,98	228,34	232,65	236,93
1400	142,71	148,56	154,29	159,92	165,45	170,89	176,25	181,52	186,72	191,85	196,91	201,91	206,85	211,72	216,55	221,31	226,03	230,7	235,32	239,9	244,44	248,93
1500	149,43	155,55	161,55	167,45	173,24	178,94	184,54	190,07	195,51	200,88	206,18	211,41	216,58	221,69	226,74	231,73	236,67	241,56	246,4	251,19	255,94	260,64
1600	156	162,39	168,66	174,81	180,86	186,8	192,66	198,42	204,11	209,72	215,25	220,71	226,1	231,44	236,71	241,92	247,08	252,18	257,23	262,24	267,19	272,1
1700	162,43	169,08	175,61	182,02	188,32	194,51	200,6	206,61	212,53	218,36	224,12	229,81	235,43	240,98	246,47	251,9	257,27	262,58	267,84	273,05	278,21	283,33
1800	168,74	175,65	182,43	189,09	195,63	202,06	208,4	214,63	220,78	226,85	232,83	238,74	244,57	250,34	256,04	261,68	267,26	272,78	278,25	283,66	289,02	294,33
1900	174,93	182,1	189,13	196,03	202,81	209,48	216,04	222,51	228,89	235,17	241,38	247,5	253,55	259,53	265,44	271,29	277,07	282,79	288,46	294,07	299,63	305,13
2000	181,02	188,43	195,71	202,85	209,86	216,77	223,56	230,25	236,85	243,35	249,77	256,11	262,37	268,56	274,67	280,72	286,71	292,63	298,49	304,3	310,05	315,75
2100	187	194,66	202,18	209,55	216,8	223,93	230,95	237,86	244,68	251,4	258,03	264,58	271,05	277,44	283,75	290	296,19	302,3	308,36	314,36	320,3	326,19
2200	192,89	200,8	208,55	216,16	223,63	230,99	238,23	245,36	252,39	259,32	266,16	272,91	279,58	286,18	292,69	299,14	305,52	311,83	318,07	324,26	330,39	336,46
2300	198,69	206,84	214,82	222,66	230,36	237,93	245,39	252,74	259,98	267,12	274,16	281,12	287,99	294,78	301,5	308,14	314,7	321,21	327,64	334,01	340,33	346,58
2400	204,41	212,79	221	229,06	236,99	244,78	252,45	260,01	267,46	274,8	282,05	289,21	296,28	303,27	310,17	317	323,76	330,45	337,07	343,63	350,12	356,56
2500	210,05	218,66	227,1	235,38	243,53	251,54	259,42	267,18	274,84	282,39	289,83	297,19	304,45	311,63	318,73	325,75	332,69	339,57	346,37	353,11	359,78	366,39
2600	215,62	224,45	233,11	241,62	249,98	258,2	266,29	274,26	282,12	289,87	297,51	305,06	312,52	319,89	327,17	334,38	341,51	348,56	355,55	362,46	369,31	376,1
2700	221,11	230,17	239,05	247,78	256,35	264,78	273,08	281,25	289,31	297,25	305,09	312,84	320,48	328,04	335,51	342,9	350,21	357,44	364,61	371,7	378,72	385,68
2800	226,54	235,82	244,92	253,86	262,64	271,28	279,78	288,15	296,41	304,55	312,58	320,51	328,35	336,09	343,74	351,31	358,8	366,22	373,55	380,82	388,02	395,15
2900	231,9	241,4	250,72	259,87	268,86	277,7	286,4	294,97	303,42	311,76	319,98	328,1	336,12	344,05	351,88	359,63	367,3	374,88	382,39	389,83	397,2	404,5
3000	237,2	246,92	256,45	265,81	275	284,04	292,95	301,71	310,36	318,88	327,29	335,6	343,8	351,91	359,92	367,85	375,69	383,45	391,14	398,74	406,28	413,75

σmax   180 Mpa   E 210000 Mpa   Zx 9,29 cm^3   θy   Ty   22,5 °   10 s

$$\sigma_x = \frac{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right) l_x}{4 \cdot V_{x-x}}$$
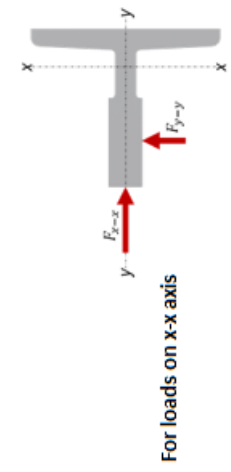
Resulting stress < σmax
Resulting stress > σmax

For loads on x-x axis

T82/B - Maximum distance between brackets [mm]

Weight [kg]	Height [m]																					
	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	2287,2	2241,7	2199,6	2160,6	2124,2	2090,1	2058,1	2027,9	1999,5	1972,6	1947,1	1922,8	1899,8	1877,7	1856,7	1836,6	1817,3	1798,9	1781,1	1764	1747,6	1731,8
600	2152,3	2109,5	2069,9	2033,2	1998,9	1966,8	1936,7	1908,4	1881,6	1856,3	1832,3	1809,5	1787,7	1767	1747,2	1728,3	1710,2	1692,8	1676,1	1660	1644,5	1629,6
700	2044,5	2003,9	1966,3	1931,4	1898,8	1868,3	1839,7	1812,8	1787,4	1763,3	1740,5	1718,8	1698,2	1678,5	1659,7	1641,8	1624,5	1608	1592,1	1576,9	1562,2	1548
800	1955,5	1916,6	1880,7	1847,3	1816,1	1787	1759,6	1733,9	1709,5	1686,5	1664,7	1644	1624,3	1605,5	1587,5	1570,3	1553,8	1538	1522,8	1508,2	1494,2	1480,6
900	1880,2	1842,8	1808,3	1776,2	1746,2	1718,2	1691,9	1667,1	1643,7	1621,6	1600,6	1580,7	1561,7	1543,6	1526,4	1509,8	1494	1478,8	1464,2	1450,2	1436,6	
1000	1815,3	1779,2	1745,9	1714,9	1685,9	1658,9	1633,5	1609,6	1587	1565,6	1545,4	1526,2	1507,8	1490,4	1473,7	1457,7	1442,4	1427,8				
1100	1758,6	1723,6	1691,3	1661,2	1633,2	1607	1582,4	1559,2	1537,4	1516,7	1497,1	1478,4	1460,7	1443,8	1427,6							
1200	1708,3	1674,3	1642,9	1613,7	1586,5	1561,1	1537,2	1514,7	1493,4	1473,3	1454,3	1436,2										
1300	1663,3	1630,2	1599,7	1571,3	1544,8	1520	1496,7	1474,8	1454,1	1434,5												
1400	1622,7	1590,5	1560,6	1532,9	1507,1	1482,9	1460,2	1438,8														
1500	1585,8	1554,3	1525,1	1498,1	1472,8	1449,2	1427															
1600	1552,1	1521,2	1492,7	1466,2	1441,5																	
1700	1521	1490,8	1462,8	1436,8																		
1800	1492,3	1462,7	1435,2																			
1900	1465,7	1436,5																				
2000	1440,8																					
2100																						
2200																						
2300																						
2400																						
2500																						
2600																						
2700																						
2800																						
2900																						
3000																						

δmax	3 mm	E 210000 Mpa	Ix	49,4 cm^4	θy	22,5 °	Ty	10 s

$$l_x = \sqrt[3]{\dfrac{\delta_{max} \cdot 48EI_{x-x}}{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\,\pi \cdot Z\right)}}$$

*Maximum allowable distance between brackets is 2900 mm

Value

Max distance, l > 2900 mm
Max distance, 2900 mm > l > 2500 mm
Max distance, 2500 mm > l > 2000 mm
Max distance, 2000 mm > l > 1500 mm
Max distance, 1500 mm > l > 1000 mm
Max distance, l < 1000 mm
Exceeds maximum allowable stress

For loads on x-x axis

T82/B - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	Height [m]																						
	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	69,993	72,861	75,673	78,434	81,148	83,816	86,443	89,031	91,581	94,096	96,579	99,029	101,45	103,84	106,21	108,55	110,86	113,15	115,42	117,66	119,89	122,09
600	79,04	82,278	85,454	88,572	91,636	94,649	97,615	100,54	103,42	106,26	109,06	111,83	114,56	117,26	119,93	122,57	125,19	127,77	130,33	132,87	135,38	137,87
700	87,594	91,183	94,703	98,158	101,55	104,89	108,18	111,42	114,61	117,76	120,86	123,93	126,96	129,95	132,91	135,84	138,74	141,6	144,44	147,25	150,03	152,79
800	95,75	99,673	103,52	107,3	111,01	114,66	118,25	121,79	125,28	128,72	132,12	135,47	138,78	142,05	145,29	148,49	151,65	154,79	157,89	160,96	164	167,02
900	103,57	107,81	111,98	116,06	120,08	124,03	127,91	131,74	135,51	139,24	142,91	146,54	150,12	153,66	157,16	160,62	164,04	167,43	170,79	174,11	177,4	180,66
1000	111,11	115,66	120,12	124,51	128,81	133,05	137,22	141,33	145,38	149,37	153,31	157,2	161,04	164,84	168,59	172,31	175,98	179,61	183,21	186,78	190,31	193,8
1100	118,4	123,25	128	132,67	137,26	141,78	146,22	150,6	154,91	159,17	163,37	167,51	171,61	175,65	179,65	183,61	187,52	191,4	195,23	199,03	202,79	206,52
1200	125,47	130,61	135,65	140,6	145,46	150,25	154,95	159,59	164,16	168,67	173,12	177,52	181,86	186,14	190,38	194,58	198,72	202,83	206,89	210,92	214,9	218,85
1300	132,34	137,77	143,08	148,31	153,44	158,48	163,45	168,34	173,16	177,92	182,61	187,25	191,82	196,35	200,82	205,24	209,62	213,95	218,23	222,48	226,68	230,85
1400	139,05	144,74	150,33	155,82	161,21	166,51	171,73	176,87	181,93	186,93	191,86	196,73	201,54	206,29	210,99	215,63	220,23	224,78	229,28	233,74	238,16	242,54
1500	145,59	151,56	157,41	163,15	168,79	174,35	179,81	185,19	190,5	195,73	200,89	205,99	211,02	216	220,92	225,78	230,6	235,36	240,08	244,75	249,37	253,96
1600	151,99	158,22	164,33	170,32	176,22	182,01	187,71	193,33	198,87	204,33	209,72	215,05	220,3	225,5	230,63	235,71	240,74	245,71	250,63	255,51	260,34	265,12
1700	158,26	164,75	171,11	177,35	183,48	189,52	195,46	201,31	207,07	212,76	218,37	223,91	229,39	234,8	240,14	245,43	250,67	255,84	260,97	266,05	271,07	276,06
1800	164,41	171,14	177,75	184,24	190,61	196,88	203,05	209,13	215,12	221,02	226,86	232,61	238,3	243,92	249,47	254,97	260,4	265,78	271,11	276,38	281,6	286,78
1900	170,44	177,43	184,27	191	197,61	204,1	210,5	216,8	223,01	229,14	235,18	241,15	247,04	252,87	258,63	264,32	269,96	275,54	281,06	286,52	291,94	297,3
2000	176,37	183,6	190,69	197,64	204,48	211,2	217,82	224,34	230,77	237,11	243,36	249,54	255,64	261,67	267,63	273,52	279,35	285,12	290,83	296,49	302,09	307,65
2100	182,2	189,67	196,99	204,18	211,24	218,19	225,02	231,76	238,4	244,95	251,41	257,79	264,09	270,32	276,47	282,56	288,59	294,55	300,45	306,29	312,08	317,82
2200	187,94	195,64	203,19	210,61	217,89	225,06	232,11	239,06	245,91	252,66	259,33	265,91	272,41	278,83	285,18	291,46	297,68	303,82	309,91	315,94	321,91	327,83
2300	193,6	201,53	209,31	216,94	224,45	231,83	239,09	246,25	253,31	260,26	267,13	273,91	280,6	287,22	293,76	300,23	306,63	312,96	319,23	325,44	331,59	337,69
2400	199,17	207,33	215,33	223,19	230,91	238,5	245,98	253,34	260,6	267,75	274,82	281,79	288,68	295,48	302,21	308,87	315,45	321,97	328,42	334,81	341,14	347,41
2500	204,66	213,05	221,27	229,34	237,28	245,08	252,76	260,33	267,78	275,14	282,4	289,56	296,64	303,64	310,55	317,39	324,16	330,85	337,48	344,05	350,55	356,99
2600	210,08	218,69	227,13	235,42	243,56	251,57	259,46	267,22	274,88	282,43	289,88	297,23	304,5	311,68	318,78	325,8	332,74	339,62	346,42	353,16	359,84	366,45
2700	215,44	224,26	232,92	241,42	249,77	257,98	266,07	274,03	281,88	289,62	297,26	304,81	312,26	319,62	326,9	334,1	341,22	348,27	355,25	362,16	369	375,79
2800	220,72	229,77	238,64	247,34	255,9	264,31	272,6	280,76	288,8	296,73	304,56	312,29	319,92	327,47	334,92	342,3	349,6	356,82	363,97	371,05	378,06	385,01
2900	225,95	235,21	244,28	253,2	261,96	270,57	279,05	287,4	295,64	303,76	311,77	319,68	327,49	335,22	342,85	350,4	357,87	365,26	372,58	379,83	387,01	394,12
3000	231,11	240,58	249,87	258,98	267,94	276,76	285,43	293,97	302,39	310,7	318,9	326,99	334,98	342,88	350,69	358,41	366,05	373,61	381,1	388,51	395,85	403,13

σmax	180 Mpa	E	210000 Mpa	Zx	10,2 cm^3	θy	22,5 °	Ty	10 s

$$\sigma_x = \frac{\frac{W}{2}\left(g \cdot \sin\theta + \left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z\right) l_x}{4 \cdot V_{x-x}}$$

Resulting stress < σmax

Resulting stress > σmax

For loads on x-x axis

xxv

T89/B - Maximum distance between brackets [mm]

Weight [kg]	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	2438	2389,5	2344,7	2303	2264,2	2227,9	2193,8	2161,6	2131,3	2102,7	2075,5	2049,6	2025	2001,6	1979,1	1957,7	1937,2	1917,5	1898,5	1880,3	1862,8	1845,9
600	2294,2	2248,6	2206,4	2167,2	2130,7	2096,5	2064,4	2034,2	2005,7	1978,7	1953,1	1928,8	1905,6	1883,5	1862,4	1842,3	1822,9	1804,4	1786,6	1769,5	1753	1737,1
700	2179,3	2136	2095,9	2058,7	2024	1991,5	1961	1932,3	1905,2	1879,6	1855,3	1832,3	1810,2	1789,2	1769,2	1750	1731,6	1714	1697,1	1680,8	1665,2	1650,1
800	2084,4	2043	2004,7	1969,1	1935,9	1904,8	1875,6	1848,2	1822,3	1797,7	1774,5	1752,4	1731,4	1711,3	1692,1	1673,8	1656,3	1639,4	1623,2	1607,7	1592,7	1578,3
900	2004,2	1964,3	1927,5	1893,3	1861,3	1831,5	1803,4	1777	1752,1	1728,5	1706,2	1684,9	1664,7	1645,4	1627	1609,4	1592,5	1576,3	1560,7	1545,8	1531,4	1517,5
1000	1935	1896,5	1861	1827,9	1797,1	1768,3	1741,2	1715,7	1691,6	1668,9	1647,3	1626,8	1607,3	1588,6	1570,9	1553,8	1537,5	1521,9	1506,9	1492,4	1478,5	1465,1
1100	1874,5	1837,2	1802,8	1770,8	1740,9	1713	1686,7	1662,1	1638,7	1616,7	1595,8	1575,9	1557	1539	1521,7	1505,2	1489,5	1474,3	1459,8	1445,8	1432,3	1419,3
1200	1820,9	1784,7	1751,2	1720,1	1691	1664	1638,5	1614,5	1591,9	1570,5	1550,2	1530,9	1512,5	1495	1478,2	1462,2	1446,9	1432,2	1418	1404,4	1391,3	1378,7
1300	1773	1737,1	1705,1	1674,9	1646,6	1620,2	1595,4	1572	1550	1529,1	1509,4	1490,6	1472,7	1455,6	1439,3	1423,7	1408,8	1394,5	1380,7	1367,5	1354,7	1342,4
1400	1729,7	1695,3	1663,5	1634	1606,4	1580,7	1556,5	1533,7	1512,2	1491,8	1472,5	1454,2	1436,7	1420,1	1404,2	1389	1374,4	1360,4	1347	1334,1		
1500	1690,4	1656,8	1625,7	1596,8	1569,9	1544,7	1521,1	1498,8	1477,8	1457,9	1439	1421,1	1404,1	1387,8	1372,3	1357,4	1343,2	1329,5				
1600	1654,4	1621,5	1591,1	1562,9	1536,5	1511,8	1488,7	1466,9	1446,3	1426,9	1408,4	1390,9	1374,2	1358,3	1343,1	1328,5						
1700	1621,3	1589,1	1559,3	1531,6	1505,8	1481,6	1458,9	1437,6	1417,4	1398,3	1380,2	1363,1	1346,7	1331,1								
1800	1590,7	1559,1	1529,9	1502,7	1477,3	1453,6	1431,4	1410,4	1390,7	1371,9	1354,2	1337,3										
1900	1562,3	1531,2	1502,5	1475,8	1451	1427,7	1405,8	1385,2	1365,8	1347,4	1330											
2000	1535,8	1505,3	1477,1	1450,8	1426,4	1403,5	1382	1361,8	1342,7	1324,6												
2100	1511	1481	1453,2	1427,4	1403,4	1380,8	1359,7	1339,8														
2200	1487,8	1458,2	1430,9	1405,5	1381,8	1359,6	1338,8															
2300	1465,9	1436,8	1409,8	1384,8	1361,4	1339,6																
2400	1445,3	1416,5	1390	1365,3	1342,3																	
2500	1425,7	1397,4	1371,2	1346,8	1324,1																	
2600	1407,2	1379,2	1353,4	1329,3																		
2700	1389,6	1362	1336,4																			
2800	1372,9	1345,6																				
2900	1356,9	1329,9																				
3000	1341,7																					

Legend:

- **Value**
- Max distance, l > 2900 mm
- Max distance, 2900 mm > l > 2500 mm
- Max distance, 2500 mm > l > 2000 mm
- Max distance, 2000 mm > l > 1500 mm
- Max distance, 1500 mm > l > 1000 mm
- Max distance, l < 1000 mm
- Exceeds maximum allowable stress

δmax	3 mm	E	210000 Mpa	Ix	59,83 cm^4	θy	22,5 °	Ty	10 s

*Maximum allowable distance between brackets is 2900 mm

$$l_x = \sqrt[3]{\frac{\delta_{max} \cdot 48 E I_{x-x}}{\frac{W}{2}\left(g \cdot \sin\theta + \left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z\right)}}$$

For loads on x-x axis

T89/B - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	53,032	55,205	57,335	59,427	61,483	63,505	65,495	67,456	69,388	71,294	73,174	75,031	76,865	78,678	80,47	82,242	83,995	85,73	87,448	89,149	90,834	92,503
600	59,886	62,339	64,746	67,108	69,429	71,713	73,96	76,174	78,356	80,508	82,632	84,729	86,8	88,846	90,87	92,871	94,851	96,81	98,75	100,67	102,57	104,46
700	66,367	69,087	71,753	74,371	76,944	79,474	81,965	84,418	86,837	89,222	91,575	93,899	96,194	98,463	100,71	102,92	105,12	107,29	109,44	111,57	113,68	115,76
800	72,546	75,519	78,434	81,295	84,108	86,874	89,596	92,278	94,921	97,529	100,1	102,64	105,15	107,63	110,08	112,51	114,9	117,28	119,63	121,95	124,26	126,54
900	78,473	81,688	84,841	87,936	90,978	93,97	96,915	99,816	102,68	105,5	108,28	111,03	113,74	116,42	119,07	121,7	124,29	126,86	129,4	131,92	134,41	136,88
1000	84,183	87,632	91,014	94,335	97,598	100,81	103,97	107,08	110,15	113,17	116,16	119,1	122,02	124,89	127,74	130,55	133,33	136,09	138,81	141,51	144,19	146,84
1100	89,705	93,381	96,985	100,52	104	107,42	110,79	114,1	117,37	120,6	123,78	126,92	130,02	133,09	136,12	139,12	142,08	145,02	147,92	150,8	153,65	156,47
1200	95,063	98,958	102,78	106,53	110,21	113,84	117,4	120,92	124,38	127,8	131,17	134,5	137,79	141,03	144,25	147,42	150,57	153,68	156,76	159,8	162,83	165,82
1300	100,27	104,38	108,41	112,37	116,25	120,08	123,84	127,55	131,2	134,8	138,36	141,87	145,34	148,77	152,15	155,5	158,82	162,1	165,35	168,56	171,75	174,91
1400	105,35	109,67	113,9	118,06	122,14	126,16	130,11	134,01	137,84	141,63	145,37	149,06	152,7	156,3	159,86	163,38	166,86	170,31	173,72	177,1	180,45	183,76
1500	110,31	114,83	119,26	123,61	127,89	132,1	136,24	140,31	144,33	148,3	152,21	156,07	159,89	163,66	167,38	171,07	174,72	178,33	181,9	185,44	188,94	192,41
1600	115,16	119,88	124,51	129,05	133,51	137,9	142,23	146,48	150,68	154,82	158,9	162,93	166,92	170,85	174,74	178,59	182,4	186,17	189,9	193,59	197,25	200,87
1700	119,91	124,82	129,64	134,37	139,02	143,59	148,09	152,52	156,89	161,2	165,45	169,65	173,8	177,9	181,95	185,96	189,92	193,84	197,73	201,57	205,38	209,16
1800	124,57	129,67	134,68	139,59	144,42	149,17	153,84	158,45	162,99	167,46	171,88	176,24	180,55	184,81	189,02	193,18	197,3	201,37	205,41	209,4	213,36	217,28
1900	129,14	134,43	139,62	144,71	149,72	154,64	159,49	164,26	168,97	173,61	178,19	182,71	187,18	191,59	195,95	200,27	204,54	208,76	212,95	217,09	221,19	225,26
2000	133,63	139,11	144,48	149,75	154,93	160,02	165,04	169,98	174,85	179,65	184,39	189,07	193,69	198,26	202,77	207,24	211,65	216,03	220,35	224,64	228,89	233,09
2100	138,05	143,71	149,25	154,7	160,05	165,31	170,49	175,6	180,63	185,59	190,48	195,32	200,09	204,81	209,47	214,09	218,65	223,17	227,64	232,07	236,45	240,8
2200	142,4	148,23	153,95	159,57	165,09	170,52	175,86	181,13	186,32	191,43	196,48	201,47	206,4	211,26	216,07	220,83	225,54	230,2	234,81	239,38	243,9	248,38
2300	146,68	152,69	158,58	164,37	170,06	175,65	181,15	186,58	191,92	197,19	202,39	207,53	212,6	217,62	222,57	227,47	232,32	237,12	241,87	246,58	251,24	255,86
2400	150,9	157,09	163,15	169,1	174,95	180,7	186,37	191,95	197,44	202,87	208,22	213,5	218,72	223,88	228,98	234,02	239,01	243,95	248,83	253,67	258,47	263,22
2500	155,07	161,42	167,65	173,77	179,78	185,69	191,51	197,24	202,89	208,46	213,96	219,39	224,76	230,06	235,29	240,48	245,6	250,68	255,7	260,67	265,6	270,48
2600	159,17	165,7	172,09	178,37	184,54	190,61	196,58	202,47	208,27	213,99	219,63	225,2	230,71	236,15	241,53	246,85	252,11	257,32	262,47	267,58	272,64	277,65
2700	163,23	169,92	176,48	182,91	189,24	195,47	201,59	207,63	213,57	219,44	225,23	230,94	236,59	242,17	247,68	253,14	258,53	263,87	269,16	274,4	279,58	284,72
2800	167,24	174,09	180,81	187,4	193,89	200,26	206,54	212,72	218,81	224,82	230,76	236,61	242,39	248,11	253,76	259,35	264,88	270,35	275,77	281,13	286,44	291,71
2900	171,19	178,21	185,09	191,84	198,48	205	211,43	217,76	223,99	230,15	236,22	242,21	248,13	253,98	259,77	265,49	271,15	276,75	282,29	287,78	293,22	298,61
3000	175,11	182,28	189,32	196,22	203,01	209,69	216,26	222,73	229,11	235,41	241,62	247,75	253,8	259,79	265,71	271,56	277,35	283,07	288,75	294,36	299,93	305,44

σmax	180 Mpa	E 210000 Mpa	Zx 14,35 cm^3	θy 22,5 °	Ty 10 s

$$\sigma_x = \frac{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right) l_x}{4 \cdot V_{x-x}}$$
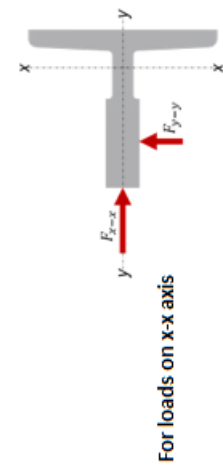
Resulting stress < σmax

Resulting stress > σmax

For loads on x-x axis

T114/B - Maximum distance between brackets [mm]

Weight [kg]	\ Height [m] 8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	3514,9	3445	3380,4	3320,4	3264,4	3212	3162,8	3116,5	3072,8	3031,5	2992,3	2955	2919,6	2885,7	2853,4	2822,5	2792,9	2764,5	2737,2	2711	2685,7	2661,4
600	3307,7	3241,9	3181,1	3124,6	3071,9	3022,6	2976,3	2932,8	2891,6	2852,7	2815,8	2780,8	2747,4	2715,6	2685,2	2656,1	2628,2	2601,5	2575,8	2551,1	2527,3	2504,4
700	3142	3079,5	3021,8	2968,1	2918,1	2871,2	2827,3	2785,9	2746,8	2709,9	2674,8	2641,5	2609,8	2579,6	2550,7	2523	2496,6	2471,2	2446,8	2423,3	2400,8	2379
800	3005,2	2945,5	2890,2	2838,9	2791	2746,2	2704,2	2664,6	2627,2	2591,9	2558,4	2526,5	2496,2	2467,3	2439,6	2413,2	2387,9	2363,6	2340,3	2317,8	2296,2	2275,4
900	2889,5	2832,1	2778,9	2729,6	2683,6	2640,5	2600	2562	2526,1	2492,1	2459,9	2429,2	2400	2372,3	2345,7	2320,3	2296	2272,6	2250,2	2228,6	2207,8	2187,8
1000	2789,8	2734,3	2683	2635,4	2591	2549,4	2510,3	2473,6	2438,9	2406,1	2375	2345,4	2317,2	2290,4	2264,8	2240,2	2216,7	2194,2	2172,5	2151,7	2131,6	2112,3
1100	2702,5	2648,8	2599,1	2553	2509,9	2469,7	2431,8	2396,2	2362,6	2330,9	2300,7	2272,1	2244,8	2218,8	2193,9	2170,2	2147,4	2125,6	2104,6	2084,4	2065	2046,3
1200	2625,3	2573,1	2524,8	2480	2438,2	2399,1	2362,3	2327,7	2295,1	2264,2	2234,9	2207,1	2180,6	2155,4	2131,2	2108,1	2086	2064,8	2044,4	2024,8	2006	1987,8
1300	2556,2	2505,4	2458,4	2414,7	2374	2335,9	2300,1	2266,5	2234,7	2204,6	2176,1	2149	2123,2	2098,6	2075,1	2052,6	2031,1	2010,4	1990,6	1971,5	1953,1	1935,4
1400	2493,8	2444,2	2398,4	2355,8	2316,1	2278,9	2244	2211,2	2180,2	2150,8	2123	2096,6	2071,4	2047,4	2024,5	2002,5	1981,5	1961,4	1942	1923,4	1905,5	1888,2
1500	2437,1	2388,7	2343,9	2302,2	2263,4	2227,1	2193	2160,9	2130,6	2101,9	2074,7	2048,9	2024,3	2000,9	1978,4	1957	1936,5	1916,8	1897,9	1879,7	1862,2	1845,3
1600	2385,2	2337,8	2294	2253,2	2215,2	2179,7	2146,3	2114,9	2085,2	2057,2	2030,6	2005,3	1981,2	1958,3	1936,3	1915,4	1895,3	1876	1857,5	1839,7	1822,5	1806
1700	2337,5	2291,1	2248,1	2208,2	2170,9	2136,1	2103,4	2072,6	2043,5	2016	1989,9	1965,2	1941,6	1919,1	1897,6	1877	1857,4	1838,5	1820,3	1802,9	1786,1	1769,9
1800	2293,4	2247,8	2205,6	2166,5	2130	2095,8	2063,7	2033,5	2005	1978	1952,4	1928,1	1904,9	1882,9	1861,8	1841,6	1822,3	1803,8	1786	1768,8	1752,4	1736,5
1900	2252,4	2207,7	2166,3	2127,8	2091,9	2058,3	2026,8	1997,2	1969,1	1942,6	1917,5	1893,6	1870,9	1849,2	1828,5	1808,7	1789,8	1771,6	1754,1	1737,3	1721,1	1705,5
2000	2214,3	2170,2	2129,5	2091,7	2056,4	2023,4	1992,5	1963,3	1935,8	1909,7	1885	1861,5	1839,2	1817,9	1797,5	1778,1	1759,4	1741,5	1724,3	1707,8	1691,9	1676,5
2100	2178,5	2135,2	2095,2	2058	2023,3	1990,8	1960,3	1931,6	1904,5	1878,9	1854,6	1831,5	1809,5	1788,6	1768,5	1749,4	1731	1713,4	1696,5	1680,2	1664,6	1649,5
2200	2145	2102,4	2062,9	2026,3	1992,1	1960,2	1930,2	1901,9	1875,2	1850	1826,1	1803,3	1781,7	1761	1741,3	1722,5	1704,4	1687,1	1670,4	1654,4	1639	1624,1
2300	2113,5	2071,5	2032,6	1996,5	1962,8	1931,3	1901,8	1873,9	1847,7	1822,8	1799,2	1776,8	1755,5	1735,1	1715,7	1697,1	1679,3	1662,2	1645,8	1630,1	1614,9	1600,2
2400	2083,7	2042,3	2004	1968,4	1935,2	1904,1	1875	1847,5	1821,6	1797,1	1773,9	1751,8	1730,8	1710,7	1691,6	1673,2	1655,7	1638,8	1622,7	1607,1	1592,1	
2500	2055,5	2014,7	1976,9	1941,8	1909	1878,4	1849,6	1822,6	1797	1772,8	1749,9	1728,1	1707,4	1687,6	1668,7	1650,6	1633,3	1616,7	1600,7			
2600	2028,8	1988,5	1951,2	1916,6	1884,2	1854	1825,6	1798,9	1773,7	1749,8	1727,2	1705,7	1685,2	1665,7	1647	1629,2	1612,1	1595,7				
2700	2003,5	1963,6	1926,8	1892,6	1860,7	1830,8	1802,8	1776,4	1751,5	1727,9	1705,6	1684,3	1664,1	1644,8	1626,4	1608,8	1591,9					
2800	1979,3	1940	1903,6	1869,8	1838,3	1808,8	1781,1	1755	1730,4	1707,1	1685	1664	1644,1	1625	1606,8							
2900	1956,3	1917,4	1881,5	1848	1816,9	1787,7	1760,4	1734,6	1710,3	1687,3	1665,4	1644,7	1625	1606,1								
3000	1934,3	1895,9	1860,3	1827,3	1796,5	1767,6	1740,6	1715,1	1691	1668,3	1646,7	1626,2	1606,7									

δmax	3 mm	E 210000 Mpa	Ix 179,3 cm^4	θy 22,5 °	Ty 10 s

Value (legend)

Max distance, l > 2900 mm
Max distance, 2900 mm > l > 2500 mm
Max distance, 2500 mm > l > 2000 mm
Max distance, 2000 mm > l > 1500 mm
Max distance, 1500 mm > l > 1000 mm
Max distance, l < 1000 mm
Exceeds maximum allowable stress

*Maximum allowable distance between brackets is 2900 mm

$$l_x = \sqrt[s]{\dfrac{\delta_{max} \cdot 48 E I_{x-x}}{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right)}}$$

For loads on x-x axis

T114/B - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	36,892	38,404	39,886	41,341	42,771	44,178	45,563	46,926	48,271	49,596	50,905	52,196	53,472	54,733	55,98	57,212	58,432	59,639	60,834	62,017	63,19	64,351
600	41,66	43,367	45,041	46,684	48,299	49,888	51,451	52,991	54,509	56,006	57,484	58,942	60,383	61,807	63,215	64,607	65,984	67,347	68,697	70,033	71,356	72,668
700	46,169	48,061	49,916	51,737	53,527	55,287	57,02	58,727	60,409	62,068	63,705	65,322	66,919	68,497	70,057	71,599	73,126	74,636	76,132	77,613	79,08	80,533
800	50,468	52,535	54,563	56,554	58,51	60,435	62,329	64,194	66,033	67,847	69,637	71,404	73,149	74,874	76,579	78,266	79,934	81,585	83,22	84,839	86,442	88,031
900	54,59	56,827	59,02	61,174	63,29	65,371	67,42	69,438	71,427	73,389	75,325	77,236	79,124	80,99	82,835	84,659	86,464	88,25	90,018	91,769	93,503	95,222
1000	58,563	60,962	63,315	65,625	67,895	70,128	72,326	74,491	76,625	78,729	80,806	82,857	84,882	86,884	88,862	90,819	92,755	94,671	96,568	98,447	100,31	102,15
1100	62,404	64,961	67,469	69,93	72,349	74,729	77,071	79,378	81,652	83,894	86,107	88,292	90,45	92,583	94,692	96,777	98,84	100,88	102,9	104,9	106,89	108,85
1200	66,131	68,841	71,498	74,107	76,67	79,192	81,674	84,118	86,528	88,905	91,25	93,565	95,852	98,113	100,35	102,56	104,74	106,91	109,05	111,17	113,27	115,35
1300	69,756	72,614	75,417	78,169	80,873	83,532	86,15	88,729	91,271	93,778	96,251	98,694	101,11	103,49	105,85	108,18	110,48	112,77	115,03	117,26	119,48	121,68
1400	73,289	76,292	79,237	82,128	84,969	87,763	90,513	93,223	95,893	98,527	101,13	103,69	106,23	108,73	111,21	113,66	116,08	118,48	120,85	123,2	125,53	127,84
1500	76,739	79,883	82,966	85,993	88,968	91,894	94,774	97,611	100,41	103,16	105,89	108,57	111,23	113,85	116,44	119,01	121,54	124,05	126,54	129	131,44	133,86
1600	80,113	83,395	86,614	89,774	92,88	95,934	98,941	101,9	104,82	107,7	110,54	113,35	116,12	118,85	121,56	124,24	126,89	129,51	132,1	134,67	137,22	139,74
1700	83,417	86,834	90,186	93,477	96,71	99,891	103,02	106,1	109,14	112,14	115,1	118,02	120,91	123,76	126,58	129,36	132,12	134,85	137,55	140,23	142,88	145,5
1800	86,657	90,207	93,689	97,107	100,47	103,77	107,02	110,23	113,38	116,5	119,57	122,61	125,6	128,56	131,49	134,39	137,25	140,09	142,89	145,67	148,43	151,16
1900	89,837	93,518	97,128	100,67	104,15	107,58	110,95	114,27	117,55	120,77	123,96	127,11	130,21	133,28	136,32	139,32	142,29	145,23	148,14	151,02	153,87	156,7
2000	92,962	96,771	100,51	104,17	107,78	111,32	114,81	118,25	121,63	124,98	128,27	131,53	134,74	137,92	141,06	144,17	147,24	150,28	153,29	156,27	159,23	162,15
2100	96,036	99,971	103,83	107,62	111,34	115	118,61	122,16	125,66	129,11	132,51	135,88	139,2	142,48	145,72	148,93	152,11	155,25	158,36	161,44	164,49	167,52
2200	99,061	103,12	107,1	111,01	114,85	118,62	122,34	126	129,61	133,17	136,69	140,16	143,58	146,97	150,31	153,62	156,9	160,14	163,35	166,53	169,67	172,79
2300	102,04	106,22	110,32	114,35	118,3	122,19	126,02	129,79	133,51	137,18	140,8	144,37	147,9	151,39	154,83	158,24	161,62	164,96	168,26	171,53	174,78	177,99
2400	104,98	109,28	113,5	117,64	121,71	125,71	129,65	133,53	137,35	141,13	144,85	148,53	152,16	155,74	159,29	162,8	166,27	169,7	173,1	176,47	179,81	183,11
2500	107,87	112,29	116,63	120,88	125,06	129,18	133,23	137,21	141,14	145,02	148,85	152,62	156,35	160,04	163,69	167,29	170,86	174,39	177,88	181,34	184,77	188,16
2600	110,73	115,27	119,72	124,09	128,38	132,6	136,75	140,85	144,88	148,86	152,79	156,67	160,5	164,28	168,02	171,72	175,38	179,01	182,59	186,14	189,66	193,15
2700	113,55	118,2	122,77	127,25	131,65	135,98	140,24	144,44	148,57	152,66	156,68	160,66	164,59	168,47	172,3	176,1	179,85	183,57	187,24	190,89	194,49	198,07
2800	116,34	121,11	125,78	130,37	134,88	139,31	143,68	147,98	152,22	156,4	160,53	164,6	168,62	172,6	176,53	180,42	184,27	188,07	191,84	195,57	199,27	202,93
2900	119,09	123,97	128,76	133,46	138,07	142,61	147,08	151,48	155,82	160,1	164,33	168,5	172,62	176,69	180,71	184,69	188,63	192,52	196,38	200,2	203,98	207,73
3000	121,82	126,81	131,7	136,51	141,23	145,87	150,44	154,95	159,39	163,76	168,08	172,35	176,56	180,72	184,84	188,91	192,94	196,92	200,87	204,78	208,65	212,48

σmax	E	Zx	θy	Ty
180 Mpa	210000 Mpa	29,74 cm^3	22,5 °	10 s

$$\sigma_x = \frac{\frac{W}{2}\left(g \cdot \sin\theta + \left(2\frac{\pi}{T}\right)^2 \cdot \frac{\theta}{180}\pi \cdot Z\right) l_x}{4 \cdot V_{x-x}}$$

Resulting stress < σmax
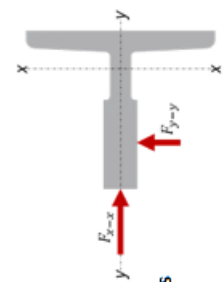Resulting stress > σmax
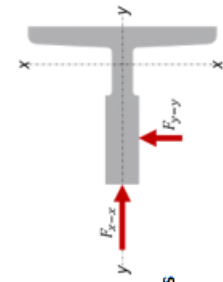
For loads on x-x axis

T125/B - Maximum distance between brackets [mm]

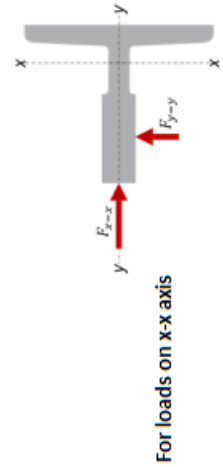| Weight [kg]	Height [m] 8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	3319,3	3253,3	3192,3	3135,6	3082,7	3033,3	2986,8	2943,1	2901,8	2862,8	2825,8	2790,6	2757,1	2725,1	2694,6	2665,4	2637,5	2610,6	2584,9	2560,1	2536,2	2513,2
600	3123,6	3061,5	3004,1	2950,7	2901	2854,4	2810,7	2769,6	2730,7	2694	2659,1	2626	2594,5	2564,4	2535,7	2508,3	2482	2456,7	2432,5	2409,1	2386,7	2365,1
700	2967,1	2908,2	2853,6	2802,9	2755,7	2711,4	2669,9	2630,8	2594	2559	2525,9	2494,5	2464,6	2436	2408,7	2382,6	2357,6	2333,7	2310,6	2288,5	2267,2	2246,6
800	2838	2781,5	2729,4	2680,9	2635,7	2593,4	2553,7	2516,3	2481	2447,6	2416	2385,9	2357,3	2330	2303,9	2278,9	2255	2232,1	2210	2188,8	2168,5	2148,8
900	2728,7	2674,5	2624,3	2577,7	2534,2	2493,6	2455,4	2419,4	2385,5	2353,4	2323	2294	2266,5	2240,3	2215,2	2191,2	2168,2	2146,1	2124,9	2104,6	2085	2066,1
1000	2634,5	2582,2	2533,7	2488,7	2446,8	2407,5	2370,6	2335,9	2303,2	2272,2	2242,8	2214,9	2188,3	2162,9	2138,7	2115,6	2093,4	2072,1	2051,6	2031,9	2013	1994,8
1100	2552,1	2501,4	2454,5	2410,9	2370,3	2332,2	2296,5	2262,9	2231,2	2201,1	2172,7	2145,6	2119,9	2095,3	2071,8	2049,4	2027,9	2007,3	1987,5	1968,4	1950,1	1932,4
1200	2479,2	2429,9	2384,3	2342	2302,5	2265,5	2230,9	2198,2	2167,4	2138,2	2110,6	2084,3	2059,3	2035,4	2012,6	1990,8	1969,9	1949,9	1930,6	1912,1	1894,3	1877,1
1300	2413,9	2365,9	2321,6	2280,3	2241,9	2205,9	2172,1	2140,3	2110,3	2081,9	2055	2029,4	2005	1981,8	1959,6	1938,4	1918,1	1898,6	1879,8	1861,8	1844,4	1827,7
1400	2355	2308,2	2264,9	2224,7	2187,2	2152,1	2119,1	2088,1	2058,8	2031,1	2004,8	1979,9	1956,1	1933,5	1911,8	1891,1	1871,3	1852,2	1833,9	1816,4	1799,4	1783,1
1500	2301,5	2255,7	2213,4	2174,1	2137,4	2103,1	2070,9	2040,6	2012	1984,9	1959,3	1934,9	1911,6	1889,5	1868,3	1848,1	1828,7	1810,1	1792,3	1775,1	1758,5	1742,6
1600	2252,5	2207,7	2166,3	2127,8	2092	2058,4	2026,9	1997,2	1969,2	1942,7	1917,6	1893,7	1871	1849,3	1828,6	1808,8	1789,8	1771,6	1754,1	1737,3	1721,1	1705,5
1700	2207,4	2163,5	2123	2085,3	2050,1	2017,2	1986,3	1957,2	1929,8	1903,8	1879,2	1855,8	1833,3	1812,3	1792	1772,6	1754	1736,2	1719	1702,5	1686,7	1671,4
1800	2165,8	2122,7	2082,9	2045,9	2011,4	1979,1	1948,8	1920,3	1893,4	1867,9	1843,7	1820,8	1798,9	1778,1	1758,2	1739,1	1720,9	1703,4	1686,6	1670,4	1654,8	1639,8
1900	2127,1	2084,8	2045,7	2009,4	1975,5	1943,8	1914	1886	1859,6	1834,5	1810,8	1788,3	1766,8	1746,3	1726,8	1708,1	1690,2	1673	1656,4	1640,6	1625,3	1610,5
2000	2091	2049,5	2011	1975,3	1942	1910,8	1881,6	1854	1828	1803,4	1780,1	1757,9	1736,8	1716,7	1697,5	1679,1	1661,5	1644,6	1628,4	1612,8	1597,7	1583,2
2100	2057,1	2016,4	1978,6	1943,4	1910,7	1880	1851,2	1824,1	1798,5	1774,3	1751,4	1729,6	1708,8	1689	1670,1	1652	1634,7	1618,1	1602,1	1586,7	1572	1557,7
2200	2025,6	1985,4	1948,1	1913,5	1881,3	1851,1	1822,7	1796,1	1770,9	1747	1724,4	1703	1682,5	1663	1644,4	1626,6	1609,5	1593,2	1577,4	1562,3		
2300	1995,8	1956,2	1919,5	1885,4	1853,6	1823,9	1795,9	1769,6	1744,7	1721,3	1699,1	1677,9	1657,8	1638,6	1620,2	1602,7	1585,9	1569,7				
2400	1967,7	1928,6	1892,4	1858,8	1827,5	1798,2	1770,6	1744,8	1720,2	1697,1	1675,1	1654,3	1634,4	1615,5	1597,4	1580,1	1563,5					
2500	1941,1	1902,6	1866,9	1833,7	1802,8	1773,9	1746,7	1721,1	1697	1674,2	1652,5	1631,9	1612,3	1593,7	1575,8	1558,8						
2600	1915,9	1877,8	1842,6	1809,9	1779,4	1750,8	1724	1698,8	1675	1652,4	1631	1610,7	1591,4	1573								
2700	1892	1854,4	1819,6	1787,3	1757,1	1728,9	1702,5	1677,5	1654	1631,8	1610,7	1590,6	1571,5									
2800	1869,2	1832	1797,7	1765,7	1736	1708,1	1681,9	1657,3	1634,1	1612,1	1591,2	1571,4										
2900	1847,4	1810,7	1776,8	1745,2	1715,8	1688,2	1662,4	1638,1	1615,1	1593,4	1572,7											
3000	1826,7	1790,4	1756,8	1725,6	1696,5	1669,3	1643,7	1619,6	1596,9	1575,4												

Value (colour scale)

Max distance, l > 2900 mm
Max distance, 2900 mm > l > 2500 mm
Max distance, 2500 mm > l > 2000 mm
Max distance, 2000 mm > l > 1500 mm
Max distance, 1500 mm > l > 1000 mm
Max distance, l < 1000 mm
Exceeds maximum allowable stress

δmax	3 mm	E	210000 Mpa	Ix	151 cm^4	Ty	10 s	θy	22,5 °

*Maximum allowable distance between brackets is 2900 mm

$$l_x = \sqrt[3]{\dfrac{\delta_{max} \cdot 48 E I_{x-x}}{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right)}}$$

For loads on x-x axis

T125/B - Resulting stress for maximum distance between brackets [MPa]

Weight [kg]	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
500	39,607	41,23	42,821	44,383	45,919	47,429	48,915	50,379	51,822	53,246	54,65	56,037	57,407	58,761	60,099	61,422	62,732	64,028	65,31	66,581	67,839	69,086
600	44,726	46,558	48,355	50,12	51,853	53,559	55,237	56,89	58,52	60,127	61,714	63,28	64,826	66,355	67,866	69,361	70,839	72,303	73,751	75,186	76,607	78,015
700	49,566	51,597	53,589	55,544	57,466	59,355	61,216	63,048	64,854	66,635	68,393	70,129	71,843	73,537	75,212	76,868	78,507	80,128	81,734	83,324	84,898	86,459
800	54,181	56,401	58,578	60,715	62,816	64,882	66,915	68,918	70,892	72,839	74,761	76,658	78,532	80,383	82,214	84,025	85,816	87,588	89,343	91,081	92,803	94,508
900	58,607	61,008	63,363	65,675	67,947	70,182	72,381	74,548	76,683	78,789	80,868	82,92	84,947	86,95	88,93	90,888	92,826	94,743	96,642	98,521	100,38	102,23
1000	62,872	65,448	67,974	70,454	72,891	75,288	77,648	79,972	82,263	84,522	86,752	88,953	91,128	93,277	95,401	97,502	99,58	101,64	103,67	105,69	107,69	109,67
1100	66,996	69,741	72,433	75,076	77,673	80,227	82,742	85,218	87,66	90,067	92,443	94,789	97,106	99,396	101,66	103,9	106,11	108,31	110,48	112,62	114,75	116,86
1200	70,998	73,906	76,759	79,56	82,312	85,019	87,683	90,308	92,895	95,446	97,964	100,45	102,91	105,33	107,73	110,1	112,45	114,77	117,07	119,35	121,61	123,84
1300	74,889	77,957	80,966	83,921	86,824	89,679	92,489	95,258	97,987	100,68	103,33	105,96	108,55	111,11	113,64	116,14	118,61	121,06	123,49	125,89	128,27	130,63
1400	78,682	81,906	85,067	88,171	91,221	94,221	97,174	100,08	102,95	105,78	108,57	111,32	114,04	116,73	119,39	122,02	124,62	127,2	129,74	132,27	134,77	137,24
1500	82,385	85,761	89,071	92,321	95,515	98,656	101,75	104,79	107,8	110,76	113,68	116,56	119,41	122,23	125,01	127,76	130,49	133,18	135,85	138,49	141,11	143,7
1600	86,007	89,531	92,987	96,38	99,714	102,99	106,22	109,4	112,53	115,63	118,68	121,69	124,66	127,6	130,51	133,38	136,22	139,04	141,82	144,58	147,32	150,02
1700	89,555	93,224	96,822	100,35	103,83	107,24	110,6	113,91	117,18	120,39	123,57	126,71	129,8	132,86	135,89	138,88	141,84	144,77	147,67	150,55	153,39	156,21
1800	93,033	96,845	100,58	104,25	107,86	111,41	114,9	118,34	121,73	125,07	128,37	131,63	134,84	138,02	141,17	144,28	147,35	150,4	153,41	156,39	159,35	162,28
1900	96,448	100,4	104,27	108,08	111,82	115,5	119,11	122,68	126,19	129,66	133,08	136,46	139,79	143,09	146,35	149,57	152,76	155,92	159,04	162,13	165,2	168,23
2000	99,803	103,89	107,9	111,84	115,71	119,51	123,26	126,95	130,58	134,17	137,71	141,2	144,66	148,07	151,44	154,77	158,07	161,34	164,57	167,77	170,94	174,09
2100	103,1	107,33	111,47	115,54	119,53	123,46	127,33	131,14	134,9	138,61	142,26	145,87	149,44	152,96	156,45	159,89	163,3	166,67	170,01	173,32	176,6	179,84
2200	106,35	110,71	114,98	119,18	123,3	127,35	131,34	135,28	139,15	142,97	146,74	150,47	154,15	157,78	161,37	164,93	168,44	171,92	175,37	178,78	182,16	185,51
2300	109,55	114,04	118,44	122,76	127,01	131,18	135,29	139,34	143,34	147,27	151,16	154,99	158,78	162,53	166,23	169,89	173,51	177,09	180,64	184,16	187,64	191,09
2400	112,7	117,32	121,85	126,29	130,66	134,96	139,19	143,35	147,46	151,51	155,51	159,45	163,35	167,2	171,01	174,78	178,5	182,19	185,84	189,46	193,04	196,59
2500	115,81	120,56	125,21	129,78	134,27	138,68	143,03	147,31	151,53	155,69	159,8	163,85	167,86	171,82	175,73	179,6	183,43	187,22	190,97	194,68	198,36	202,01
2600	118,88	123,75	128,53	133,22	137,82	142,36	146,82	151,21	155,54	159,82	164,03	168,19	172,31	176,37	180,39	184,36	188,29	192,18	196,03	199,84	203,62	207,36
2700	121,91	126,9	131,8	136,61	141,34	145,98	150,56	155,07	159,51	163,89	168,21	172,48	176,7	180,86	184,98	189,06	193,09	197,07	201,02	204,93	208,81	212,64
2800	124,9	130,02	135,04	139,96	144,8	149,57	154,25	158,87	163,42	167,91	172,34	176,71	181,03	185,3	189,52	193,69	197,82	201,91	205,96	209,96	213,93	217,86
2900	127,86	133,09	138,23	143,28	148,23	153,11	157,9	162,63	167,29	171,88	176,42	180,9	185,32	189,69	194,01	198,28	202,51	206,69	210,83	214,93	218,99	223,02
3000	130,78	136,14	141,39	146,55	151,62	156,61	161,51	166,35	171,11	175,81	180,45	185,03	189,55	194,02	198,44	202,81	207,14	211,41	215,65	219,85	224	228,12

Height [m]

σmax	180 Mpa
E	210000 Mpa
Zx	26,16 cm^3
θy	22,5 °
Ty	10 s

$$\sigma_x = \frac{\dfrac{W}{2}\left(g \cdot \sin\theta + \left(2\dfrac{\pi}{T}\right)^2 \cdot \dfrac{\theta}{180}\pi \cdot Z\right) l_x}{4 \cdot V_{x-x}}$$

Resulting stress < σmax
Resulting stress > σmax

For loads on x-x axis

Vard PNO1967 "Sunshine"

Main deck	3	
Loa	145	m
Breadth Mld.	20	m
Depth bulchead	6,8	m
Rotation axis from BL	3,4	m
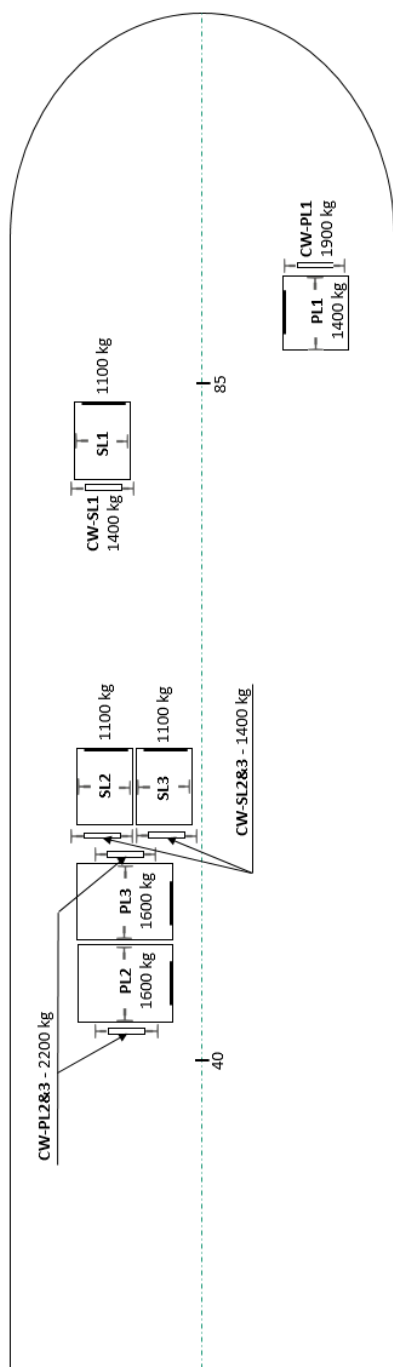
Passanger lift

	PL1	PL2	PL3	
Type	Traction	Traction	Traction	
Trunk size, LxW	2300x2400	2500x2100	2500x2100	mm
Car size, LxWxH	1525x1525x2200	2030x1370x2200	2030x1370x2200	mm
Speed	1 / 1,6	1 / 1,6	1 / 1,6	m/s
Travelling height	14,7	17,7	17,7	m
Deck travel	3 to 8	3 to 9	3 to 9	
Stops	6	7	7	
Shaft head	3700	3700	3700	mm
Pit	1100	1100	1100	mm
Distance to mass	18,6	21,6	21,6	m
Capacity	1000	1200	1200	kg
Car weight	1400	1600	1600	kg
Absolut weight	2400	2800	2800	kg
CW	1900	2200	2200	kg

Service lift

	SL1	SL2	SL3	
Type	Traction	Traction	Traction	
Trunk size, LxW	2100x1600	2100x1600	2100x2100	mm
Car size, LxWxH	1350x1100x2200	1350x1100x2200	1350x1100x2200	mm
Speed	1 / 1,6	1 / 1,6	1 / 1,6	m/s
Travelling height	14,7	14,7	14,7	m
Deck travel	2 to 7	3 to 8	3 to 8	
Stops	6	6	6	
Top	3600	3600	3600	mm
Pit	1100	1100	1100	mm
Distance to mass	15,8	18,6	18,6	m
Capacity	600	600	600	kg
Car weight	1100	1100	1100	kg
Absolut weight	1700	1700	1700	kg
CW	1400	1400	1400	kg

Diagram labels: CW-PL1 1900 kg; PL1 1400 kg; CW-SL1 1400 kg; SL1 1100 kg; SL2 1100 kg; SL3 1100 kg; PL3 1600 kg; PL2 1600 kg; CW-PL2&3 - 2200 kg; CW-SL2&3 - 1400 kg; 85; 40

Estimation

Elevator/CW	BRK direction	Weight, W[kg]	Height, Z[m]	GR Dimention	BRK distance, l[m]	Stress [Mpa]	Deflection [mm]	GR length needed, h[m]
PL1	Longitudinal	1400	18,6	**T90/B**	**1,8**	89,7	2,56	37
PL2	Longitudinal	1600	21,6	**T90/B**	**1,7**	103,6	2,64	43
PL3	Longitudinal	1600	21,6	**T90/B**	**1,7**	103,6	2,64	43
CW - PL1	Transverse	1900	18,6	**T90/B**	**1,6**	120,9	2,51	37
CW - PL2	Transverse	2200	21,6	**T90/B**	**1,5**	140,5	2,57	43
CW - PL3	Transverse	2200	21,6	**T90/B**	**1,5**	140,5	2,57	43
SL1	Transverse	1100	15,8	**T90/B**	**2**	81,8	2,66	37
SL2	Transverse	1100	18,6	**T90/B**	**2**	87,5	2,84	37
SL3	Transverse	1100	18,6	**T90/B**	**2**	87,5	2,84	37
CW - SL1	Transverse	1400	15,8	**T70-1/A**	**1,5**	150,9	2,75	37
CW - SL2	Transverse	1400	18,6	**T70-1/A**	**1,5**	161,5	2,95	37
CW - SL3	Transverse	1400	18,6	**T70-1/A**	**1,5**	161,5	2,95	37

Procurement

	T70-1/A	T75-3/B	T82/B	T89/B	T90/B	T114/B	T125/B
Nr of GR á 5 m	23				72		
Weight [kg]	1012				4896		
Price [EUR]	1564				11098		

Flip page!

Load case 1: Direct load on x-x

Welded bracket:
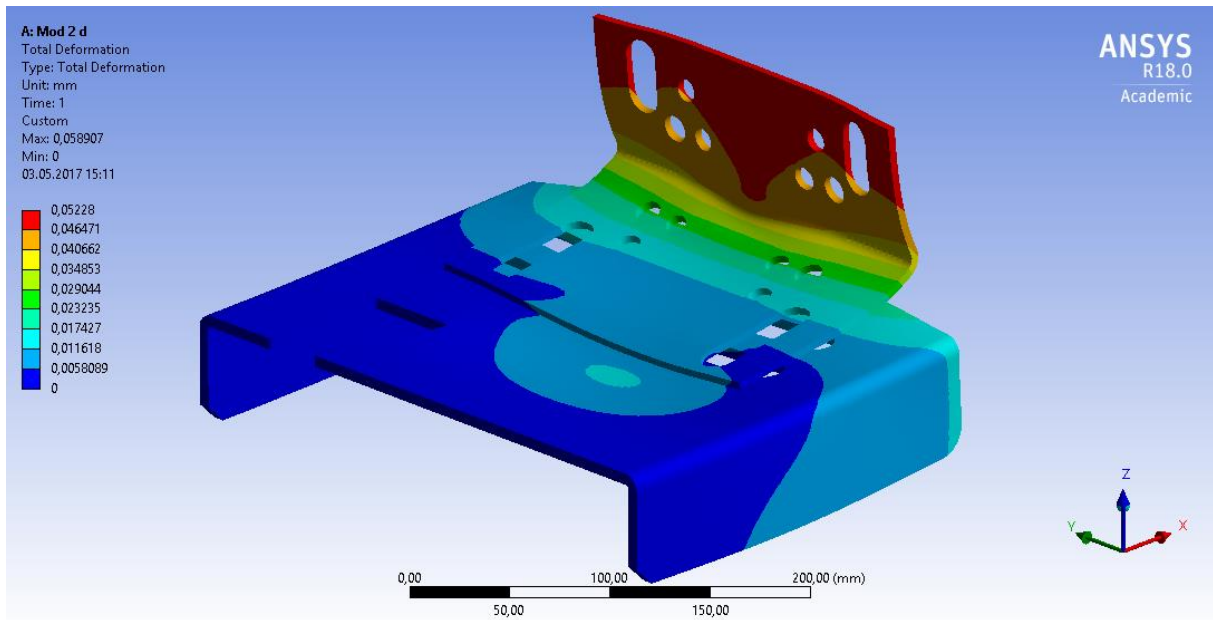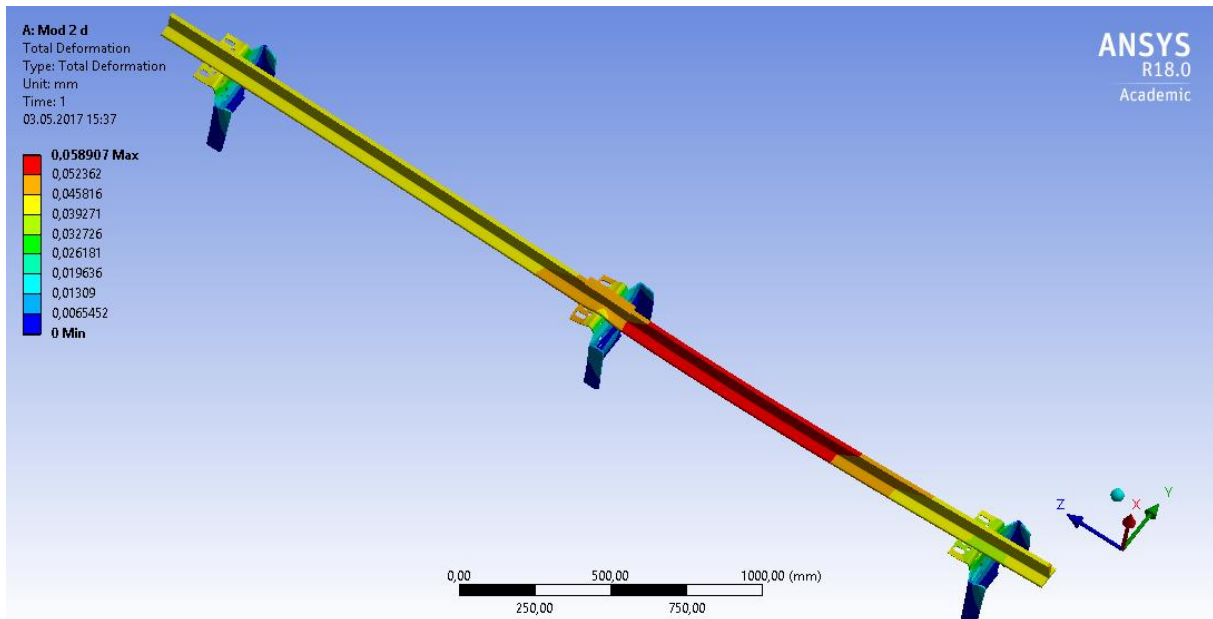
Adjustable bracket:
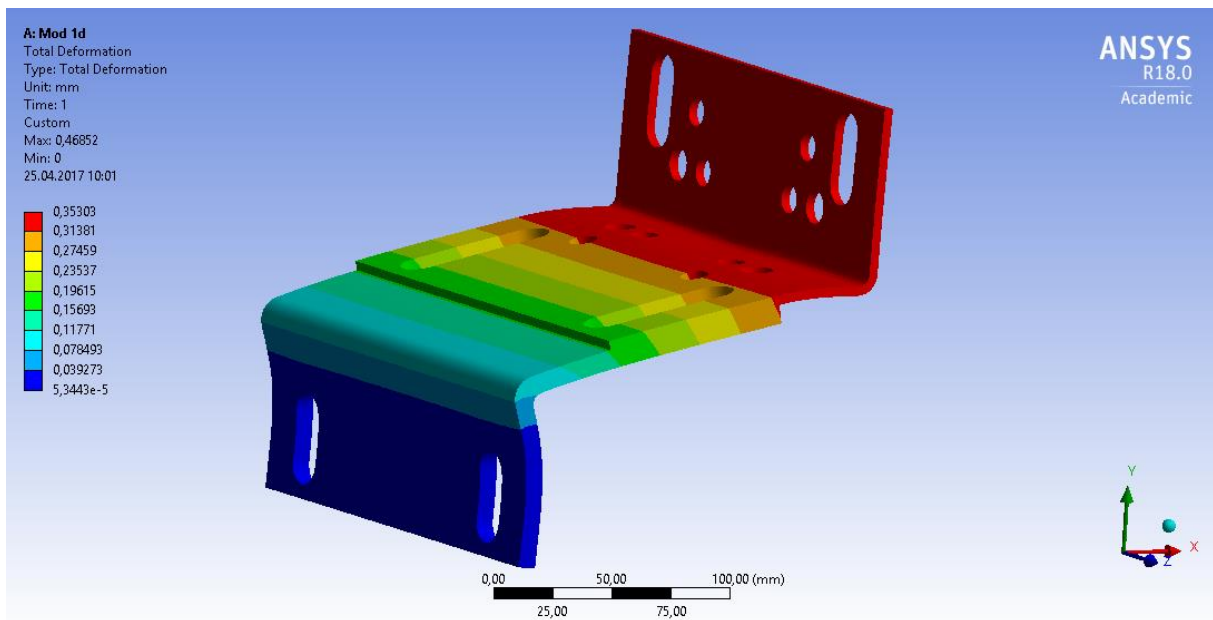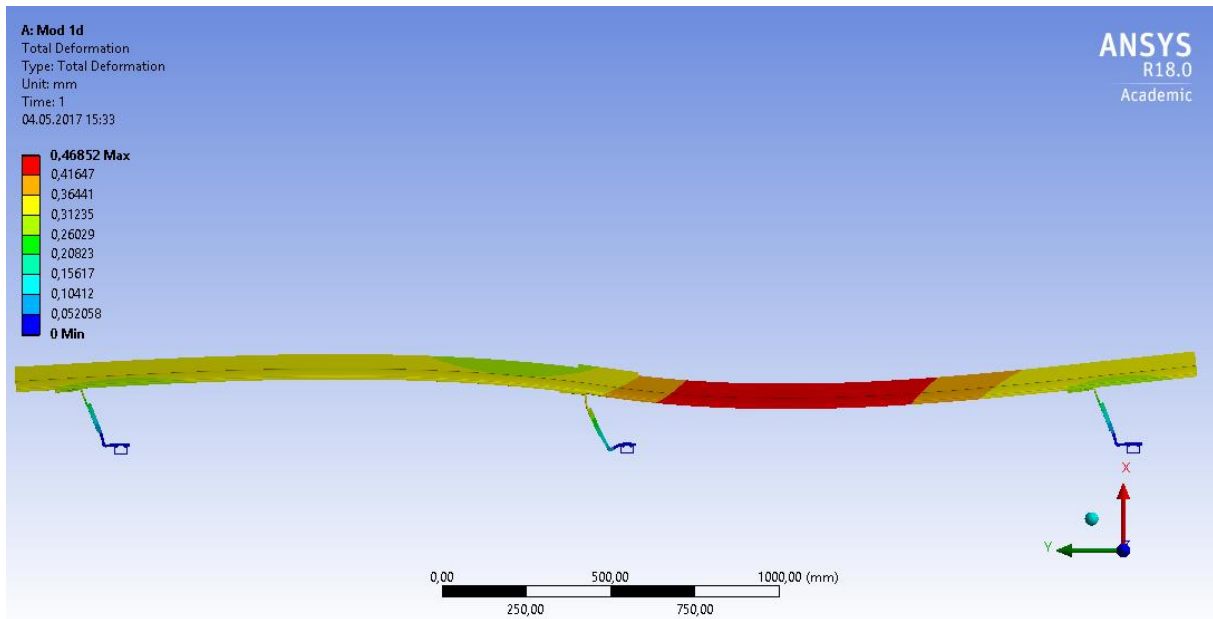
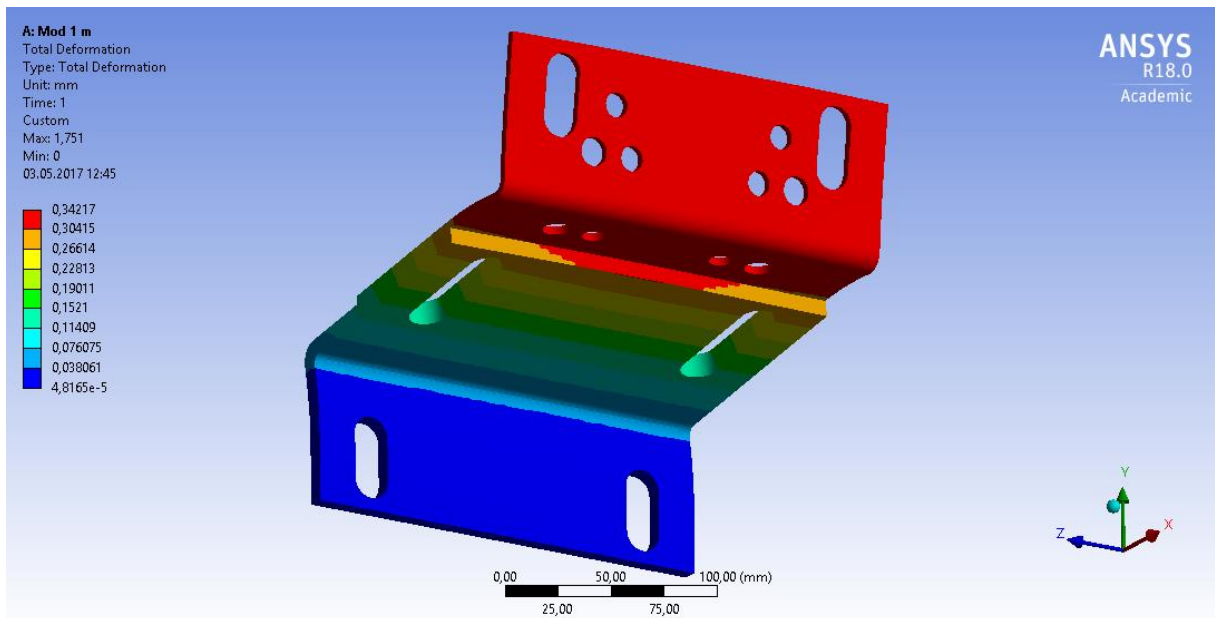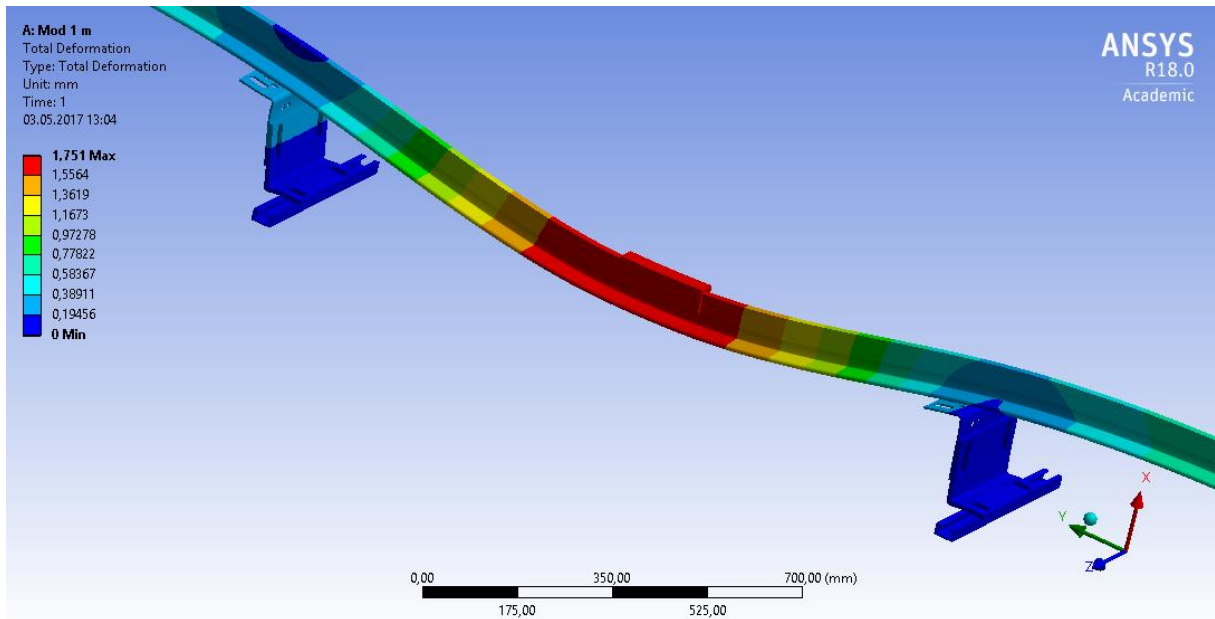**Load case 2:** Direct load on y-y

Welded bracket:
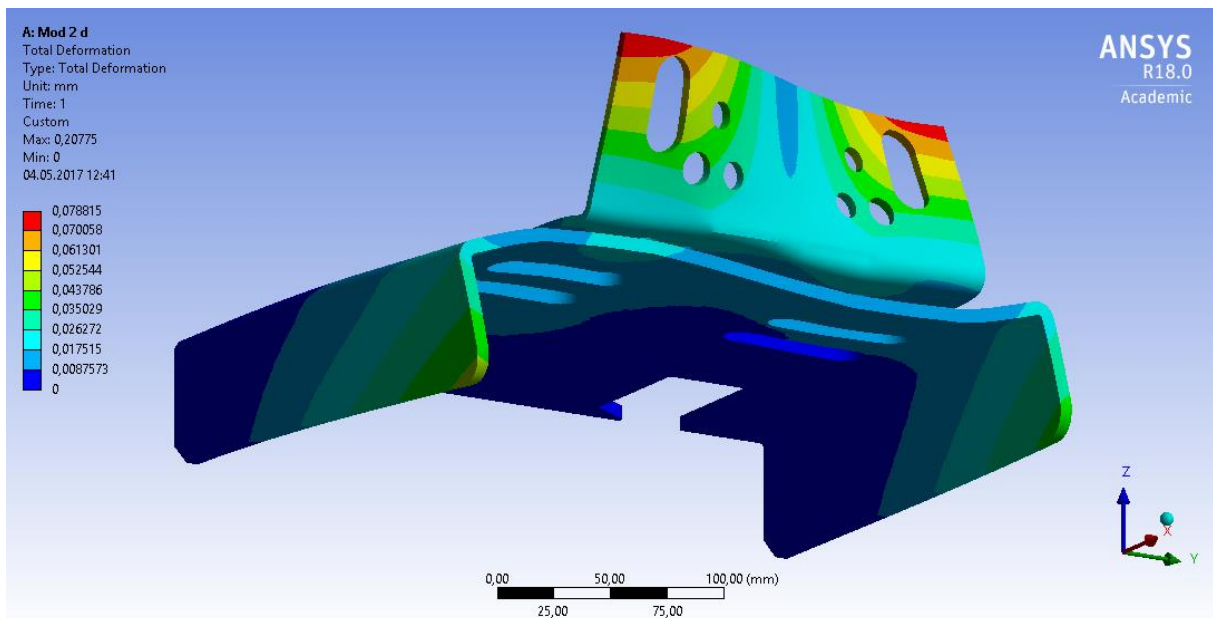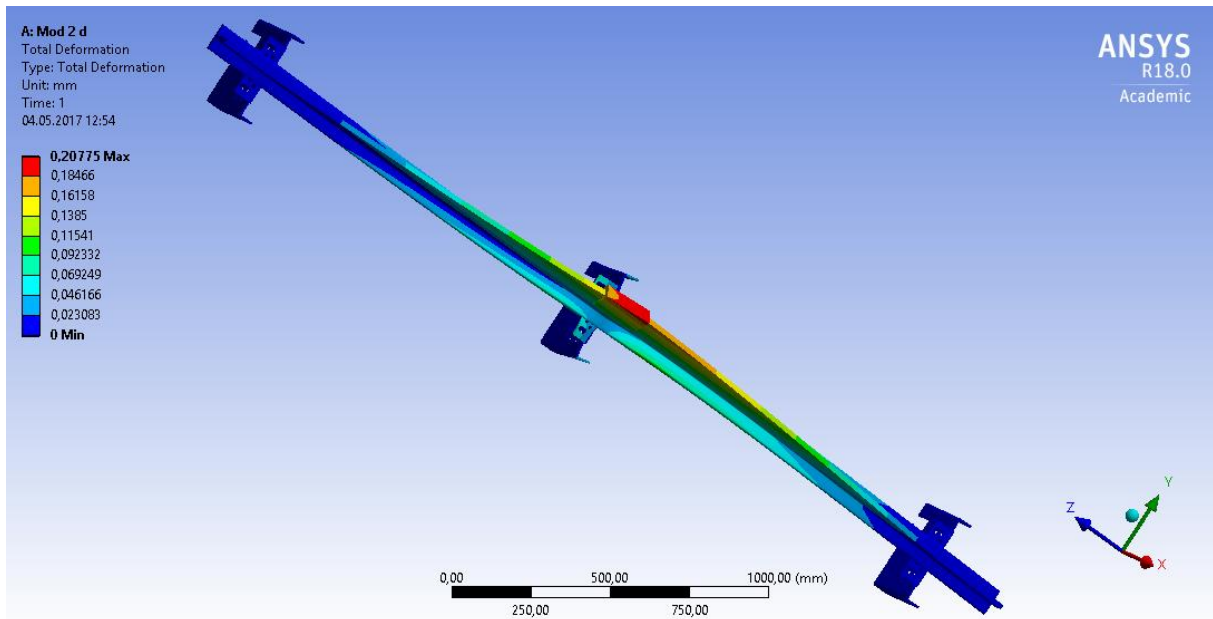
Adjustable bracket:
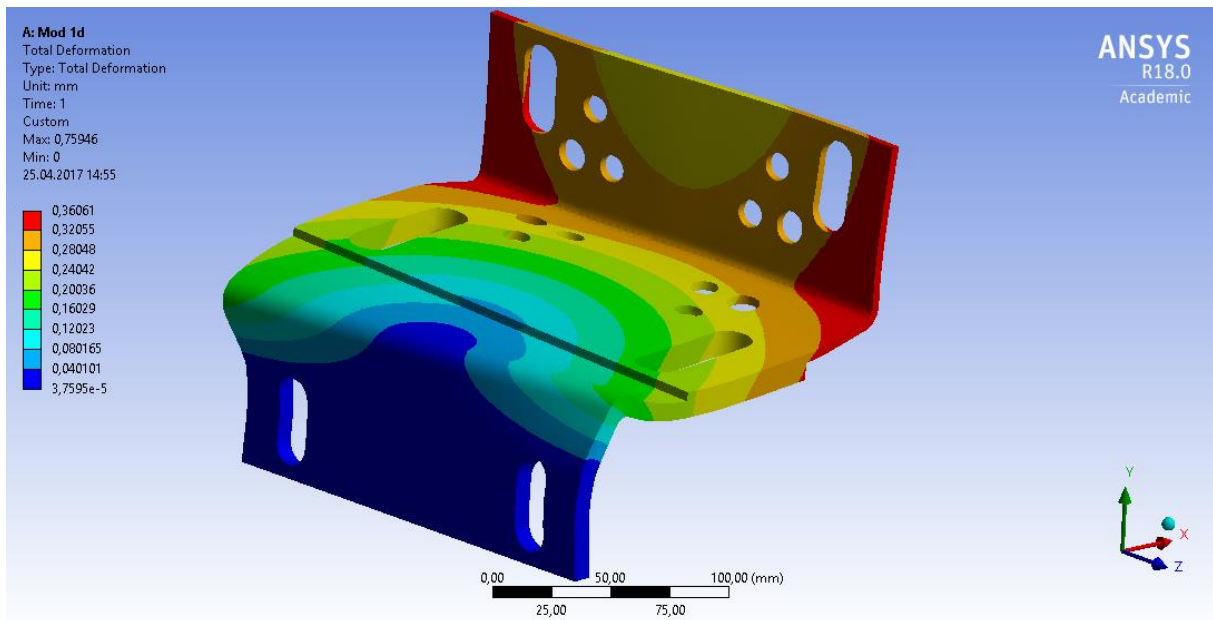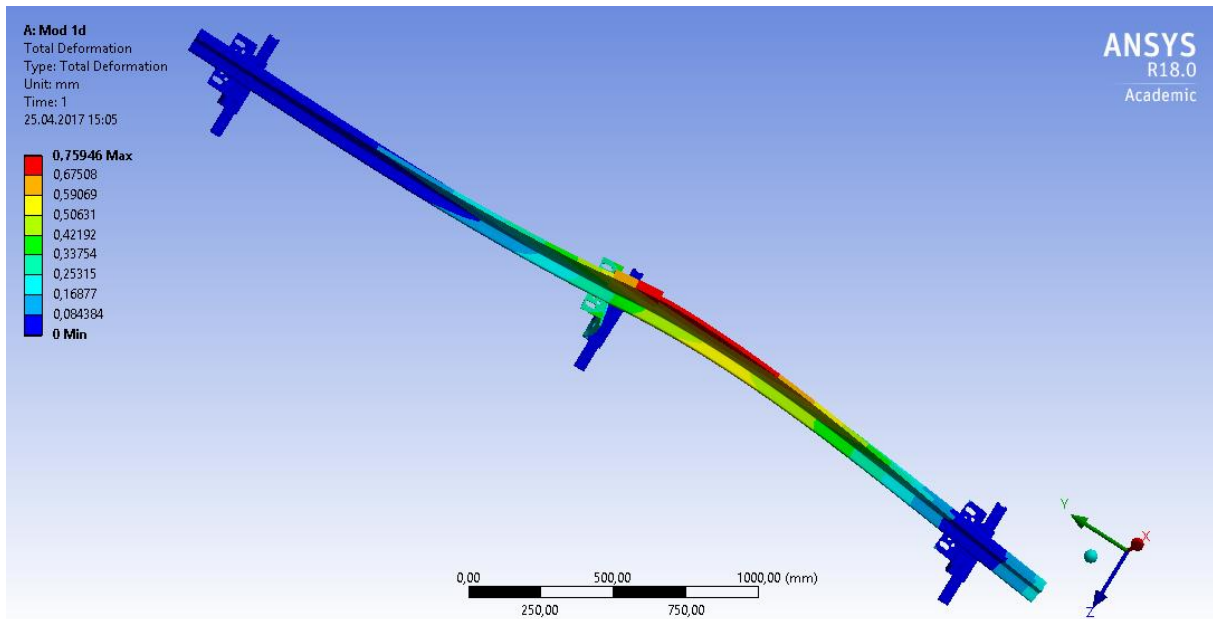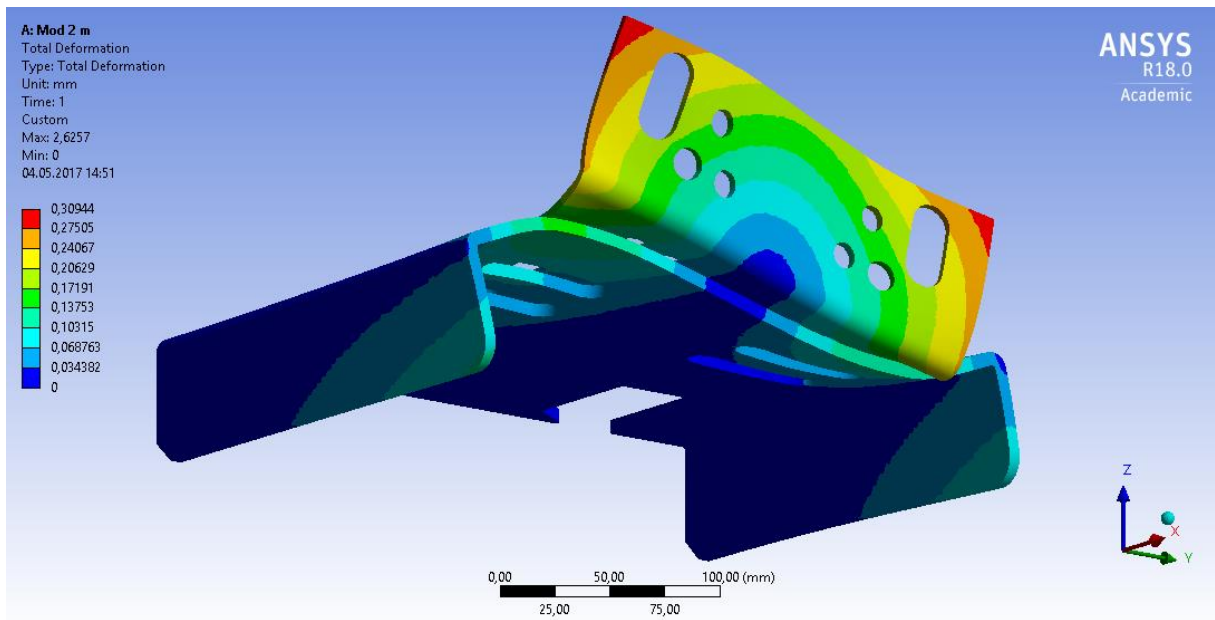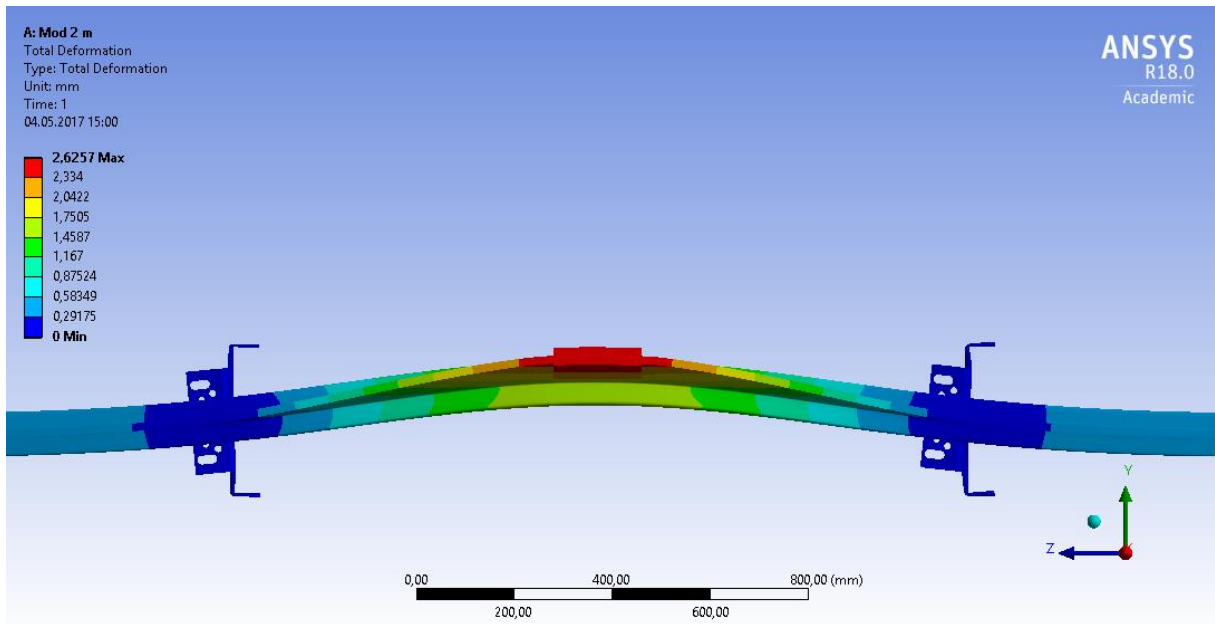
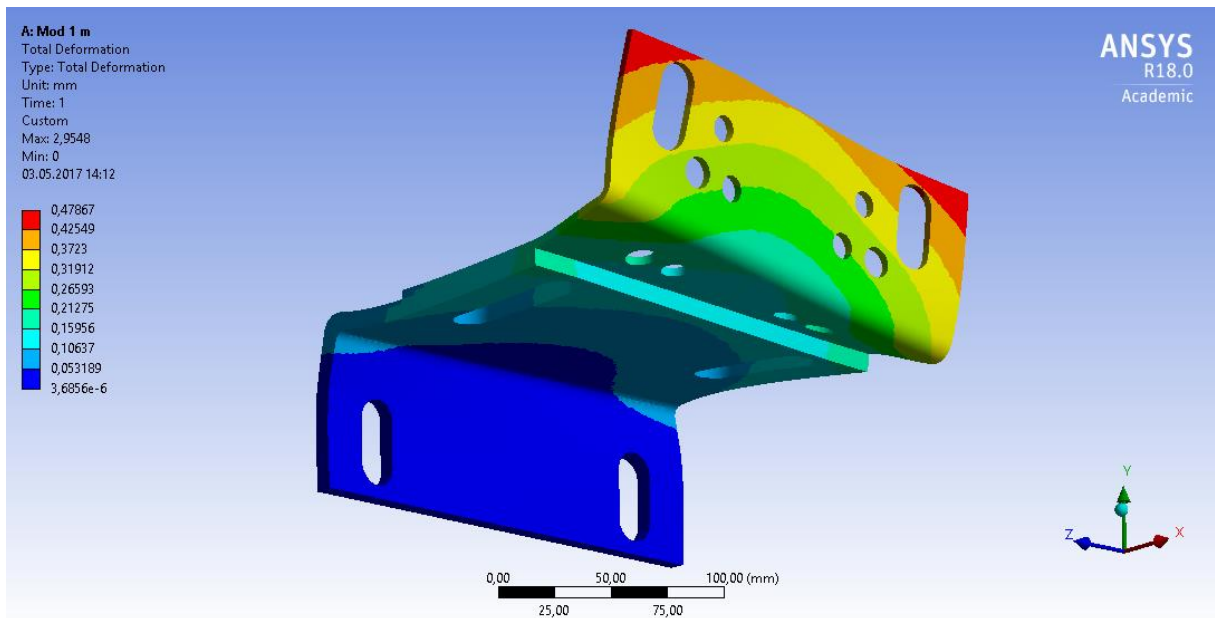**Load case 3:** Centered load on x-x
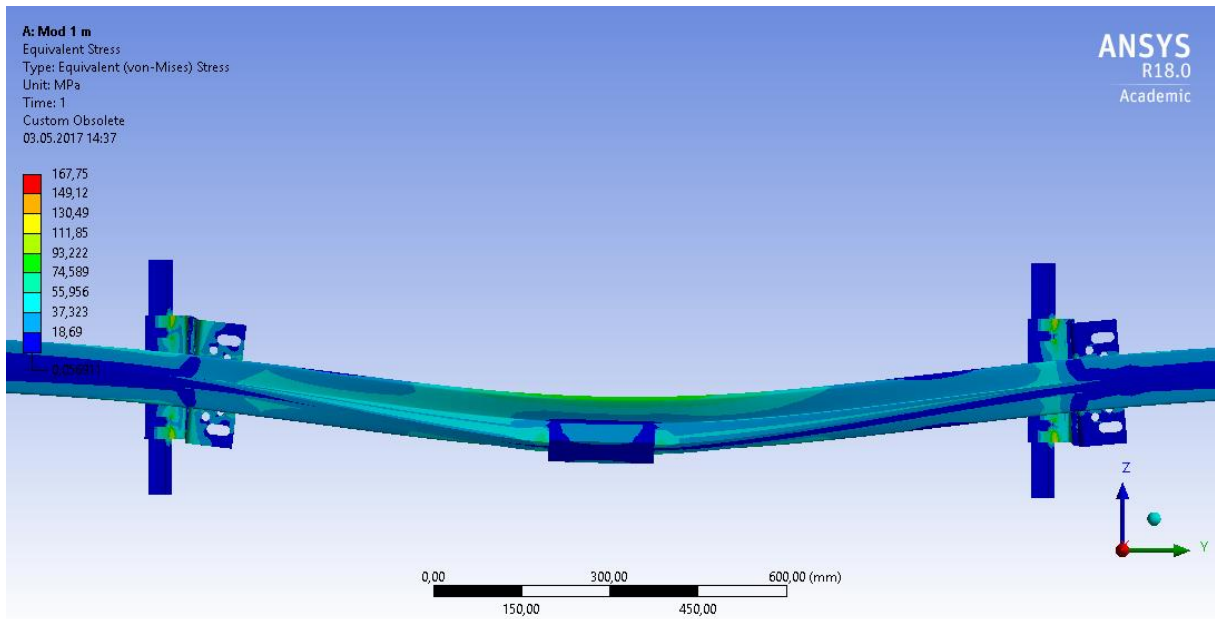
Welded bracket:
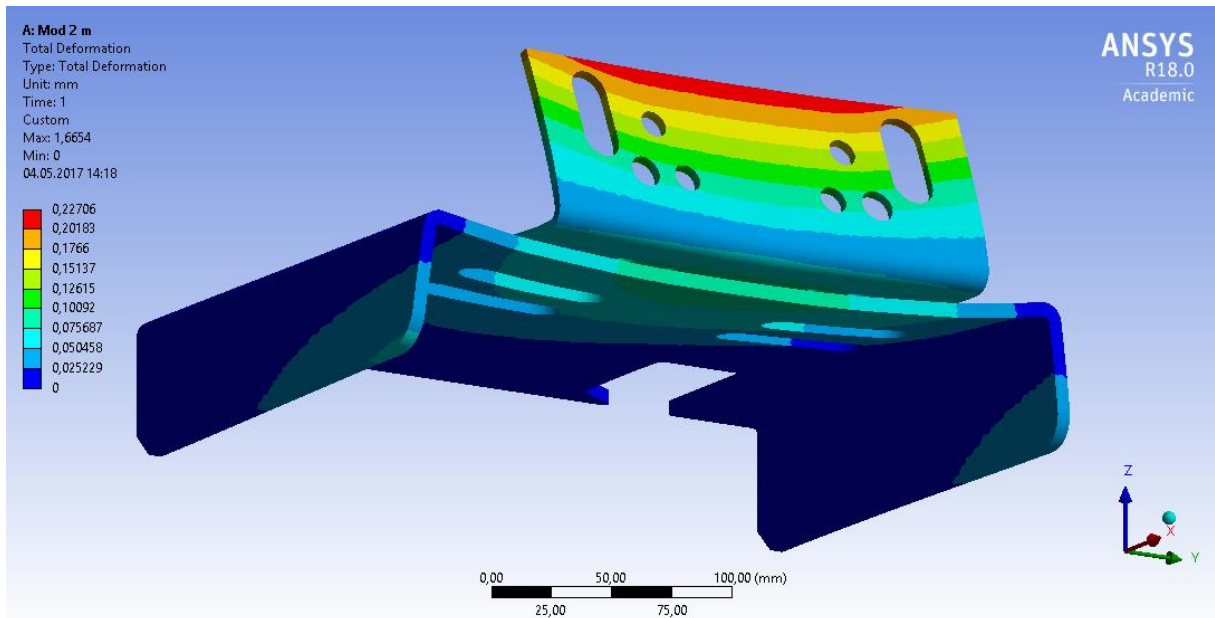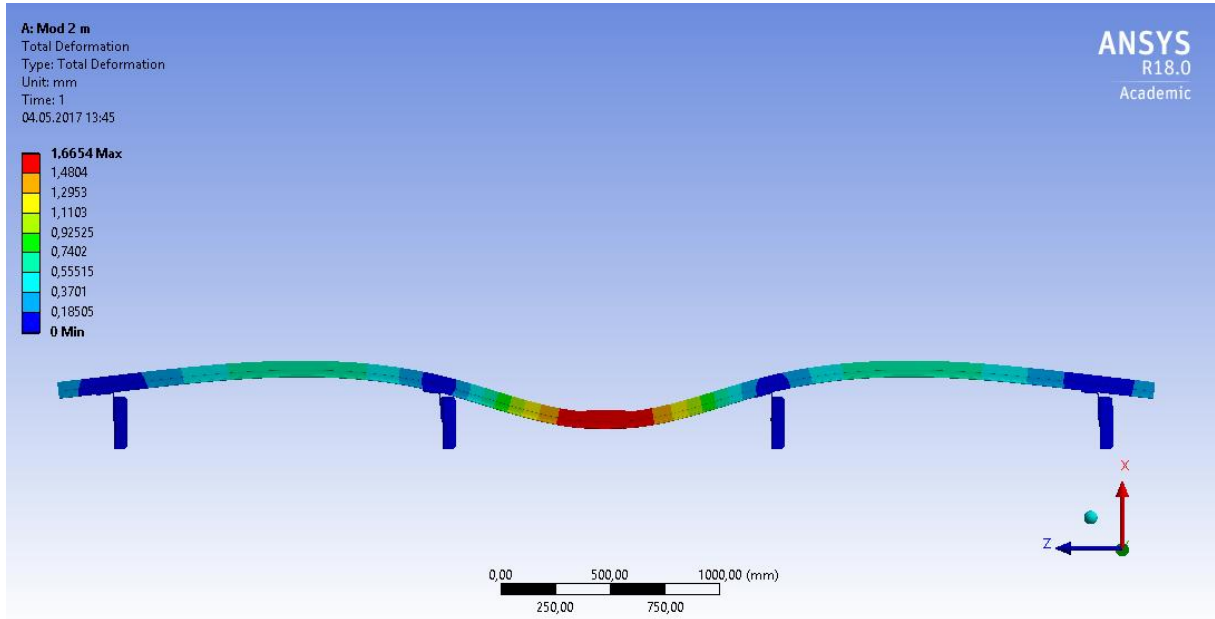
Adjustable bracket:

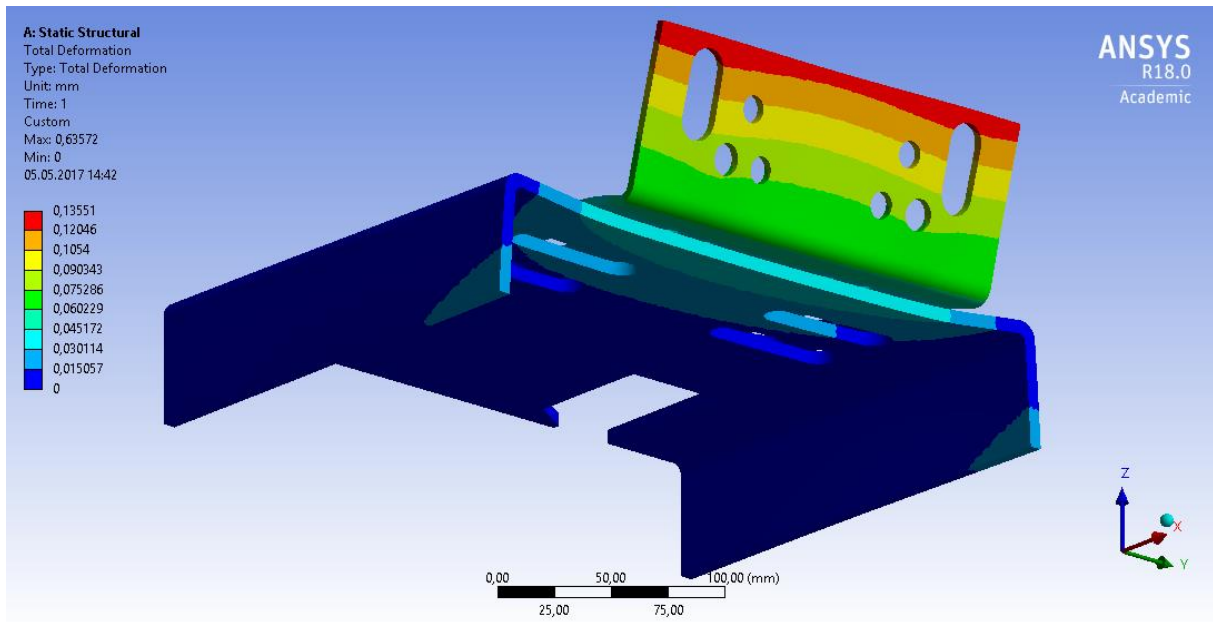**Load case 4:** Centered load on y-y
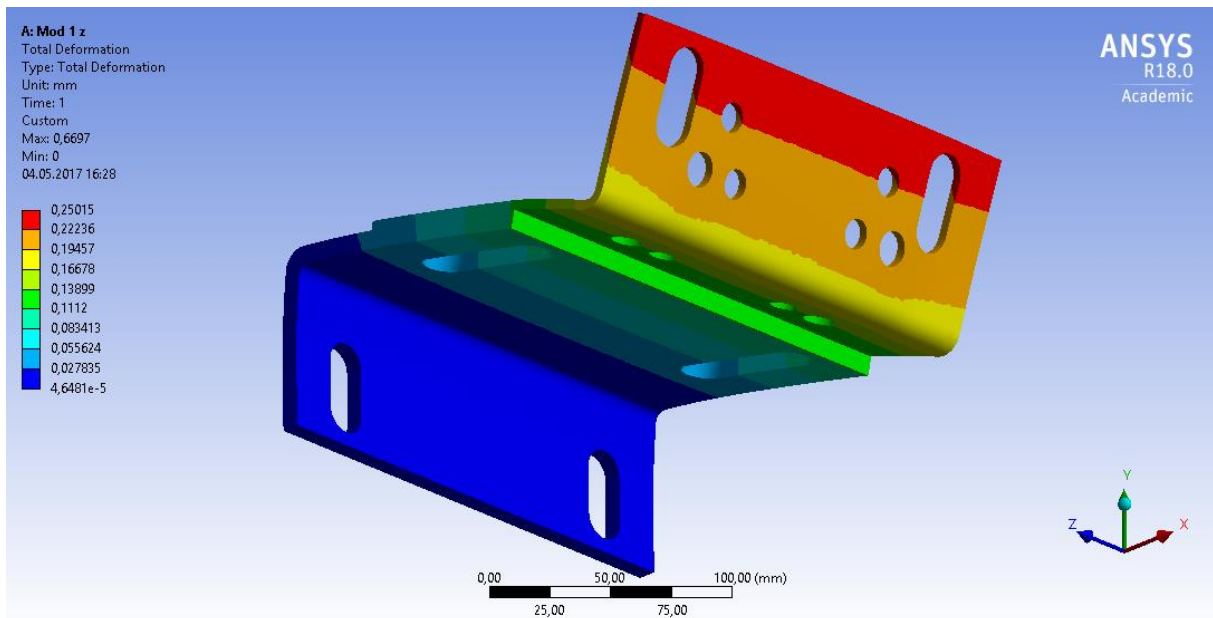
Welded bracket:

Adjustable bracket:

Load case 5: Vertical drag with slip

Welded bracket:

Adjustable bracket:

Title: *Optimization of Elevator Guide Systems for Marine Installations*

Abstract

A gap in knowledge is identified amounts the suppliers of marine elevators in Norway. Traditionally, their methods are based on the expertise from land-based installations, where the dimensions of the critical components are increased drastically in order to compensate for the potential impacts caused by the maritime conditions. In relation to this, there are reason to suspect over-engineering that effects both the weight and cost of the finished products. In order to get an installation certified, the system must be validated against the requirements for marine operations set by a certification society. When the maritime conditions are introduced, the elevator components responsible for maintaining the structural stability is referred to as the Elevator Guide System. This system contains a set of guide rails that shall provide a sufficient support of the moving elements within the shaft and several brackets along the guide that connects the rail to the trunk wall.

An extensive study on existing standards related to the issue is conducted in order to identify the essential requirements and how they relate to the application. Based on this research, the mathematical relationships are defined and applied for the appropriate components in order to develop an optimized method for sizing of the guide rails. In addition, a structural analysis is performed for the system, using two alternative constructions for the bracket solution. The alternative methods for executing the installation of the guide system are defined as four separate concepts that are assessed against the principles of complexity, risk and cost.

The analytic results reviled an applicable and highly effective method for sizing of the guide rails, where the optimal dimension within the requirements is suggested for any given project. The conducted FEM-simulation provided a sufficient validation for both bracket solutions against the applied worst-case load conditions that were identified. An estimation of the potential savings across the concepts for installation indicated a significant difference in expenditures related to the applied specifications on sizing method and bracket solution.

The assessment carried out in this study suggests that the concepts based on the traditional method of sizing should not be considered for future installations as the overall reduction potential indicates a substantial advantage of implementing the optimized method, which has been approved by DNV GL as an appropriate method for validation. In addition, the applied bracket solution can severely influence the installation time. However, the preferred bracket is only applicable for elevator trunks with smooth surfaces, which really is the case, as shipyards tend to locate the necessary stiffeners on the inside of the elevator shaft. To resolve this issue, the supplier should address this in the early stages of a project, indicating the bracket placement. In doing so, the opportunity of implementing the best possible solution for each individual installation should be made feasible.