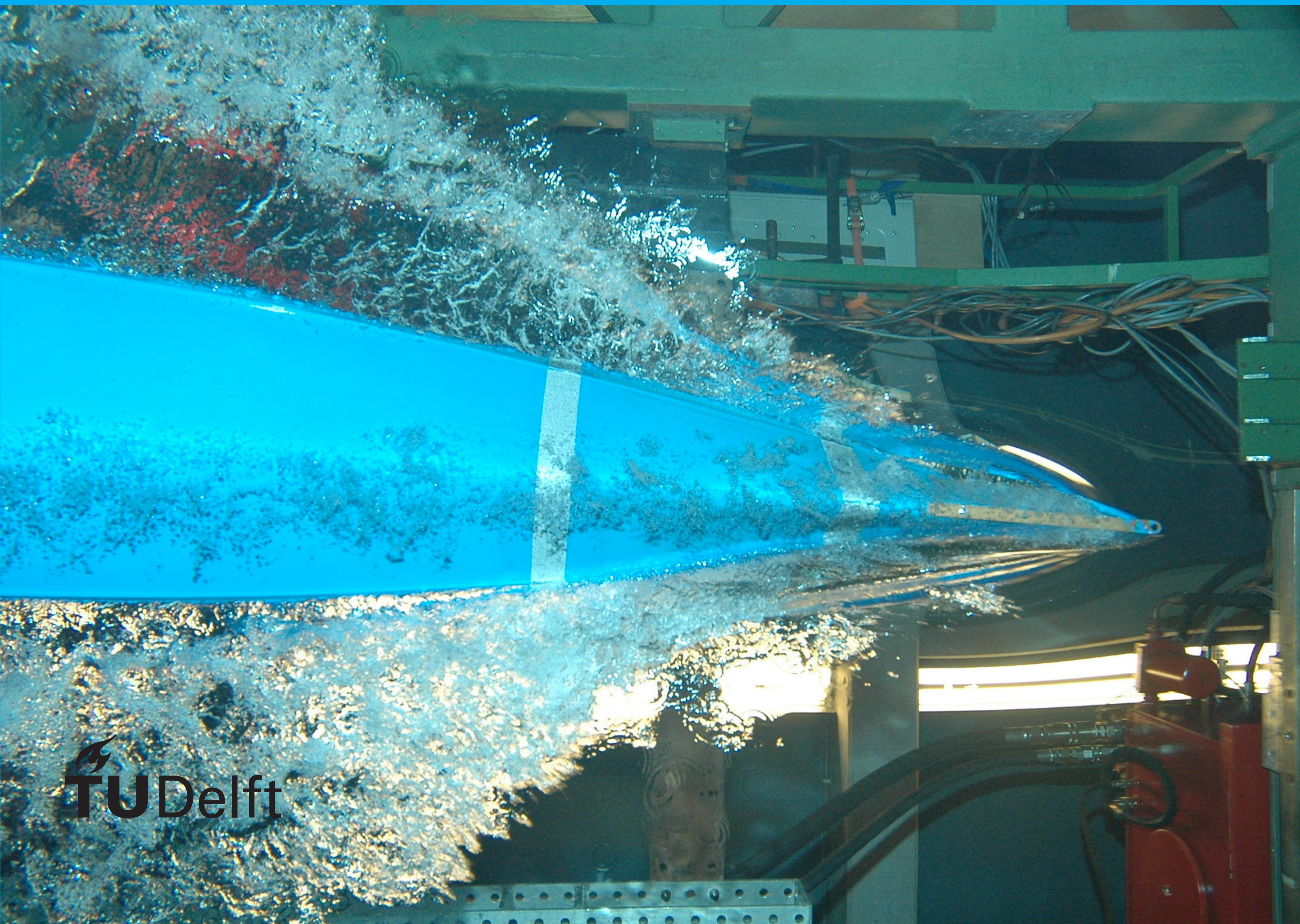
Effects of the use of modern CAE tools on the design process

Case: Design, strength calculation and optimization of a gantry on a trailing suction hopper dredger vessel

P. Wróbel



TU Delft

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Case: Design, strength calculation and optimization of a gantry on a trailing suction hopper dredger vessel

by

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Preface

Over the years the introduction of new Computer Aided Engineering (CAE) software into the design process allowed engineers to significantly shorten the time necessary to produce finished designs. There seems to be an agreement that using CAE tools shortens the time of the design process and improves the quality of finished products. Although, oftentimes in research it is the improvement in quality, which is focused on when presenting new tools. However, in an industrial setting, what also matters and is frequently the main concern are the improvements in time efficiency. It would be undesirable for the newly incorporated software to elongate the process.

In this study, the effects of incorporation of a new CAE tool on the design process is researched in an industrial setting. The opportunity, which allowed for this research is the incorporation of a new post-processing software for the finite element analysis Jan De Nul Marine Engineering and Design Department. In order for the new tool to be implemented, its effects on the design process should be tested. In order to do that, the methods of design were researched in order to find what is the current design methodology and its structure. This is done based on a case study, a draghead gantry for a trailing suction hopper dredger vessel. In this case study the equipment is designed according to the methodology used in the department. Based on the first design, the methodology of design used in the department was codified. Then, problems which were found in that process are addressed and a new design methodology is proposed based on the solutions, literature and adaptation to the new software. Next, the new design process is presented. Lastly, the results of both approaches are shown and compared.

This endeavor would not have been possible without Jan De Nul Marine Engineering and Design Department. I am grateful for the opportunity of working in Jan De Nul during the duration of this project. I would also like to thank my supervisors ir. Wouter van den Bos from the side of TU Delft, MEng Gemma Coughlin and Wouter Tollet, M.Sc. from Jan De Nul. Their support and supervision were very helpful during this project. Moreover, I would like to thank the chair and thesis committee. Many thanks to the whole team of Jan De Nul Marine Engineering and Design Department, it was a pleasure working in Aalst. Lastly, I would like to thank my family, my girlfriend and my friends who were supporting me during my time in Belgium and in the Netherlands.

P. Wróbel
Wrocław, February 2023

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Introduction

1.1. Background

The Marine Design and Engineering Department of Jan De Nul Company is currently in a phase of implementation of SDC Verifier finite element analysis post-processing software into their current design process. This is a significant step as it requires not only training to incorporate the new software efficiently, but might also require changes in the procedures of work. The inclusion of new software and the tools included within it has to provide significant benefits in order to be cost-effective. This is due to the additional resources that have to be spent on the new software and training. Additionally, the transition process might cause losses of efficiency in the short-term and the long-term benefits have to compensate for that. Therefore, the benefits of this change in the design methodology have to be assessed. In order to do that, an assessment of the current methodology of structural design in the Jan De Nul Marine Design and Engineering Department and its adaptation, to maximize the efficiency of work while keeping the current quality of design at the same level or improving it, has to be performed.

1.2. Research gap

The general consensus among the researchers seems to be that introducing Computer Aided Design into the design process is beneficial for both efficiency of designing and the quality of a final product. Studies regarding the implementation of CAD in companies tend to not focus on a specific type of software. Moreover, usually the benefits and drawbacks are measured by conducting a survey among the employees using the software or the managerial body.

While many studies which measure the benefits of implementation of FEA with or without post-processing software are usually focused on the accuracy of obtained results and how optimal the final design is. A research gap exists where the efficiency of designing work is measured after proper implementation of a post-processing software in an industrial setting.

1.3. Research goals and scope

This research aims to find what is the effect of using modern Computer Aided Engineering (CAE) tools on the design process of heavy equipment. In particular, the software which is the focal point of the study is SDC Verifier post-processor. In order to achieve this goal the following research questions and sub-questions are going to be answered:

- What is the state of the art regarding design methods in the scientific literature?

- What are the characteristics of the current methodology of design in Jan De Nul Marine Design and Engineering Department based on the example of draghead gantry design?
  - What is the structure of work?
  - What are standard procedures?
  - How is accordance with standards checked?
- What could be the methodology of heavy equipment design?
  - What could be done to increase the quality and efficiency of the design process?
  - What should be done to better incorporate the post-processing software into the design process?
- What is the design process when using the new methodology of design?
- What is the performance of the proposed new method on the design process of a draghead gantry crane?
  - What is the difference in time spent on certain tasks during the design process?
  - What are the advantages and disadvantages of the new methodology of design?
  - What are the advantages and disadvantages of the use of post-processing software?

To answer these questions a literature study and a case study are conducted. For the case study, a design of a draghead gantry is chosen as an exemplary design process. During the study two designs of a draghead gantry are prepared, first one is performed using the current methodology of design with additional use of the post-processing software. During this process, the current methods of work in Jan De Nul Marine Design and Engineering Department are researched. Using information gathered throughout the design process, solutions for the encountered problems, guidelines for the design and changes to the process set to increase the efficiency and quality of the design are developed. Next, a second design developed based on the new methodology is performed. Lastly, based on the comparison between the two processes and their results, conclusions are drawn regarding the efficiency and quality of new methods.

1.4. Report Structure

The report is structured in the following manner. In the second chapter, the literature review is presented. Different approaches to the design process and capabilities of modern Computer Aided Engineering tools are discussed.

In the third chapter, the current design methodology in the Jan De Nul Marine Design and Engineering Department is discussed. The structure of the methodology, procedures and problems are summarised.

In the fourth chapter, the new methodology of design is developed. The problems in the current methodology are addressed and the adjustments needed for the incorporation of the post-processing software are discussed. Lastly, the structure of the new methodology of design is presented.

In the fifth chapter the process of design of a new draghead gantry, while using the new methodology of design is presented. The steps of the design process are presented and discussed.

In the sixth chapter the evaluation of the new methodology of design is presented. The time summaries of the design phases are compared and the results are discussed.

Lastly, in the seventh chapter the overall conclusions are presented. Additionally, recommendations for future research are discussed.

2

Literature Review

2.1. Introduction

In this chapter review of the recent developments in the scientific literature concerning design. First, the studies concerning the design process are presented and discussed. Second, the literature concerning the incorporation of the prior knowledge in the design methodology is reviewed. Then, the concept of integrated design is presented. Next, the computer aided design and the finite element analysis software are shortly introduced. Lastly, the post-processing software and its capabilities are presented.

2.2. Design process

Designing as a process can be a demanding task in a competitive environment of today's industry. The areas of operation in companies often involve synthesising knowledge from many fields of research into one design. This is especially visible in highly innovative and rapidly developing domains such as aerospace or maritime engineering. Where large systems such as airplanes or ships consists of many subsystems of different nature, which have to cooperate to fulfill the requirements of safety, quality and purpose. The complexity of problems frequently requires approaching them from different angles and thus working in a multidisciplinary team of engineers or designers. This can cause many issues, since the viewpoints of these experts may significantly differ. In order to enhance their ability to develop better solutions, researchers are developing a wide array of methodologies of design. These are supposed to be guidelines, enabling a design process to be more effective and structured. The highly active time in the design theory research took place in the second half of the 20^{th} century. However, frequently attempts to structure and rationalise the design process are based on "good practice" and the expertise of the authors rather than an approach tested against other methods. It is rare that a methodology is tested in an empirical study, which could provide verification to the benefits claimed in the text (Gericke and Blessing, 2011).

Over the years multiple different methodologies were proposed by researchers (Pahl et al., 2007) for mechanical engineering design. One of the most prominent and influential models, is what Roozenburg and Cross call a consensus model of the engineering process (Roozenburg and Cross, 1991), it is a model which is described in VDI publications (VDI, 1987), presented in Figure 2.1, and for example, a slightly altered version in Pahl and Beitz textbook on Systematic Approach (Pahl et al., 2007). This is a theoretical model, which is not problem specific and could be used for any design and which despite its age is referenced and thought in academia in many countries (Kannengiesser and Gero, 2017). It guides a designer through a list of tasks which should be completed in specific stages of the design process. These tasks are: performance specification, function structure, principal solution, module structure, preliminary layout, definitive layout and documentation. They are closely related to the generic stages in the procedural approaches which can be found in literature across different disciplines (Gericke and Blessing, 2011).

In the consensus model, the tasks are then grouped into phase of clarification of the task, conceptual design, embodiment design and detailed design. The problem solving in consensus model should follow the two dimensions, which were presented for engineering design by Asimow (Asimow, 1962). The main stages of design are considered the vertical dimension which are phases of the product life cycle. While in the horizontal dimension the specific problem solving process takes place for each of the design stages. An important characteristic of this process is the preconception that the design should follow from an abstract idea to a very detailed design, with a strong emphasis of the conceptual phase, which is also one of the main criticisms of the consensus model presented by Roozenburg and Cross (Roozenburg and Cross, 1991). This is due to the fact that in practice frequently, design or its parts can be based on already proven solutions without the need to invent them anew. Moreover, the consensus model does not provide much advice for the procedural approach to the latter phases of design. The other criticism, and perhaps the most important one is that it has been stated that in industrial design the behavior of an engineer is rarely correlated with the prescription presented by the consensus model. The process of working from a concept design to a concrete solution is said to be highly iterative, recursive and in which the choices are relying on the anticipated solutions to the problems, which in opposition to the model's premise.

The criticisms of the consensus model presented by Roozenburg and Cross do not invalidate it. However, they shed light on a problem which is explored by Konda et al. (Konda et al., 1992) in their work. The authors advocate in their research altering the approach to both design theory and design practice in order to create and incorporate, what they call a shared memory. Which is defined as codified knowledge, experience, models and techniques shared within a group of professionals. To define this concept further, two dimensions of the shared memory are specified. A vertical memory is defined as concerning more and more intricate knowledge or expertise in a specific field of expertise, while horizontal memory is knowledge shared between different fields of expertise or professionals with a vastly distinct perspectives.

A case is made that the classical approach to design exhibits certain weaknesses, which are the following (Konda et al., 1992):

- During the design of an artifact, the process demands knowledge of realisation of subsequent stages of development, which is held by stakeholders involved in these stages.
- When the knowledge of subsequent stages is not accessible for stakeholders involved in the early stages, a redesign might be necessary when the process crosses between these stages.
- The differences between the knowledge and capabilities of stakeholders involved in subsequent stages of design might cause professionals from an earlier stage to overstep their duties into a later phase, causing a mismatch and consequently a need to redesign.
- The design process itself might be not sufficiently versatile to adapt to sudden changes in the design environment.

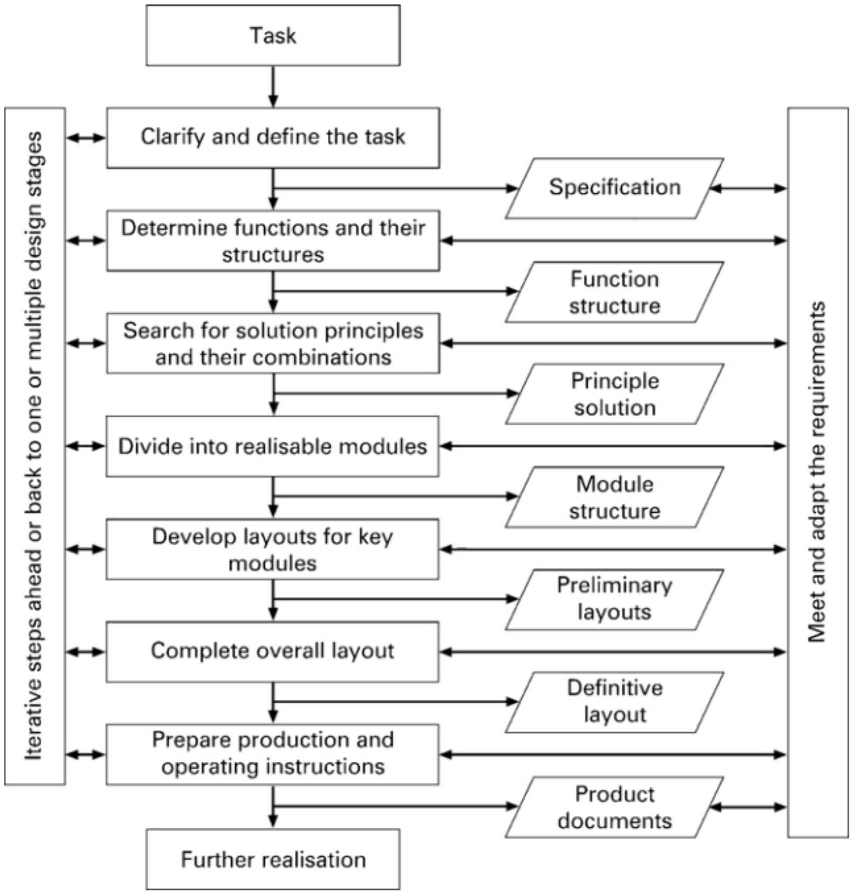

Figure 2.1: VDI recommended design process (VDI, 1993).

One of the approaches to alleviating these weaknesses is creating a shared memory in the organisation through effective integrated engineering (Konda et al., 1992). Authors bring up point made by Clark et al., 1991, that in order to gain competitive advantage in a computerised industry company's or organisations have to integrate software, hardware and professionals into one consolidated and effective system. Therefore, a departure from the classical consensus model might be needed in order to effectively create ”shared memory” and integrate the engineering process.

On the other hand, a case can be made for the consensus model to be mostly natural approach to the design process. A study by Kannengiesser and Gero, 2017 explored the possibility of using the systematic approach developed by Pahl and Beitz as a predictive model of design. The research was performed on a group of engineering students during their formal design education. According to the results, the systematic approach is partly incomplete as a predictive model. Although, it does predict the behavior and the design issues of engineering students for the most part. This is especially interesting since it was not explicitly taught to the students according to the authors. Moreover, the differences in the model and behavior of the students seem to be matching the criticisms presented by Roozenburg and Cross, 1991, regarding the solution anticipation at the earlier phases of the design process. Students were focusing on specific design solutions early on rather than postponing it to the later phases.

Currently, the more recently developed methodologies, seem to be more abstract and engage with the design problem in less detail, with a more idealistic view. Authors stress the importance of collaboration and integration, which are the important factors for competitiveness mentioned by Konda et al., 1992. Moreover, the research is still based more on the personal expertise and experience of the authors rather than on empirical studies (Badke-Schaub and Voute, 2018).

2.3. Prior knowledge

The main criticisms of the classic design approach, mentioned by Konda et al., 1992 are touching on efficiently sharing the memory between professionals and capably using it during the design process. Effective maintaining and reusing the knowledge is an essential part of building expertise in a field of design. In her work, Oxman, 1990 states that structured prior knowledge of the concepts, prototypes and precedents, on which future works can be based is an inherent part of design. The context of this statement is architecture, however it is also undoubtedly true for mechanical engineering design. Especially, considering the existence of engineering guidebooks and standardised parts which require prior knowledge to be effectively included in the design.

Significant benefits can be gained by an organisation or group of professionals by sharing the knowledge and using prior knowledge efficiently. This includes successful past designs and their components, which can be fully or partly reused in newly developed artifacts. Design reuse as a research field is focused on taking full advantage of that practice by minimizing the designer's effort and required resources while maximizing the customer's satisfaction (Sivaloganathan and Shahin, 1999).

Incorporating prior knowledge and design reuse is also important due to the changes which the design process underwent in recent history. The designers are pressured to lower development times and costs while keeping the quality of the products constant or higher. Therefore, re-engineering became important due to the need to increase the efficiency of already developed solutions or finding new, better ones. Hence, there is a risk of wasting resources by reinventing some already available designs. The methodology of design should be adjusted to avoid that risk (Veeke et al., 2008).

There are significant benefits to be gained by incorporating design reuse methods into the design process. In their study A. Duffy and Ferns, 1998 performed an investigation working with the industry in order to identify the main and foreseen benefits of implementing the design reuse model in companies' design methodologies, and then to quantify them. The study was performed by analyzing the current perceived performance gain from the tendency of engineers to use already proven designs in their work and potential future improvements after the implementation of a structured approach that favored design reuse. According to the results, effective implementation of design reuse may cause improvements in lead times, costs, quality and performance. Figure 2.2 illustrates the potential benefits as reported by A. Duffy and Ferns, 1998.

The biggest benefits, as perceived by the industry partners working with Duffy and Ferns, are to be gained in form of lowering the costs of design. An improvement of 23% is definitely a significant one, especially at the department or organisational level. The improvements in time and performance domains are still large and important, since lowering the time required to be spent on the design process allows to lower the lead time and increase the output of the designer team. On the other hand, the output might stay constant but the design team can focus more on developing innovations or increasing the quality. Which might explain the perceived big possible improvements in the quality domain.

In order to properly implement design reuse Smith and Duffy, 2001 prescribe a special approach to be taken to product structuring and the design process. Also, the organisation's overall strategy has to be aimed at improving and reusing the knowledge resources. This is due to the fact that the designing process generates a large amount of data, information and knowledge, however if there is

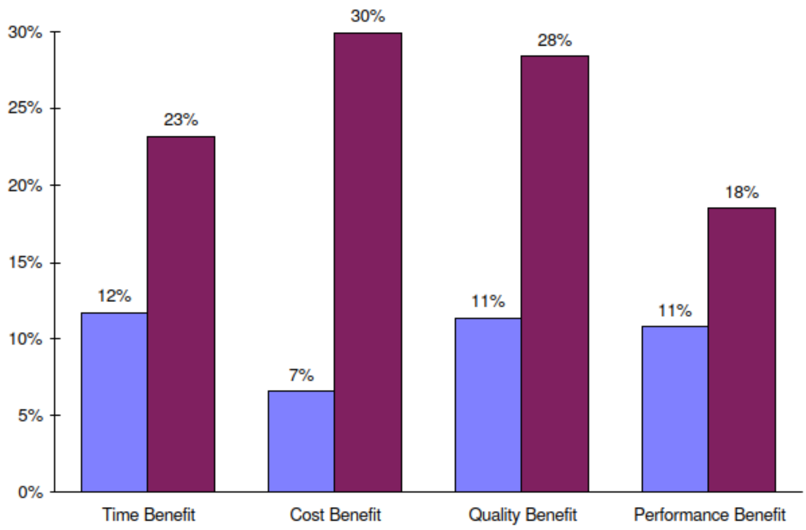

Figure 2.2: Current and potential benefits from design reuse (A. Duffy and Ferns, 1998).

no concrete strategy for collecting it or the strategy which is used is lacking, a lot of these resources may be unusable even if somehow collected. The design reuse model structure is presented in Figure 2.3.

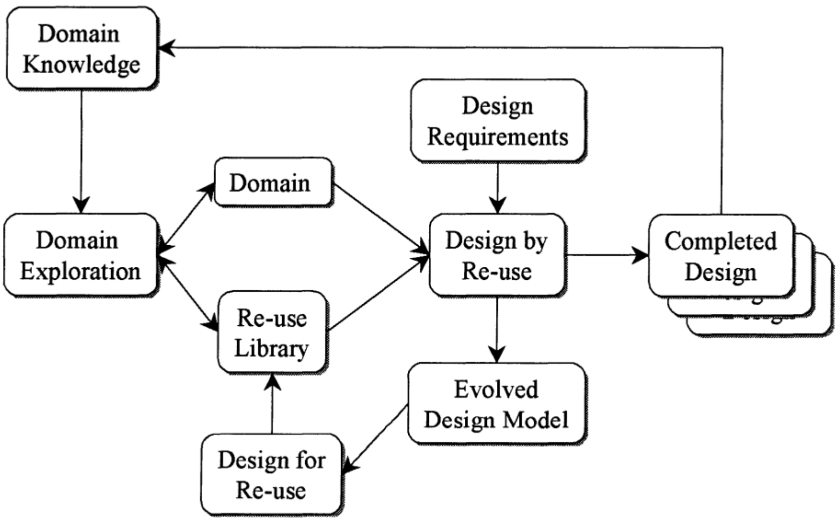

Figure 2.3: Design reuse model (Smith and Duffy, 2001).

The components of this diagram as defined by A. H. Duffy and Duffy, 1996 are the following:

- Design requirements - the declared design need.
- Domain knowledge - the knowledge from the field specific to the design.
- Reuse library - the storage of structured design knowledge, data and information.
- Domain model - the perception of the particular design domain, relevant to the current design problem, by the designer.

- Evolved design model - an account of the evolved design.
- Completed design model - an account of a fully developed design, which satisfies the set requirements.

While the processes are:

- Design by reuse - the action of performing the search for knowledge resources that can be used in the current design problem.
- Domain exploration - the action of conceptualizing the domain to understand the features of it from which the knowledge can be identified, extracted and stored for use in design.
- Design for reuse - the action of recording the knowledge so that it can be used for future designs.

Apart from structuring the process Smith and Duffy, 2001 advocate structuring the designs or products accordingly to enhance the possibilities of design reuse. The design can be decomposed into multiple subsystems which are less complex than the whole design. An added benefit of this approach is that with employment of effective communication, designers can work concurrently on the sub-designs and therefore, lowering the lead times. Moreover, with the correct application of the design reuse model, these subsystem designs might be later used in other projects, which is the main advantage in this case. Thus products and designs should be structured in a manner which allows for easier extraction of knowledge and information, modularization into elements which are to fulfill simplified requirements in comparison to the whole design should be, therefore, advantageous. Another approach can be development of a base design which is easily modifiable to fill requirements at hand. However, in some instances problems may arise for structuring, authors state that during that phase there is a need for initial access to the whole knowledge with inclusion of high-level and abstract information, from an evolving process. Also, this knowledge needs to be structured effectively for it to be reused efficiently. This is not always easy when some of the knowledge is constrained to individual designers. That problem could be alleviated by employing the concepts of shared memory and integrating parts of the design as mentioned by Konda et al., 1992.

2.4. Integrated design

The concept of integrating product design was first developed in research by K. Olsson, 1976. The idea behind it is integrating multiple domains of an organisation in subsequent phases of product development to enhance this process. The product development process by Olsson is modelled as four activities which run in parallel, Marketing, distribution and sales, Development and design, Production and Project management and economics. Integrated product design by Olsson is presented in Figure 2.4.

The process is divided into five phases throughout which the tasks are integrated between the sections of the organization. Marketing, distribution and sales are working on the environment by capturing the needs and demands then analyzing and evaluating the market, to prepare it for product launch and launching the product in the fifth phase. Development and design is working concurrently to first, providing the possible alternatives of design and then, defining the principles of the design. In the third phase engineering design is prepared, next it is modified to ensure that production is possible and in the end a final design is prepared. When the first phase is beginning, Production is starting to determine its needs based on the information provided by Marketing and Development and design, which are

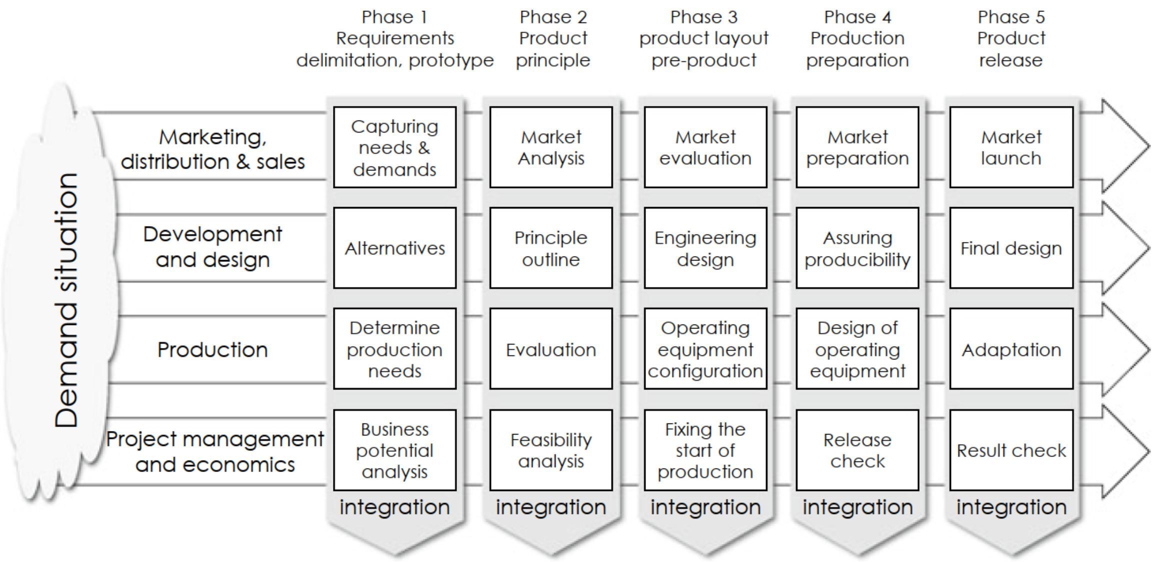

Figure 2.4: The IPD Model (F. Olsson, 1985) from Vajna, 2020.

evolved in the next phase when the principles of the design are defined. During the third phase equipment configuration needed in the future is being defined and then designed to end with adoption of the product into the Production. Throughout, the whole process the Project management and ergonomics oversee the process to ensure a successful launch of the product, in the first phase business potential of hypothetical product is analysed. Then the principles of the product are outlined and concurrently the feasibility analysis is performed, next the production start is fixed, release is checked and finally the results of the product are checked.

This model was the first to incorporate management in product development and parallel processing of tasks. Moreover, the activities in all of the strands are comparable and have a similar pattern. The IPD requires a lot of communication and knowledge sharing between the departments in comparison to traditional product development processes. Therefore, future models which were based on the concept developed by Olsson, started putting a lot of emphasis on communication, knowledge sharing and software which can help with the development process (Vajna, 2020).

For example in the IPD process developed by Ehrlenspiel (Ehrlenspiel, 2009) there are three domains of integration (Vajna, 2020):

- Personal integration - members of the organization should start to think and act in an integrative manner. During product development workers should be conscious of the boundaries in the organisation and these should be taken into account in the process. Moreover, it is important that the knowledge owned by the individual members of the organisation is shared and integrated. Overall, the focus on synthesis in the work should be developed.
- Informational integration - information which is necessary to make decisions should be available to the managing individuals, when the decisions have to be made. Moreover, data integration should be performed which is used for computer-integrated development using computer aided design software and integrated models of the product.
- Organizational integration - the form of organisation should help in the integrative manner of

working and performing tasks by the departments and employees. This is important in both the abstract hierarchical organisation and the material organisation of the office space. Flat organisation structures and common office spaces for integrated teams could be one of the solutions.

This holistic approach to the integration of people, information and organisations is present also in other studies. For example in the work of Meerkamm, 1994 the fundamentals of integrated product development are:

- humans,
- methodology,
- organization,
- technology.

One of the most recent works in the field of integrated product design is Integrated Design Engineering(IDE) by Vajna, 2020. The holistic model of the IDE procedure is presented in Figure 2.5.

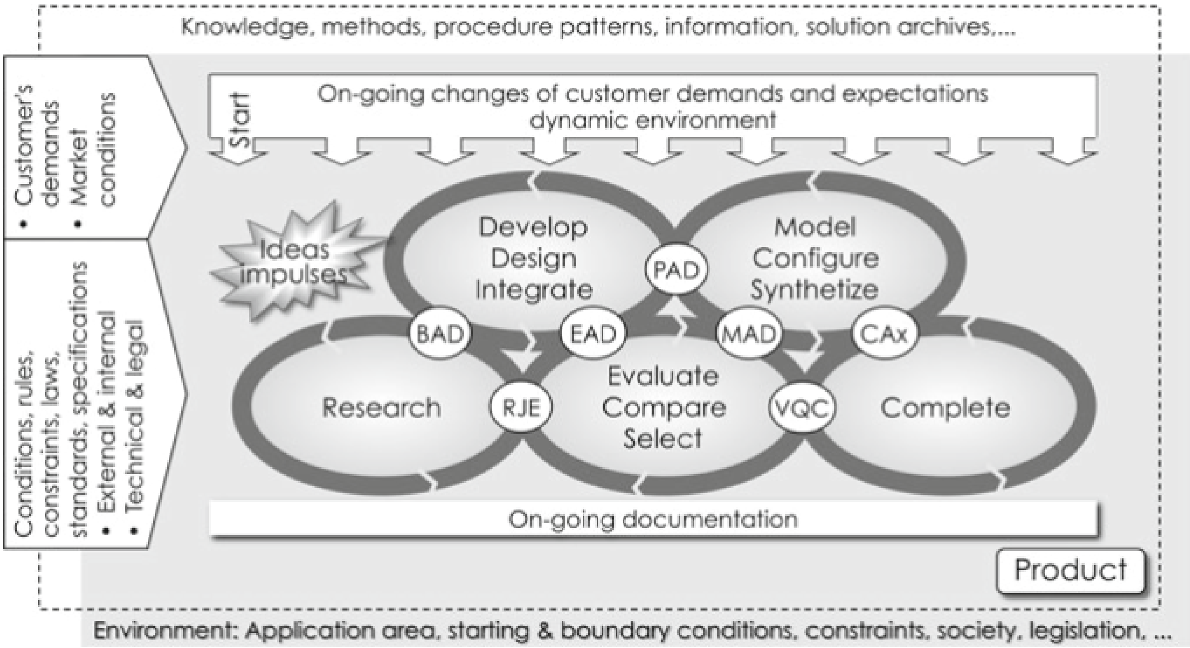

Figure 2.5: The IDE procedure holistic model (Vajna, 2020).

There are five activity groups presented in the model (Vajna, 2020):

- **Research** is performed at the applicable point in time, to support other activities presented in the model, by gathering knowledge and information required to execute them.
- **Develop, Design and Integrate** are activities that conceptualize the design. Develop is the designation that encapsulates the various stages of successive conceptual materialization of an object. Design is the geometric development of an object according to the requirements. Integration serves to merge and complete the partial solutions to complement the whole object so that its characteristics are preserved and are identifiable.
- **Evaluate, Compare and Select** are activities that support the decisions. These are all used for assessing, calculating, simulating, animating, testing and determining the economic facets of objects according to the subjective criteria at subjective points in time.

- **Model, Configure and Synthesise** are activities that support materialisation. A model is a representation of an object, which is depending on the stage of development can range between a drawing, a numerical calculation model and technical drawings. Configuring is a manner of concretizing the object such as dimensioning. Synthesise is connected with the materialization of a preferable solution from a group of other solutions.
- **Complete** assures that all of the required activities are completed in the development phase.

These activities are connected by supporting activities and links (Vajna, 2020):

- **BAD** is brain aided design, it encapsulates methods and procedures, which are abstract. These help to conceptualize the design in the early phases of development, creativity techniques and their proper use. It helps with working in an abstract space and with a better understanding of the project and its framework, therefore, collection of knowledge, information and requirements but also development, design and integration.
- **PAD** is pencil aided design, are procedures performed with sketches which allow for creating, visualising and adjusting the solutions without the need to produce elaborate models in the beginning phases of design. Thanks to that quick feasibility checks can be performed according to the specified requirements.
- **MAD** is model aided design is supporting the design conceptualization by providing a physical representation of an object, thanks to which an impression of its characteristics is gained. Model may go through alterations in the development process, from a very simple at the beginning stages, becoming a computer aided type model later, to a construction of some kind of a prototype in the final phases.
- **EAD** is evaluation aided design, it encapsulates all of the result evaluation methods.
- **RJE** are rate, judge and estimate, these are techniques of systematization of the research results.
- **VCQ** are verify, quantify and check, these are techniques of systematization of the solutions achieved before documentation.
- **CAx** is a term to describe computer aided tools of any kind.

The authors offer a look at the integrated design, with a more abstract approach, which allows for a larger area of application of the model. IDE treat the product as a result of human work, which is artificial in its nature, regardless whether it is material or not. This is contrary to most integrated product design models which focus mostly on the development of mechanical artifacts. However, also here additional important elements of product development are efficient communication between all of the stakeholders, knowledge sharing and efficient use of available technology, use of methods from different fields of industry or research that suit the problem the best and dynamic multidisciplinary work environment with an integrated approach to the hierarchy (Vajna, 2020).

2.5. Computer Aided Design

Efficient use of available tools is a prevalent element and one of the fundamentals of different methodologies of design and product development. In the context of design, an incredibly important breakthrough was the incorporation of Computer Aided Design (CAD) tools in the array of tools available to a designer or an engineer. Computerisation of the profession of designer made the development times of new products and designs significantly shorter. Thanks to computerised drawing not only the hand drawing and redrawing is no longer necessary but also sharing and storing the designs become much easier.

Currently, a multitude of CAD software developers provides the market with a wide array of software solutions. CAD tools can be used to create 3-dimensional models of all kinds of products, for example ships, buildings or steel structures (José Legaz, 2015). Creating the geometry can be performed parametrically or directly. Parametric modelling allows for the geometry to be changed rapidly while maintaining the relations between dimensions and geometric constraints if a need to redesign occurs. Thanks to that dimensions and relations between features of the model do not need to be checked additionally by the engineer after the changes are applied. Apart from 3D visualisation, it allows for 2-dimensional drawings can be drafted relatively quickly compared to the classical methods. In context of the integrated design, computerised design allows for sharing knowledge between the engineers through a multitude of information exchange systems. Moreover, it is also possible to integrate CAD tools with Computer Aided Engineering (CAE) tools, such as finite element analysis (FEA) software (Bernd et al., 2007; Fuh and Li, 2005; Vajna, 2020).

2.6. Finite element analysis capabilities

Due to a wide array of design problems coming from diversified fields, there is a demand for a variety of finite element method software. Despite having the same main purpose, performing calculations of material's behavior which are complicated or even close to impossible when the material is considered as a continuum, these significantly differ. Putting aside features that do not have an influence on the calculations such as user interface or the compatibility with other software, there is a lot of difference in the capability of these products. In recent years a multitude of companies have been developing their software to satisfy the needs of the market. As a consequence, solutions with considerations of multiple fields of study have been developed, for example electric and magnetic, acoustic or simulations of composite materials(Ansys Inc., 2022a). Nevertheless, for heavy machinery and steel structures assessment there is less variety in capabilities of the commercially available software. Some of these programs are integrated directly with CAD software, which allows users to analyze the previously designed 3D model directly. A comparison of capabilities for a selection of FEA software is presented in Appendix B.

2.7. FEA post-processing software

Structural analysis performed with FEA is a valuable tool for the design process of various machines and structures. However, there are more requirements that most of the designs have to fulfill, which are required by standards or for example classification society's rules in the case of ships and ship equipment. These additional requirements are for example buckling checks, weld strength checks or fatigue checks, which can be calculated based on the results obtained in the finite element analysis manually by hand or in an integrated manner in the FEA software if it allows for that. However, there has also been a development of FEA post-processing software, which can extract the results from the analysis and perform calculations automatically. Some of these programs have been developed by researchers and some are commercially available. The tools developed by researchers, usually can be used to calculate one specific case for which an example of optimization is provided. These solutions are not very robust and they could be quite unwieldy to use in the industry. On the other hand, commercially available software provides a multitude of options and capabilities which could be used to enhance the design process (Abry et al., 2018; Alencar et al., 2021; Alhajahmad and Mittelstedt, 2021; SDC Verifier, 2022; Shojaei and Wedgewood, 2017).

There are multiple commercially available solutions, such as SDC Verifier or Heeds. However, the Jan De Nul Marine Design and Engineering Department is incorporating SDC Verifier in their methodology, therefore its capabilities are discussed.

SDC Verifier is a post-processing tool for FEA software with a multitude of integrated functions, which illustrate the possible capabilities of post-processing software. These are the following (SDC Verifier, 2022):

- **Recognition tools**:
  - **joint finder tool** is a feature that allows for an automatic detection of joints between the beams and beams and plates in the model. Software, is recognizing the joints between the beams as 1D, 2D, 3D, and joints between the plates 2D Plate, 3D Plate or Beam-Plate, when the beam is parallel to the normal vector of the connected plate. Apart from these software does recognise the free ends of beams and allows users to define additional or modify the existing joints.
  - **Connection finder tool** is based on the joint finder and allows for automatic recognition of connections between circular tubes, rectangular tubes, I-beams and any combination of those.
  - **Beam member finder** is a tool that allows for the recognition of beam members' lengths based on the results of joint finder tools. The types of joints used to split members can be chosen and beam members and their lengths can be also manually edited.
  - **Beam section tool** is used to group the line elements in the model based on their location and direction.
  - **Panel finder tool** is automatically detecting sections, plates, stiffeners and their dimensions and orientation. These can also be modified manually.
  - **Weld finder tool** is automatically detecting welds on connected surfaces in the model, according to the rules which can be modified by the user. It is also possible to add welded connections between solids manually. The weld finder tool detects the characteristics of the welds and allows for quick calculation of weld stresses, which are automatically reoriented to weld coordinates based on the recognition results.
- **Code checking** - the software has an integrated function of checking the design according to the standards added by the developer or custom checks which can be coded in by the user. Based on the elements recognised using the recognition tools, it is possible to calculate fatigue checks, plate buckling checks, weld strength checks, joint checks, beam members checks, beam checks and bolt checks.
- **Load Combination processing** - based on the basic individual loads applied in FEA it is possible to create multiple load combinations out of the loads of different types that are acting on the structure at the same time in SDC Verifier. It is possible to apply partial load factors to individual loads and safety factors to each of the load combination. Thanks to that it is possible to quickly process large numbers of load sets, with the safety factors and partial load factors being explicit. Moreover, the software has its own calculation core, therefore it is not needed to recalculate the results of new load combinations in FEA. Rather, the results are calculated by SDC Verifier. Thanks to

that the overall CPU usage is lower because the calculation is based on a much lower number of loads than it would be otherwise. Results can be organised in load groups which are sets of load combinations, then maximum or minimum results over a large number of combinations can be plotted on one plot or presented in one table. Thanks to that, the reports of calculations can be smaller, clear and easier to assess.

- **Post-processing tools**:
  - **peak finder** - this tool allows for finding the results in the model, based on the value criteria specified by the user. Thanks to that, it is possible to find highly stressed areas or the ones that are not satisfying standard checks, which are “hidden” in the model and would not be visible otherwise. However, user can select any type of calculated results and any criteria such as value ranges, percentages or numbers of elements with maximal or minimal results, which allows for conducting specific analyses required by the user.
  - **Governing loads** - this tool helps to find the governing loads and load combinations in the analysis. It is possible to select a set of elements and find the set of loads or their combinations, for which the results are the highest or the lowest. Thanks to that, in some analyses, depending on the design, it is possible to lower the number of considered load cases since some are affecting the structure less than others.
- **Report generation** - the software has a capability to automatically generate reports of FEA analysis. It is possible to generate a template report, which in case of a redesign and change in the results can be used again to include the recalculated results, without the need of manually editing the old report or writing a new one. The software has preset chapters already prepared to include standard information such as model setup (materials, properties, constraints, FEM loads and load combinations) or results. The results preset contains sets of plots, graphs and tables which present all of the standard FEA results and results of checks according to the standards.

By using a post-processing software such as SDC Verifier, it may be possible to bridge the gap between the conceptual design and detailed design phases of the classical design approach. The recognition tools, conjoined with automatic standard checks calculations provide a fast alternative to the approach where the design starts as a concept and gets more and more detailed during the design process. Thanks to the quickness of the standard check recalculation, it is acceptable to redesign parts of the structure even in the late stages of the project. Moreover, this is possible even after the report is developed, because it will be updated automatically, without the need to edit the results manually.

Additionally, it could also be advantageous to prepare a parametric beam model in which different concepts of structure can be quickly assessed using all of the loads and load combinations. These can later be immediately used to check the detailed model. Instead of performing simple calculations at the beginning of the project and slowly performing more detailed and detailed assessments, it may be possible to account for much of the complexities in the early phases of the design process.

2.8. Summary

Many different approaches to the design process were developed over the years. The older research of design theory is usually focused on a more detailed look at the methodology, whereas in the more recent studies the researchers propose a more holistic and abstract look. Taking a view on a product development form a very high level of abstraction is helpful at the company level. Moreover, methodologies similar to the one presented by Vajna (Vajna, 2020) are more suited to be used in the creation of new products which are supposed to be sold on the market. In case of methodologies which are taking more detailed approach to the design process like the consensus model, it seems that these are more suited not only for marketable products but also for an in-house design.

Consensus model is also a part of the curriculum in some of the universities. Not only that, but apart from the early fixation on solutions it also seems to be a predictive model for a natural approach to design by to-be engineers. Although, this approach was also critiqued for its focus on the conceptual design and very few pointers on how to perform the detailed design. Which is also valid for some of the more holistic approaches.

Other problems include insufficient knowledge at multiple steps of the process, lack of sufficient information exchange between the stakeholders or not incorporating the prior knowledge in the design. To solve these methodologies such as the shared memory approach or the design reuse model could be used. However, the design reuse model is very focused on its purpose, without providing much of a guidance in terms of detailed design. A similar holistic approach is represented by the shared memory concept.

Similar ideas are represented by the integrated design models. In them, the authors push forward an idea of integration of humans, knowledge, organization and technology during the product design process. The integration of technology is especially interesting as it pushes the user of methodology to try and work with the most advanced tools available to them.

By synthesising the consensus model with the ideas of integration, knowledge sharing and design reuse, while maintaining the more detailed approach to the design process an improved methodology of design could be achieved. Moreover, developing new methods with innovative tools such as FEA post-processors integrated could increase both efficiency as well as quality. This is due to, making the design process quicker and by allowing for more automated approach to standard checks, sanction for easier optimization of their results.

3

Current design methodology at Jan De Nul Marine Design and Engineering Department

3.1. Introduction

In this chapter the current methodology of design at Jan De Nul Marine Design and Engineering Department is presented and discussed. The described methodology is a result of a case study during which a draghead gantry crane for a trailing suction hopper dredger was designed. Through this case study structure of the methodology and methods used in the department were found.

In the first section, the structure of the design process is presented and described. Next, standard procedures used during the design process in the department are presented. Lastly, the problems recognised in the methodology are listed.

3.2. Design process structure

Structuring the work is an important factor in the design process, both in terms of the final design's relative quality and the efficiency of the work. Some of the companies, have an explicit workflow structure, which is required to be followed during the product development process and the design part of it. In others, the designing department is free to set up the structure of their work themselves, with minimal guidance from the upper management which is required to coordinate the work between the departments, delivering the final product on time and of the expected quality.

Without the explicit company policies that structure the design work, the employees have a lot of impact on how this process is conducted. This can be both advantageous and disadvantageous, for all of the involved stakeholders. On one hand, the process structure is more flexible and can be altered according to the needs of the current project and the needs of the department, without the involvement of upper management and thus the inevitable delays. On the other hand, too much of the flexibility to change the process can cause it to degenerate.

The designers tend to take shortcuts when necessary. If the project is very urgent, some methods or choices might be made to shorten the time required to finish it, even if in normal circumstances these would not be considered. Moreover, given the increase in efficiency and the lack of imposed structure on the process, the designers might be tempted to use these shortcuts even during the less intense time periods. This might, over time, cause these shortcuts to become the new norm and get passively embedded into the work methodology.

Even if there is no explicit structure in the design process, there dos exist an implicit one which had to develop as an effect of collective work in a team of designers. It is quite rare for the engineers in companies to work on their own. Usually, one project involves multiple designers from multiple areas of expertise who need to cooperate to deliver the final design. Therefore, the constant cooperation between the individual employees and departments is required. As a result of that, some kind of structure in the design work is bound to develop in order to allow for such cooperation. Although, the naturally developed process structure might happen to be the most efficient methodology that is possible to obtain, it is highly unlikely. Moreover, it is very hard to properly assess its effects on the quality and efficiency of work due to the lack of its definite description.

3.2.1. Black Box

In order to find the implicit structure and methods in the system it is advantageous to first look at it on a very high abstract level. The high-level description helps with finding the factors affecting the system, without obscuring it with a large number of details. Therefore, first a black box of the system was prepared, it is presented in Figure 3.1.

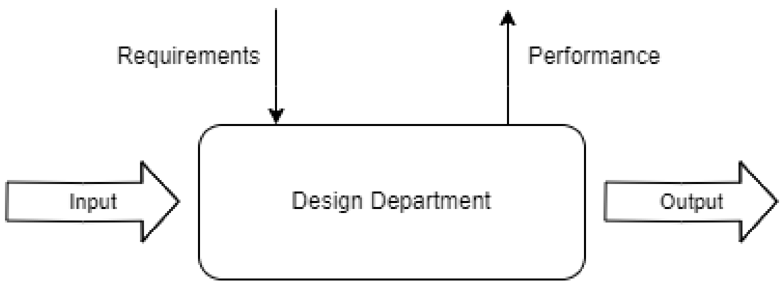

Figure 3.1: Black box of the Marine Design and Engineering Department at JDN.

The black box model is a simple model that allows for a look at the system on a high level of abstraction. It is built out of a transformative block which is fed inputs and produces outputs while fulfilling the requirements and has a measure of performance. The inputs are the material or data that is fed to the system and transformed into outputs. The requirements are the criteria that the transformative block has to fulfill and the performance are the indicators of how well the transformation is performed (Veeke et al., 2008).

In case of Jan De Nul Marine Design and Engineering Department, the aforementioned elements of the model are the following:

- input:
  - need for a machine or structure,
  - requirements of size and function of a machine or structure.
- Output - design of a machine or structure.
- Requirements:

    - adherence to law and standards,
    - adherence to company policy,
    - acceptable lead time.

- Performance:
    - size and function requirements fulfillment,
    - lead time,
    - design manufacturing ease,
    - design manufacturing cost,
    - weight of the manufactured object,
    - reliability of the produced object,
    - design's general correctness,
    - object's maintenance demands.

The black box illustrates the work environment and the expectations that the company has of Marine Design and Engineering Department at Jan De Nul. The input is a need for a machine or structure that fulfills certain function and is of a certain maximal or minimal dimensions. It is also important to note that the need comes from inside the company. Thus, all of the prepared designs are used in-house and are also manufactured in-house. Therefore, rather than designing standard equipment, a large part of the work is performed to produce a one-off object that is tailored specifically to the needs of other sections of the company. Though, many of the designs are adapted and based on the ones which were prepared previously, as well as designs based on proven mechanical concepts, which are then adapted to the specific task at hand.

In terms of the requirements, firstly the design office has to adhere to the law. This means following the standards and rules issued by the government, European Union and ship classification societies. Therefore it is required to work with standards and adhere to their requirements. However, as of the year 2022, the classification societies recognised by European Maritime Safety Agency (EMSA) do not provide specific rules for the design of dredging equipment, which is a large part of designs prepared by the design department. However, whenever there is no explicit standard for the specific object that is designed, then the equipment should be developed based on the next standard that is suited best to the task.

Secondly, the office has to adhere to the company's policies. Therefore the designs and the work should adhere to the goals of the company regarding sustainability, safety, environmental protection, etc. This could mean as little as making sure that new products are energy efficient, but it could also require adding new auxiliary systems to the equipment to lessen the negative effects of its use on the ecosystem.

Thirdly, the department works within the time constraints specified by the company. Some projects have long development times, while others have to be finished in a strict time frame. Therefore, lead times may vary significantly from design to design and work has to be organised in a manner that accounts for that. It also signifies that for some of the projects there might be a significant time pressure put on the designers to finish their work faster.

The performance can be assessed in multiple ways. First and foremost is the ability to create the designs which fulfill the requirements stated in the input as best as possible. This is an important factor in the evaluation of the performance, since failure to comply with the requirements make cause problems in fulfilling the obligations of the company in other projects.

Secondly, short lead times and meeting the deadlines are also important. Since, the designing is an early phase in the production process, delays at this stage may cause delays in many processes in the further development. On the other hand, finishing the design early will provide an additional buffer for the later stages of development, and can be an indicator of a good performance.

However, it is important not to forgo quality in exchange for time savings. Calculation reports, drawings and models should be correct in a general sense, the reports should be understandable and complete.

Objects should be possible to fabricate easily and cost effectively. Since the designed machines and structures are mostly manufactured in-house, then fabrication is considered one of the most important factors.

Moreover, not only should the product be easy to manufacture but also reliable and not too demanding in terms of maintenance. Since, most of the designs produced by the Marine Design and Engineering Department are destined for use on vessels, it is important for the equipment to be possible to perform maintenance on it during sailing. Moreover, higher reliability and fewer repairs contribute to smaller down times of the vessels and therefore, improve the overall efficiency of it.

Lastly, weight of every object put on a ship is an important factor as it affects characteristics of the vessel. Although, the individual pieces of equipment may not be of significant mass themselves, their combined effect on a craft could be significant. Also thanks to designing lighter objects, it may be possible to install additional equipment.

3.2.2. Methodology Structure

In order to find the detailed structure of work, a design of a draghead gantry for a trailing suction hopper dredger vessel was performed. Based on that experience and information gathered through discussions with the engineers working in the department, the workflow of the design process has been developed.

The structure of the Marine Design and Engineering Department consists of five areas. First, is the environment, it represents the systems outside of the Marine Design and Engineering Department. These are other departments in the company, the classification societies and general outside world. Next, is the general design department, this is the section of the Marine Design and Engineering Department which provides the loads and criteria for the designs. The third area represents the 3D CAD operator, who is preparing the model of the designed object. The fourth one is representing an expert engineer who is helping with development of the product throughout the early phases of the design. It is a person who, in this context, is largely an advisor helping with development of multiple projects. Lastly, an engineer who prepares structural calculations, checks the object according to criteria prepared by the general design department and prepares the reports of all of the calculations and checks. This system is presented in Figure 3.2.

The structure of the methodology of design in Jan De Nul Marine Design and Engineering Department is presented in Figure 3.3.

The current design process structure is consisting of for phases:

- I - preparation,
- II - detailed design,
- III - calculations,

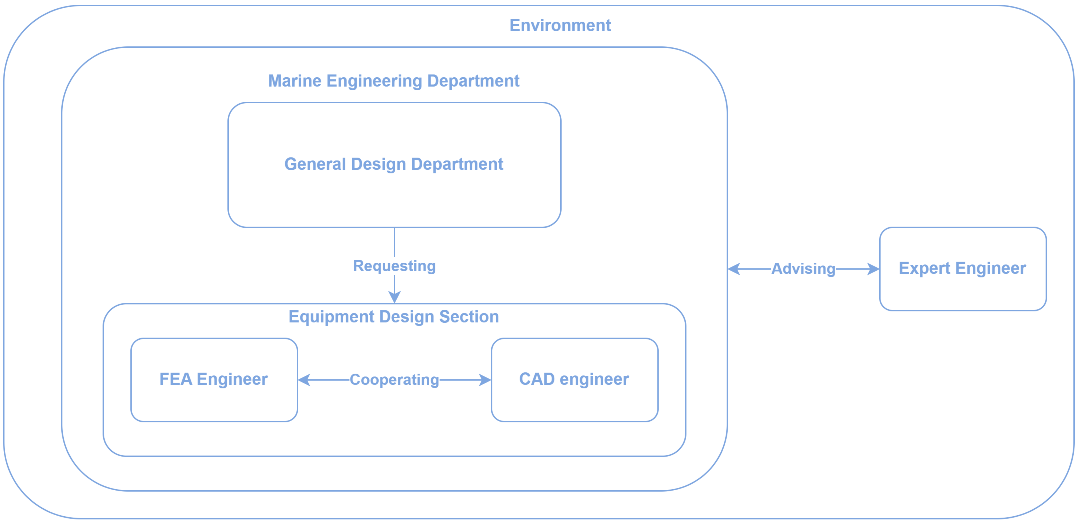

Figure 3.2: Marine Design and Engineering Department model.

- IV - corrections and reporting

Looking at the overall structure of the presented design process, it is immediately visible that a large part of the work is shifted towards the engineer who prepares the finite element analysis and the standard checks. Secondly, it can be noticed that a lot of early design work such as conceptual design and creating the early models is performed by an expert engineer in cooperation with the 3D modeller. And most importantly that the overall design process relies on the preparatory work performed by the general design department.

The need for a new machine comes from the outside environment, it happens whenever there is no object available to be bought or already developed in-house that suits the need of the company. Based on the developed requirements, the general design department prepares a design brief that states, what loads should the design carry and what criteria should it satisfy. Then the first iterative loop is performed. It is the work between an expert engineer and a 3D modeller, this is the phase which goes from conceptual to an embodiment design. The object's structure is at this point based on the experience of both engineers, with simple hand calculations being performed for rough checks. Once the 3D model is finished, it is passed to the engineer performing the finite element analysis.

Apart from the model, calculation brief is provided by the general design department to the FEA engineer. It might happen that it is lacking some of the cases and criteria that the engineer deems important. Then, depending on how urgent is the project and the availability of tools that can be quickly used, he might prepare these additional information himself or ask the general design department to prepare it.

When both the 3D model and the load and criteria are prepared for the calculations, additional FEA models might be required for other configurations of the object. If this is the case, these are prepared too. Then after applying the boundary conditions, verification of all of the models is performed, to check if the results are realistic.

Next, iterative yield strength calculations are performed. First, the load cases are input into the FEA software. Then the structure is optimized and its parts are modified for the stresses to be close to the allowable value. This is done for all of the configurations and models until satisfactory results are reached. Modifications of the structure, in simpler projects can be performed by the FEA engineer without consultation with the 3D modeller. However, in the more complicated designs, some of the changes made in FEA are concurrently incorporated by the 3D modeller in the CAD design to verify if they are possible to manufacture and that they are not interfering with any other objects or systems.

After all of the models are checked and updated the rest of the structural and equipment checks might be performed if applicable. Sometimes not all of the checks that the FEA engineer deems appropriate to be performed for a design might be included in the criteria. Then it might be decided to perform them despite that.

The buckling, weld and fatigue checks are performed using the existing tools or newly created calculation sheets. Buckling and fatigue checks are an iterative work of modifying the dimensions or applying new stiffeners to the structure and recalculating the FEA results to check if through the applied modifications an allowable result is reached. For fatigue calculations it might also happen that there is not sufficient information provided regarding the object's operation. In that case, the engineer needs to look for information in other departments. This was the case during the draghead gantry design. For the weld check only the required results from the FEA have to be retrieved. Then the dimensions or the type of welds can be changed so that the internal stresses are under the allowable value. If this is not possible, other parts of the design might be modified to reach a solution. It is also important that after each model modification, it is necessary to update all of the models and all of the checks that might be affected by it. For all of the checks it is also necessary to prepare the necessary reports.

Near the end of the process, to complete the detailed design, calculations of bolts, pins, cylinders and other parts that require a check are performed. Depending on the specific case this might require the results from FEA or can be prepared based on direct loads on the individual parts.

After all of the sub-reports from checks are prepared and the models and results are fully updated, a full report can be prepared. The final version of a 3D CAD model is adjusted to reflect the results of FEA and after drawings are finished the design can be approved.

3.3. Design's accordance to standards

One of the most important issues for the designer is for the design to be safe and compliant with the law. One of the requirements, is aimed at ensuring that is the requirement to follow the standards approved for use by the legislative bodies.

Checking the design's accordance with standards in the Marine Design and Engineering Department is discussed based on the experience gained during the draghead gantry design for the trailing suction hopper dredger vessel and discussions with the engineers. The approach discussed in this section is believed to be a representative picture of how this part of the process is performed for the dredging equipment.

Engineer who is performing the finite elements analysis and other required calculations for the designed object, at the beginning of his work receives a design brief prepared by the general design department. This document in case of the draghead gantry contains the following information:

- description of content of the document,
- general information about a system for which the object is designed,
- list of referenced documents and standards,
- short list of details of a vessel for which the object is intended,
- drawing with the position of the object on the vessel,

- list of inputs used for preparatory calculations, some of them are provided with values, some of them are provided without values and for some formulas are provided,
- description of the load cases with reference to the standard,
- results of load calculations,
- recommendation on which loading conditions should be used for FEA calculations,
- checking criteria.

The basis of design for the draghead gantry was created based on the standards presented in Table 3.1 and internal documents with recommendations regarding the coefficients used for calculations of loads.

Table 3.1: Standards used in the basis of design for the draghead gantry.

Standard	Title
DNVGL-RP-C205	Environmental conditions and environmental loads
BV-NR-467 Pt. B, Ch 7, Sec 3	Rules for the Classification of Steel Ships
BV-NR-595	Offshore Handling Systems
BV-NR-526 DT R02 E	Rules for the Certification of Lifting Appliances onboard Ship and Offshore Units
BV-NR-445	Rules for the Classification of Offshore Units

Moreover, the basis of design also contained three loading conditions developed based on the BV NR 595 standard and two empirical loading conditions. For all of the loading conditions one load on the outer sheave of the gantry is the only load considered. Even though, BV NR 595 (Bureau Veritas, 2014) does specify that the load cases should be determined by BV NR 445 Pt. B, (Bureau Veritas, 2019) in which environmental loads are included in the calculation for the load cases referenced in the text. Moreover, it is recommended to perform calculations for the gantry only in the outboard position for only one of the load cases. Additionally, the basis of the design mention only the yield strength check without any further structural assessment. Even though BV NR 595 (Bureau Veritas, 2014) does specify that buckling and fatigue should be checked.

Additional calculations of environmental and inertial loads due to the movements of the vessel had to be conducted. Because of time constraints these were performed using an already existing tool, an excel sheet which can be used to calculate default motions of the vessels, the wind loads and combine them into critical load cases according to DNV-ST-N001 (De Norske Veritas, 2021). Because of data constraints, these were calculated using the LFRD approach, which could be performed with the information given in the basis of design contrary to the WSD approach. Even though, the original criteria for the yield check were prepared for a WSD calculation. Efforts were made to choose conservative approach and safety factors for the loads.

In the supplied basis of design this was not the case, however frequently the FEA engineer is provided with a list of critical load cases in form of loads and accelerations. These are already multiplied by the safety factors from the standards but it is not specified what factors were used for which loads.

Despite the lack of it in the basis of design it was decided that buckling, weld and fatigue checks will be performed regardless. However, it was also decided that existing tools should be used for that process. These were calculated using the existing excel sheets based on the DNV standards. Welds were to be checked according to DNV-ST-N001/DNV-OS-C101 (De Norske Veritas, 2019, 2021), buckling was to be checked according to BV NI 615 (Bureau Veritas, 2018) and DNV-RP-C201 (De Norske Veritas, 2010a), and fatigue assessment was performed according to DNV-RP-C203 (De Norske Veritas, 2010b).

Other checks that were performed and for which the tools for hand calculations were developed during the design process are presented in Table 3.2.

Table 3.2: Hand checks with applicable standards.

Part	Standard
Cylinder	BV NR 526
Pins	BV NR 526
Wire rope and sheaves	BV NR 595
Bolts	DNV-ST-N001 and DNV-OS-C101
Hinges and pad eyes	BV NR 526

Despite using multiple rules from different classification societies efforts were made to make the design safe. Though, the lack of the clear set of standards that could be followed is certainly an issue.

3.4. Standard procedures

When working in a team or within an environment of people who work in the same field, a shared memory is developed. This process can be either conscious or unconscious, but it is inevitable whenever a group of, for example, engineers cooperate for an extended period of time. Part of it is their combined knowledge with respect to their field, the tools they use and the regulations under which the designs fell. However, there is also a part which is the shared preferred methods of cooperation, design, tool preparation and tool usage.

Although there is no explicit written down design methodology or rules that engineers have to follow in the department, some standard procedures inevitably did naturally develop. These range from the overall approach to the design process to performing specific checks or preparing tools for use in the current and future projects. The standard procedures, which were identified during the draghead gantry design process, are described in the sections that follow.

3.4.1. Adapting design

A significant portion of the design work consists of adapting previous designs of equipment for new tasks or different work conditions. A model of the identified process is presented in Figure 3.4.

The process begins with the stated need for an object. Then a set of requirements, which have to be fulfilled by the design is defined. Next, a design that either fulfills or partly fulfills the requirements or is in line with overall needed functionalities of an object is being searched for. If no acceptable design is found then other solutions are researched. On the other hand, if one is found then cooperation between the expert designer and 3D modelling engineer begins. The two work in iterations to prepare a CAD model that fulfills the requirements and functionalities, defined at the beginning, the best. This process is relying mainly on the experience of the expert designer. Based on the knowledge about the past designs and expertise he recommends the changes that should be made in the model, which are then carried out by the engineer. The changes include changes in geometry, new functional parts, plate thicknesses, stiffener placements, shaft sizes, bearings, cylinder choices, etc. When the expert is satisfied with the results, the design is handed over for further evaluation by other engineers.

This approach to redesign is heavily relying on the expert designer figure, and their experience and knowledge. Certainly, it is incredibly lucky to have such an asset in the company, an expert who can prepare and modify designs quickly and efficiently based on a few hand calculations and expertise. Thanks to that lead time can be greatly reduced. Especially, considering that the design adaptation process encompasses parts of the concept as well as parts of the detailed design phases. Although, whenever the expert becomes unavailable, conducting the design process in this form might become infeasible. Hence, alternatives such as usage of parametric models or simplified FEA calculations incorporated early in the process might be used instead. This could allow to partly or wholly decouple the adaptation of designs from the expert figure.

3.4.2. Plate buckling check

Most of the designs that are produced by design department are steel structures and a large part of them are plated or involve parts which are plated. Therefore one of the important part of design process is plate buckling check. The model of the identified process is presented in Figure 3.5.

When the object needs to be checked for plate buckling a following process is followed. An eigenvalue buckling check is performed on the whole finite element analysis model of an object. If the load factor value is higher than 5 for the first three modes, then the plates in the structure are deemed to be sufficiently resistant to buckling. However, if the load factor is lower than 5 then a manual hand calculation is performed for the plate, which is shown to be displaced in the simulation. First, the applicable results are retrieved from the FEA, these could be either stresses or nodal forces on the plates' edges. Though, it is important for the results to be calculated in the applicable coordinate system for the plate. Then plates' dimensions are calculated or read from CAD software. Next, everything is imported into the calculation sheet, where results are calculated according to a standard. Based on that, either additional stiffeners are added, applicable plates are thickened or the plate is deemed sufficiently stiff and is only changed in the model temporarily. After, the model is modified, the eigenvalue buckling check is performed again and either another plate has to be checked or the design is accepted if the load factor is higher than 5.

This type of check of a whole structure can either cause the plate buckling check relatively fast. If the load factor for the eigenvalue buckling check is higher than 5 in the first iteration and all of the plates are accepted as sufficiently stiff, a lot of time can be saved. On the other hand, if many panels need stiffening then the minimum number of iterations of the loop in the presented model is the number of unstiffened panels. This is due to the eigenvalue buckling revealing only one displaced plate during each calculation loop. Moreover, performing the check in this manner might not be accepted in the standard according to which the object is being designed.

3.4.3. Fatigue check

The fatigue check is performed for steel structures, which are subject to cyclical or changing loads. Fatigue is an important design factor, especially for an environment such as a vessel, in which cyclical environmental loads such as waves are inevitable. The identified standard procedure is presented in Figure 3.6.

When the structure needs to be checked for fatigue resistance, first the so-called “hot-spots” are identified based on the results of the static structural FEA analysis. These are areas with high equivalent von Mises stress, which engineer deems might be prone to fatigue damage. Once, these are identified, the maximal and minimal stresses in the hot-spot are retrieved from the multiple load case results to obtain a maximal stress range for which the structure is calculated. Next, the fatigue damage for every chosen area is calculated individually for an assumed number of cycles. If the fatigue damage is within the acceptable range then the check is concluded and the structure is deemed sufficiently resistant to fatigue. However, if the damage exceeds the limits, then the structure has to be modified and FEA calculations have to be repeated. Since, the introduced changes might cause unsuspected variation in stresses in other parts of an object, the best practice is to check the structure for new hot-spots and perform the iteration again.

This process relies on the engineer to identify the hot-spots in the structure during the static structural calculations. Therefore, it requires looking for them manually and selecting them based on the knowledge and experience. This might be a potential problem, taking into consideration that even a small cyclic difference in the stress could cause a fatigue failure. Moreover, transferring the results to a calculation sheet, modifying the model and then rerunning the static structural calculations in FEA can be a long and tedious process if multiple iterations have to be performed.

3.4.4. Weld check

When designing a welded structure it is also important to ensure that the welds are sufficiently strong to transfer the loads without failure. The procedure of weld checking which was identified is presented in Figure 3.7.

The process begins with the need to perform the weld check in the structure. First, it has to be assessed if all of the welds for which the check is applicable are modelled in a manner that allows for easy result extraction. This is usually done by modelling the weld as a bonded contact in Ansys Mechanical and using a probe to extract moment and force reactions. If that is not the case, the model has to be modified and the calculations have to be repeated. Then, when the applicable results and weld dimensions are retrieved from FEA and CAD, calculation can be performed for each of the welds individually in a calculation sheet. If the weld is not strong enough, its dimensions or type can be changed, when this is not possible, changes in the structure of the object might be necessary to lower the stresses in the area surrounding the welded connection. If this is the case, both FEA and hand calculations have to be repeated or partly repeated until all of the welds are sufficiently strong.

Similarly to the fatigue check, weld check requires the engineer to manually select all of the welds which have to be checked. Moreover, it requires them to keep track of every position, retrieved results and dimensions manually. Whenever a model needs to be modified, an additional iteration may cause all or part of the already calculated welds to be changed. If that happens a possibility of making a mistake in the manual individual calculations and tracking the inputs and outputs grows. Additionally, this method is manageable for small numbers of welds but for larger constructions the individual calculations of the welds may become tedious and repetitive. For such cases, sometimes a rule of thumb may be used instead. Then, depending on the weld type an arbitrary safety factor is set to the allowable equivalent von Mises stress and if the stresses in elements adjacent to the connection are lower than the modified allowable stress, the weld is deemed as sufficiently strong.

3.4.5. Hand Calculations

Another regularity, which was identified is the approach to hand calculations. These are all of the calculations which are not directly related to structure but have to be performed to finish a full mechanical design of an object. These are also usually performed in the end phase of the designing process, after the FEA and the buckling, weld and fatigue checks are concluded. Elements which are designed through hand calculations are:

- pins,
- shafts and axles,

- bolts,
- cylinder buckling,
- parts chosen from catalogues.

The standard approach to such calculations is first to look for a calculation sheet which was prepared for other project and which could suit the current needs. Sometimes it happens that no previous calculation sheets exist or that they are not cataloged in a manner that allows to find them easily. In that case, a new calculation sheet has to be made, which is suited to the task at hand.

However, if a previously prepared calculation sheet was found, the engineer can choose to use it as is. Sometimes more than one option is available, then one of the sheets is chosen based on the following:

- knowledge of the previous projects and their characteristics,
- additional information contained in the calculation sheet,
- experience of the engineer,
- opinion of other engineers working in the office,
- comparison between the calculation sheets.

A large part of the calculation sheets are prepared only with one project in mind and might lack the explanation for some of the coefficients or equations in general. This can make the choice even harder or cause an engineer to prepare his own sheet and forgo using previously prepared ones.

The main idea behind basing the calculations on the sheets prepared in the past is not to “reinvent the wheel”. However, in some areas lack of maintenance of a fully fledged database with properly established rules of cataloguing can be noticed. Multiple spreadsheets based on the same standards and sometimes producing different results can be found. Without explicit design methodology followed by all of the engineers in the department and without proper rules of creating hand calculation sheets, these tend to be unusable when shared between the projects. This might be due to the lack of information regarding the choices made by the engineer designing the calculation sheet or because it would require extensive research of formulas in the spreadsheet and comparing them to the ones presented in the standard to gain confidence that the tool can be used for the task at hand.

On the other hand, creating a designated tool for a specific calculation type and forcing engineers to use it regardless of the individual project’s needs might also cause issues. These could be problems with following standards in the current project when standards are chosen based on the available tool rather than what should be followed for the design.

3.4.6. Working with multiple models

Working with multiple models for some designs is also an occurrence. Some of the objects may be used in different configurations, therefore they have to be calculated in different positions for some of the load cases to ensure their structural integrity. In some cases, modeling tricks are used to ensure working with one model. However, for some objects, it is sometimes not evident how to perform all of the calculations using only one model. Then, multiple models in multiple configurations are used for the finite element analysis.

Whenever, multiple models are used for structural calculations of one objects an engineer can approach this problem in different manners:

- identify the most critical position and perform calculations only for this position,
- identify the most critical position, perform all of the calculations and checks for this position and perform a few additional calculations for other configurations,
- perform all of the applicable calculations in all of the positions and try to synthesise the results.

The first option is definitely the least work intensive and the easiest of the three in terms of performing the calculations. This is the approach which was suggested in the basis of the design for the draghead gantry. One of the positions of the gantry was deemed to be the most critical and all of the checks should be performed only in that configuration. However, this approach could cause issues as some of the positions may be critical for most of the structural elements in the object but not all of them. If the safety factors are not substantial, these may cause some of the parts to fail despite being seemingly acceptable in the structural FEA calculations.

The third option is the most work intensive and definitely the hardest to synthesize the results manually. It requires that the engineer will update all of the models with the changes made in all of the other models. This could easily lead to confusion and differences between the models. Moreover, a large part of the checks requires only that specific stresses are lower than the allowable limit in all configurations but this is different for some standard fatigue checks. This is due to the fact that for fatigue it is the sum of damage for every part of the design that has to be within specific limits. Therefore, if fatigue check is performed for more than one model, it requires the engineer to first manually find ”hot-spots” in all of the models. Then, the fatigue damage has to be calculated for all of the chosen areas, even if the stresses are lower in one configuration they have to be considered if in one of the other configurations they are regarded as hot-spot. Finally, the damage has to be summed between all of the models, and if any changes are necessary this process might have to be repeated for all of the models again. Moreover, if any of the changes affect the other checks, these also have to be updated. Therefore, this approach might be the hardest to properly implement without any errors and differences between the models.

The second approach is a compromise between the third option and the first option. For example, it might be decided that fatigue is only checked in critical configurations for multiple situations, which might not occur but could be considered a conservative assumption. Similar decisions can be made for other checks, where the most critical configuration for each of them is chosen. This could alleviate some of the problems such as the summation of the fatigue damage, though it is still necessary to update all of the models and ensure that all of the parts are the same in all of the models manually. Moreover, changes due to one check which affect other checks might still require to recalculate previously finished and accepted aspects of the design.

Working with multiple models is certainly an issue. This approach could cause significant errors in calculations as well as cause loss of time on repetitive calculations and model updates.

3.4.7. Reporting

Reporting is an important part of the design process as it is used to present the final specifications based on which the design will be accepted, classified by a classification society and manufactured. The reports prepared by the general design department include the following parts:

- project description,
- object’s requirements and specifications,

- FEA models' setup,
- structural check criteria,
- FEA structural calculations with charts,
- sections additional applicable checks with summary tables followed by individual calculations reports.

The reports are prepared using Microsoft Word software. The project description and object's requirements and specifications are consisting of a few tables and descriptions. The FEA model setup section presents the model which is the base of the calculations, meshing and final mesh parameters are presented along with all of the contacts, joints, connections, coordinate systems and constraints. All of these are substantiated with screenshots that present each instance of a FEA model's constituent or a sample of the type of it repeated within the model. Next, criteria for the yield static structural check from the basis of design are presented. After that, the structural check report is presented first a summary table with individual parts and the ratios between the stress and the allowable stress are presented and then multiple manually taken screenshots of charts are listed to substantiate the information in the table. Following, are multiple sections with buckling, weld, fatigue checks and hand calculations. Each section begins with a summary table and then filled out calculation sheets with relevant information are listed to present rationale for all of the values. Depending on a character of a check there might be screenshots of the calculated part presented. This is the case for the fatigue calculations, where screenshots of each individual hot spot are required in the calculation sheet or for buckling calculations where all of the calculated plates have to be presented on a screenshot in which they can be located in the structure.

The reports rely heavily on manually taken screenshots of charts in the FEA software. This is not a significant issue as long as the requirements do not change, even small changes in some areas of the design might require multiple screenshots to be taken again and changed in the report. Similarly, all of the calculations performed manually in the calculation sheets might be required to be changed if it happens that for example one of the loads has to be increased at the late stage of the design process. Moreover, even if all of the checks are within acceptable limits after that, it is still necessary to manually update a large number of screenshots and calculation spreadsheets.

3.4.8. Calculation sheet preparation

An important element in both calculations and reporting in the Marine Design and Engineering Department are calculation sheets. These are prepared for a specific project but efforts have been made to create universal spreadsheets that could be used in multiple projects. Standardised sheets were created for the following calculations:

- fatigue,
- weld check,
- pins and axles,
- pad eyes and shackles,
- plate buckling,
- default motions load cases,

- bolt and flange check.

Although these are usually created based on the sheets used in previous projects, adjustments are made to make them somewhat similar. All of these sheets share common elements which are included in every sheet and which are the following:

- title, author, approval and revision dates with the revision author,
- short description of what is the calculation in the sheet,
- list of standards according to which the calculations are performed,
- stated explicit values of all of the coefficients, dimensions, forces, stresses etc.,
- a bit of theoretical background for the calculation.

Moreover, some of the calculation sheets have graphical representations of the designed parts which change automatically according to input dimensions. Additionally, all of the standardised sheets have a similar graphical interface and are prepared to be put directly into the reports without the need to transfer the results somewhere else after the calculation.

On the other hand, these frequently lack instruction that could help with their efficient use. Moreover, there is not much explanation provided for some of the choices behind the coefficients used in sheets. Sometimes, some of the checks are not explained with regard to what exactly they are and what exactly is calculated apart from a symbol and reference to a standard. To check the reasoning behind the values, one has to read the standard and try to reverse engineer the route which was set by the author of the spreadsheet. Without providing the sufficient documentation on the choices made and additional descriptions of the calculations it is hard for an engineer to put a trust in tool. Especially, because sometimes mistakes can be spotted in these.

Figure 3.9, presents a fragment of a calculation sheet used for weld calculations. In the bottom right corner, the graphical representation of a weld is presented. For these symmetrical welds vectors “D(0,y)” should have corresponding values for both of them. However, one of the vectors is incorrect, this is due to a programming error in this calculation sheet. In one of the tables, one of the values affecting these is defined as a character instead of a numerical one. Since these wrong values of the vectors are used in later calculations, these are altering the final results obtained with this calculation sheet.

3.5. Problems in the current methodology

After finding what is the current methodology in terms of structure, approach to standards and the standard methods. The problems which should be solved are the following:

- using standards from different classification societies in one design,
- problems with determining safety factors on loads,
- missing input or limited calculations are advised,
- disconnect between the needs of the engineer performing the FEA and criteria provided by the general design department,
- using multiple models, which have to be updated separately,

- synthesis of results and optimization is harder when using multiple models,
- hand checks, which are performed at the end of the design process, may cause critical dimensions to change significantly,
- the currently used method of performing the buckling check may omit some plates which might buckle,
- some of the hot-spots for fatigue calculations may be missed by an engineer,
- performing buckling, fatigue and weld checks by hand, individually for large structures may prove to be a very time consuming task,
- identifying and manually keeping track of all of the elements such as plates, welds and hot-spots is prone to errors,
- bolt connections can be checked in FEA software,
- relying on calculation sheets prepared by another engineer may cause errors in calculations,
- calculation sheets lack sufficient description on for what they should and should not be used and why,
- calculation sheets lack sufficient descriptions of what is being calculated in each step,
- hesitance to use previously prepared calculation sheets causes engineers to prepare their own sheets,
- relying on manual report generation, manually taken screenshots, manual calculations and manual updating of the report,
- finishing the detailed design before any significant FEA calculation is performed,
- heavily relying on the experience of the expert designer to produce practically finished design at the start of the design process,
- some of the calculation sheets have mistakes despite being approved.

These problems are addressed in the next chapter of this report.

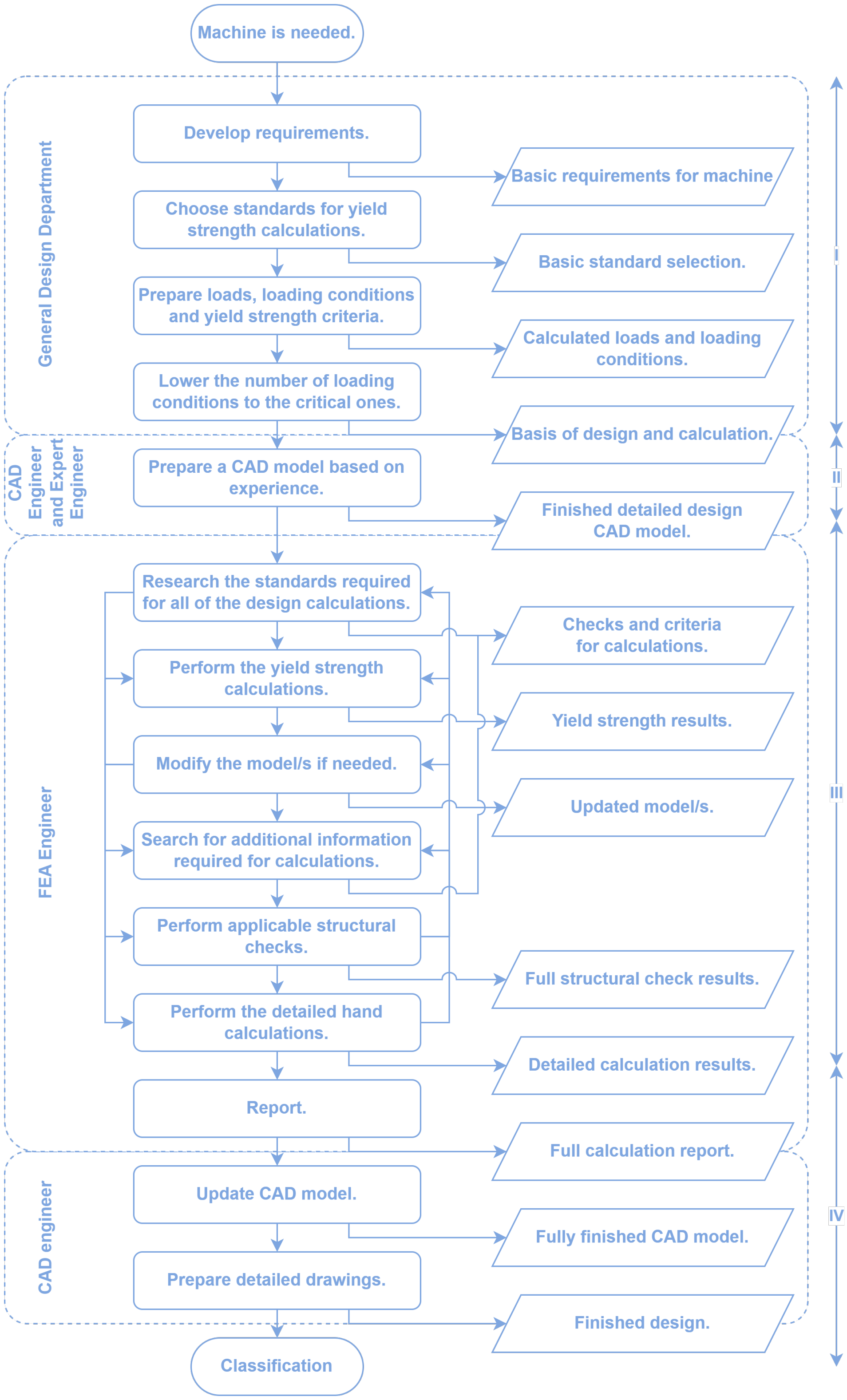

Figure 3.3: Structure of the current methodology of design.

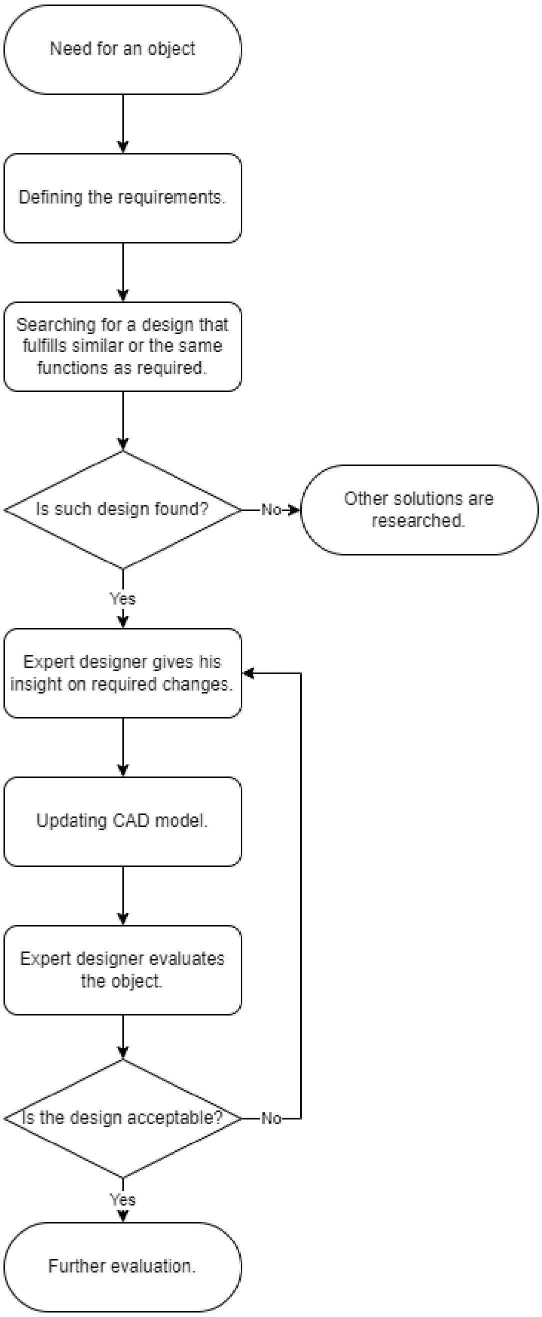

Figure 3.4: Design adaptation process.

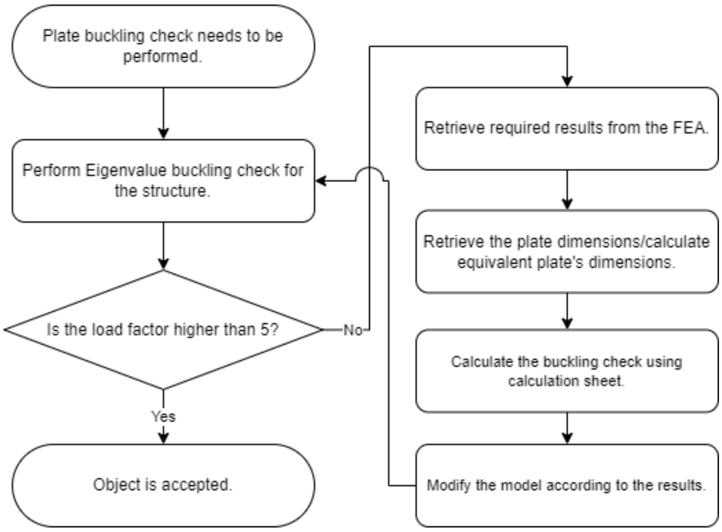

Figure 3.5: Plate buckling check process.

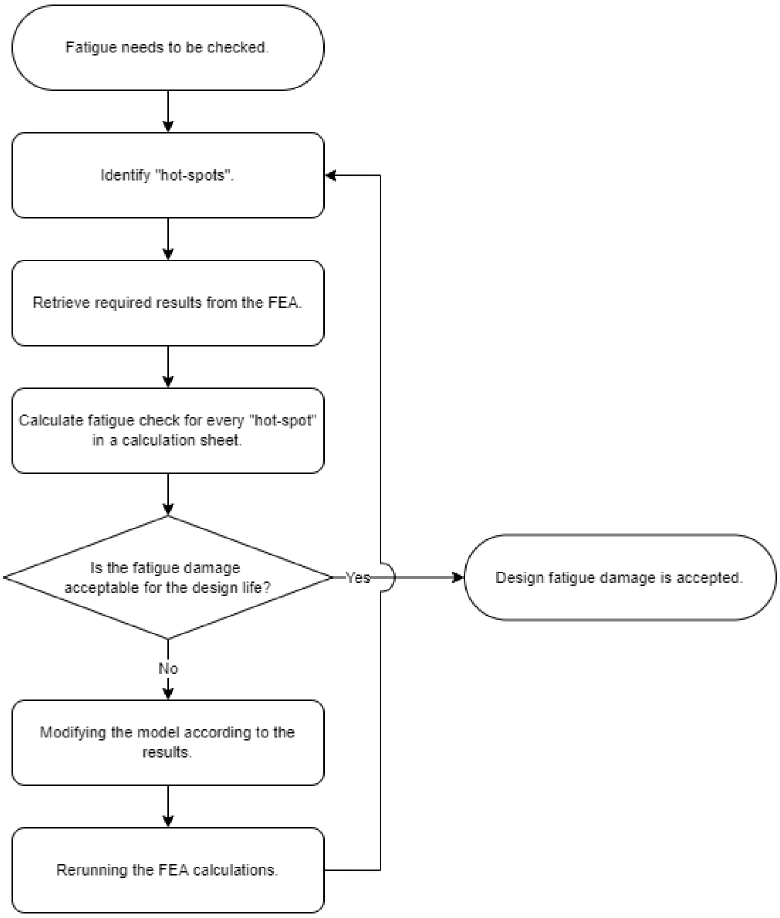

Figure 3.6: Fatigue check process.

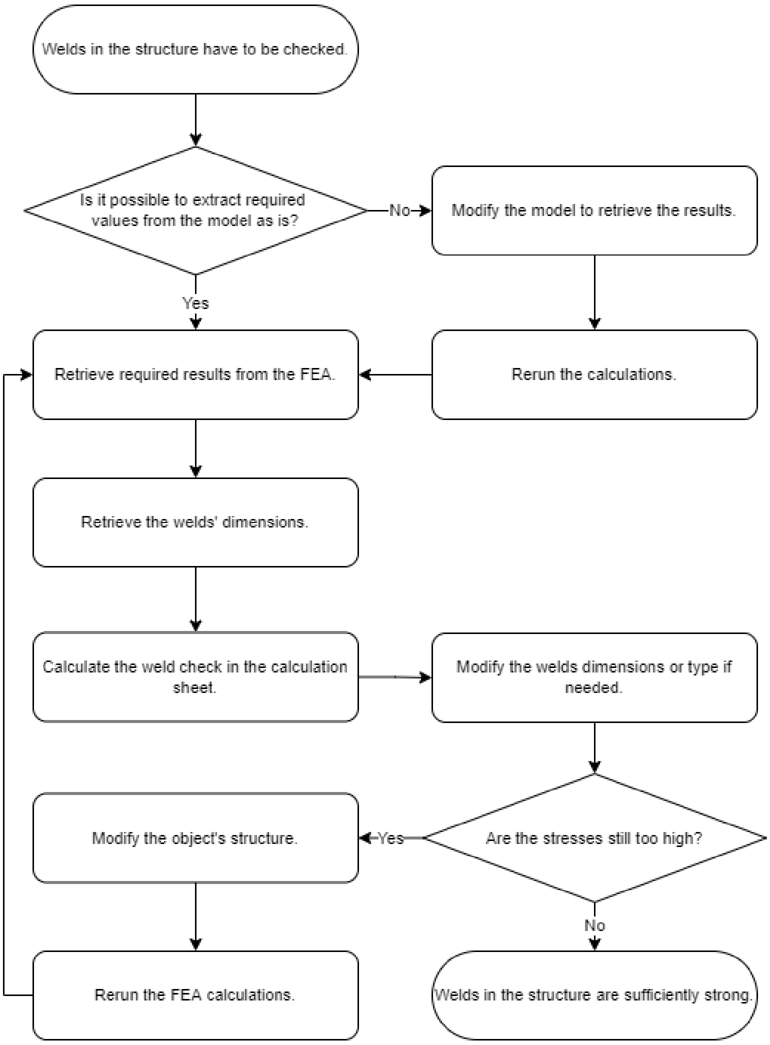

Figure 3.7: Weld check process.

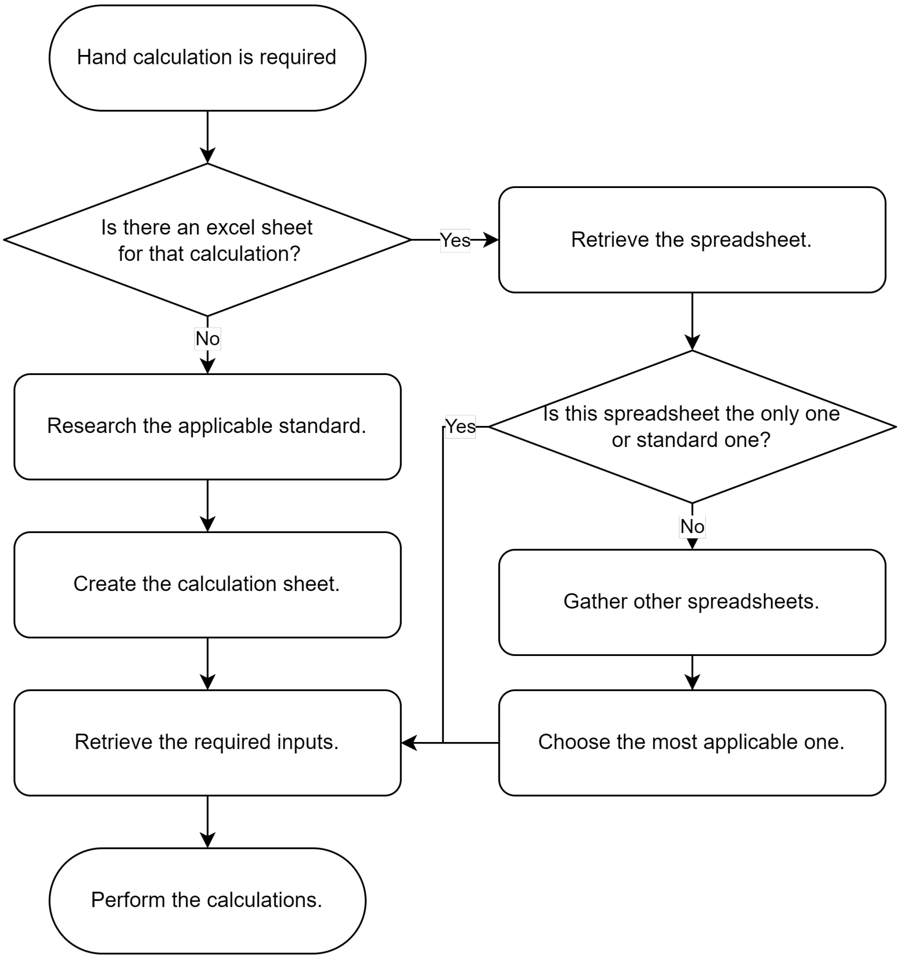

Figure 3.8: Hand calculation preparatory process.

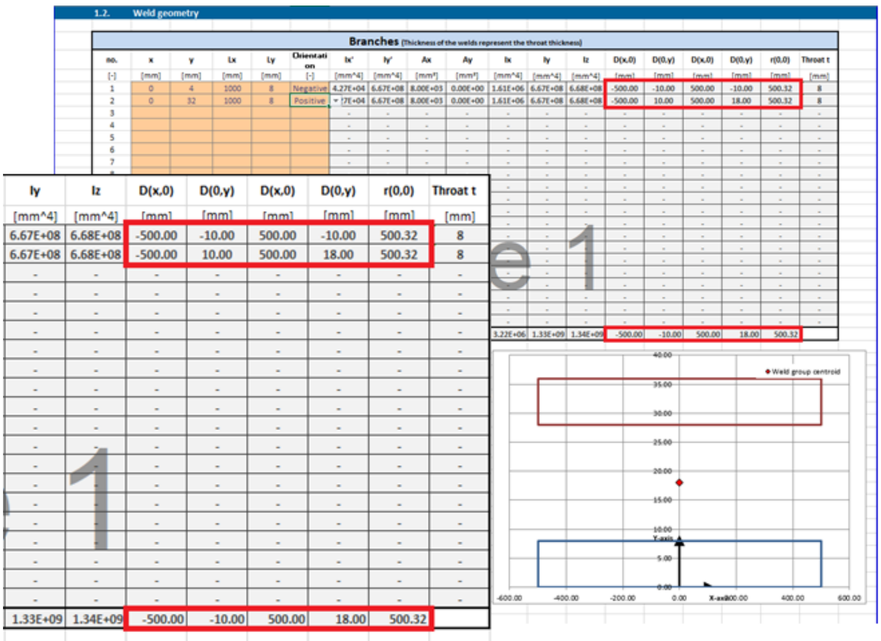

Figure 3.9: Weld check process.

4

Proposed improved methodology of design

4.1. Introduction

In this chapter a new methodology of design of heavy equipment is developed. First, the problems in the current design process are addressed and solutions are discussed. Next, different aspects of efficient incorporation of the post-processing software are considered. Lastly, the structure of a new methodology of design is presented, which is adjusted to the use of post-processing software and is intended to alleviate the problems found in the old methodology of design in the department.

4.2. Addressing the problems in the design processes

In order to prepare an enhanced methodology, solutions to the problems identified in the current methodology in the Marine Design and Engineering Department should be provided. Addressing the issues which were found is important to prevent falling into previously recognised pitfalls. It is also helping to identify what could be done in order to make improvements in terms of quality and efficiency. The problems in this section are grouped with their solutions since in many cases it is possible to alleviate multiple problems with one solution.

4.2.1. Integration of post-processing software

One of the proposed solutions to the identified problems is integrating the post-processing software into the design methodology in the department. In this case the designated software is SDC Verifier, although it is possible that other software solutions with similar functionalities could be used instead. The choice of software in this case is caused by the decision of the Marine Design and Engineering Department to explore possibilities of integration of this package.

Firstly, the designated post-processor has an integrated recognition module. Thanks to that, it is possible to automatically recognise the plates and welds in shell element based models and also joints and beam sections in models where line elements are used. All of the recognised parts can be individually selected and plotted to check their correctness and position. Moreover, it is possible to edit these parts by splitting or joining them and adding or subtracting elements and nodes. It is also possible to alter the parameters of the recognition process to suit the needs of the current project. Additionally, if necessary all of the recognised parts can be renamed to suit the needs of the engineer or adhere to the company's policy better. Therefore, keeping track of the plates and welds is an automatic or semi-automatic process. After the recognition process, an engineer can assess its correctness by looking through the tables containing the parts and by plotting the results. Normally all of these have to be selected by an engineer manually and in order to keep track of them it is necessary to manually create some kind of database, either by creating multiple charts or selections in the FEA software or by using spreadsheets and screenshots. Thanks to using a post-processor it is possible to minimize the probability of making errors, by minimizing the work that has to be put into manually maintaining a database. Example results of a recognition process are presented in Figures 4.1 and 4.2.

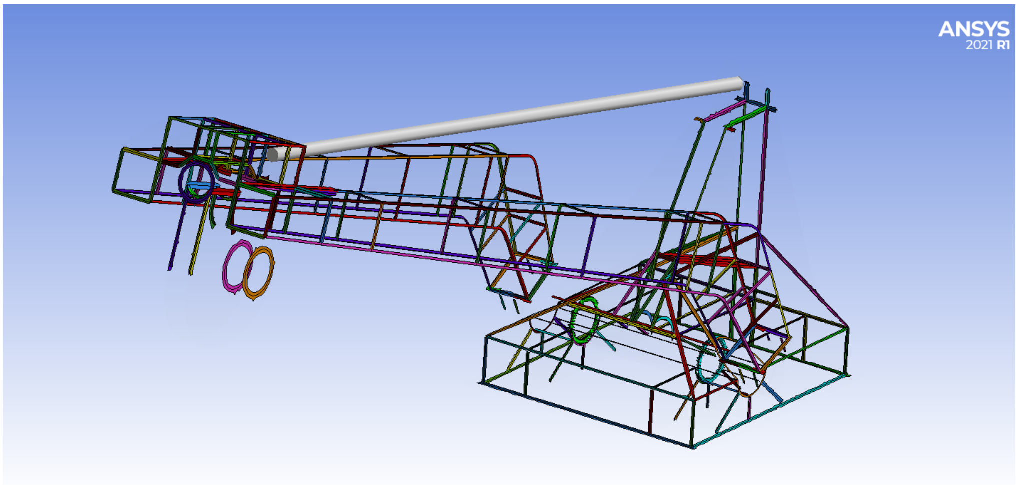

Figure 4.1: An example model with welds recognised by the SDC Verifier weld recognition tool. Elements which are parts of welds are plotted, without identification numbers.

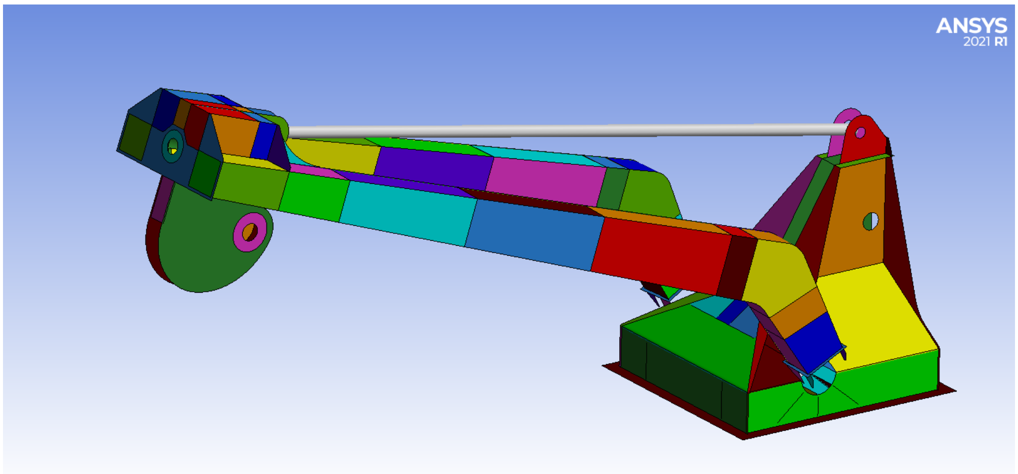

Figure 4.2: An example model with welds recognised by the SDC Verifier plate recognition tool. Unstiffened plates are plotted, without identification numbers.

Secondly, thanks to the calculation module it is possible to perform different checks automatically in the post-processor. Fatigue, weld and buckling checks can be performed semi-automatically based on the parts which were identified in the recognition process. These calculations can be performed either by using the check prepared by the developer based on the assortment of different standards which are frequently used in the industry or by preparing own standards by the user. Thanks to that problems with each of these checks can be solved.

For fatigue calculations, it is not necessary to identify hot-spots and keep track of them. It is also much harder to erroneously miss a hot-spot that may be not evident from observing results of a static structural analysis. This is due to the automatic nature of the calculation, once all of the input required for the calculation is provided by the user, fatigue is calculated for either the full structure or for all of the chosen areas.

For buckling calculations, it is also not necessary to keep track of the plates and manually calculate stresses in them. Moreover, it is possible for the post-processor to recognise the plates dimensions and to calculate the equivalent plate's dimensions. Thanks to these two enhancements, time may be saved and a full buckling check can be automatically calculated for every plate. Therefore, the currently used method relying on the eigenvalue checks could be changed for a method that is closely following the standards. This ensures not only that the design will be classifiable but also it is guaranteed to be safe.

For weld calculations, after the recognition process is concluded, it is necessary to input the data required for stress calculations. Although the length of each weld is recognised automatically, the user still needs to choose the weld type and input the rest of the weld dimensions to perform the check. However, due to the automatic recognition and, the fact that the weld database is managed in the post-processor automatically is an improvement compared to performing these tasks manually and calculating a weld check for each weld individually.

Additionally, since it is possible to define user checks it should be possible to model the bolts in the model and perform calculations of bolts with the finite element analysis. Rather than performing hand calculations in the ending phase of the designing process, the bolt calculations might be done earlier. The inclusion of bolt calculations in the FEA allows making adjustments in geometry dependant on the bolt size such as for example flanges, earlier than at the very end of calculations. Thanks to that, the last-minute changes and resulting recalculations could be avoided.

Thirdly, the software developer in this case is supplying the user with a selection of standards which are already coded in. Additionally, the basis of calculations and the equations used for performing them are described on the website. Although, it is impossible to rule out the possibilities of making errors when using any tool, in case of many commercial solutions it is frequently possible to request support from the developer in cases where engineers might be not sure about the tool's performance. As an example, in case of SDC Verifier the company includes a support function directly in the software with the ability to consult one of the company's employees. Therefore, when a tool is developed by an external company, sometimes there is an added layer of support which can be exploited by an end user. Which is not always possible with internally developed tools.

Lastly, the post-processor allows for automatic report generation. This makes it easier to perform changes in the design after the first report was generated already. If one of the load or load case have to be changed after the first report was already delivered, it is possible to simply modify them and use the previously setup calculations and report to generate all new results and report automatically. Thanks to that the manual work involved in last-minute design changes such as recalculating the checks, taking new screenshots and copying the results and figures to the text editor can be performed automatically.

4.2.2. Changes in the approach to FEA preparation and modeling

Part of the problems is caused by the approach to modeling and FEA preparation. By changing the current methods accordingly, it could be possible to solve these issues.

For some of the models, bolt connections are calculated using a spreadsheet. However, Ansys Mechanical software offers solutions for calculations of slip critical and tensile bolt connections in its toolbox. Thanks to this, it is possible to retrieve stresses directly from FEA rather than calculating them by hand. Bolts can be modelled either as line elements, solids or using the “Beam Connection” option. Then the bolt pretension can be applied to the models either by using Ansys Parametric Design Language (APDL) console or by inserting “Bolt Pretension” into the solution setup and choosing the correct geometry. Though, the use of this method is limited, bolt pretension may not provide correct solutions for bolts undergoing large rotations. This is due to the preload direction being constant throughout the simulation. In this case, bolts should be modelled as solids and the pretension can be applied using a translational joint. The exact procedures can be found in Ansys Innovation Course (Ansys Inc., 2020).

Currently, models are prepared in direct modeling CAD software and then they are prepared for FEA in Space Claim which is a CAD software integrated with Ansys Mechanical. However, it is possible to create models in Space Claim itself, either by direct modelling or parametric modelling (Ansys Inc., 2022b). The advantage of using the parametric approach is the possibility to create a base model for a certain type of object, which then can be easily modified with the set parameters. Then, the model can be directly imported into FEA, with minimal modifications or no modifications at all. Thanks to this, it could be possible to use a model with a high level of detail in the concept phase of the design process. Moreover, by doing so, the expert designer might not be required to check and assess CAD models during the redesign process, since these can be directly calculated using finite element analysis.

Using multiple models for calculations of one design is prone to errors and requires manually updating the models. In the whole field of FEA, millions of cases might exist in which the person performing the analysis might be inclined to think that the task at hand might be only solved by splitting the models into separate parts or performing the analysis using multiple models. In case of the draghead gantry design the problem was caused by the need to model the luffing cylinder as a line body, without the use of translational joint and performing the analysis in multiple configurations. An example solution to this problem which can be used during the calculations to avoid using multiple models for some objects is presented.

In order to simulate a working cylinder in FEA, so that multiple configurations of one model can be analysed in one calculation setup, the elements used to model the cylinder have to change their length. This can be achieved by simulating their thermal expansion, which is one of the features in Ansys Mechanical “Static Structural” calculations. The setup of the model used as a proof of concept and two different configurations with sample stresses are presented in Figures 4.3, 4.4 and 4.5.

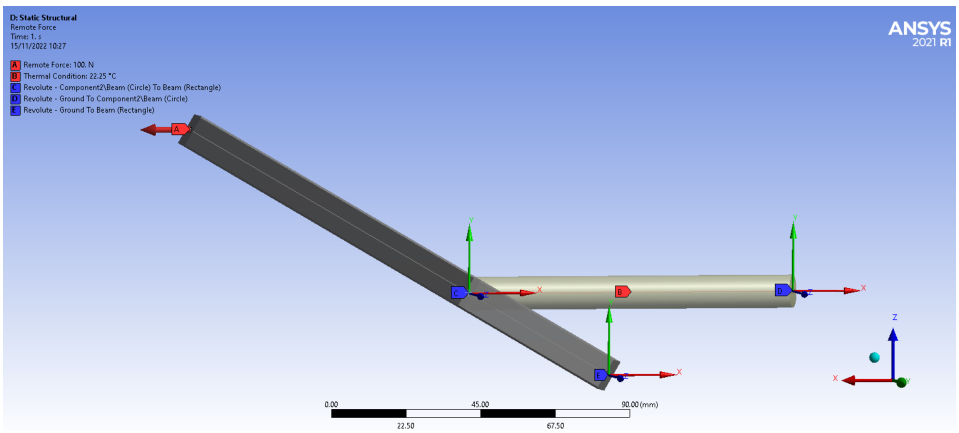

Figure 4.3: Model setup for the proof of concept for simulation of working cylinder using thermal expansion.

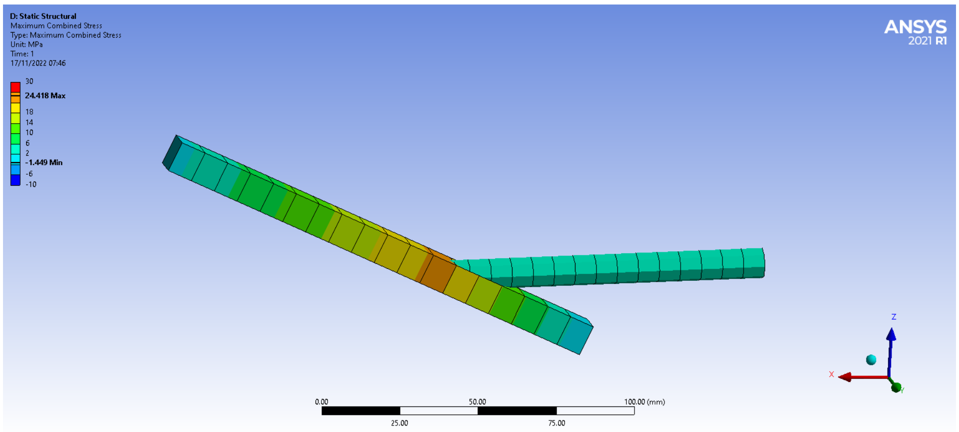

Figure 4.4: Results of sample calculation in position 1.

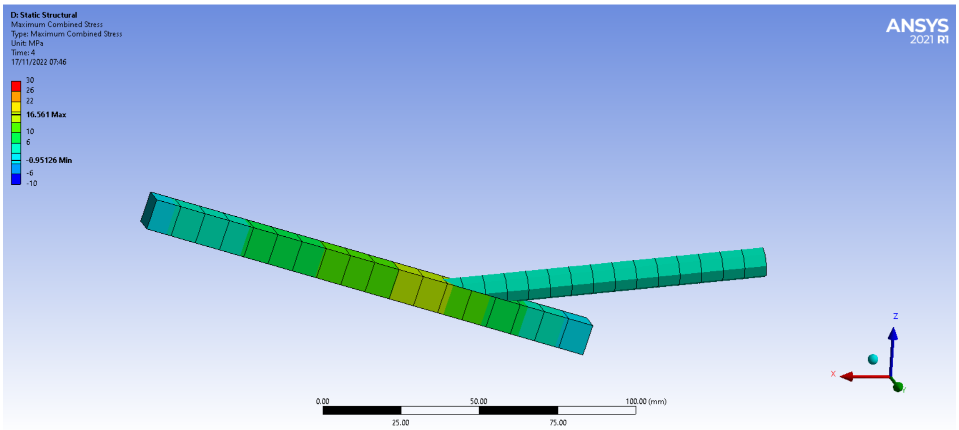

Figure 4.5: Results of sample calculation in position 2.

Two line bodies are used to assess this method. As presented in Figure 4.3 three revolute joints are used to constrain them and “Thermal Condition” object is applied to the round body, which allows changing the temperature of the body during the simulation. The thermal expansion coefficient is adjusted to simulate large expansion with minimal changes in temperature, its value is kept at $0.111K^{-1}$ the difference between positions 1 and 2 is 0.25K. The mass of the model is constant throughout the simulation. Based on that and the results presented in Figures 4.4 and 4.5 it is concluded that it is possible to simulate movement caused by the cylinder in this manner.

4.2.3. Changes to the methodology structure

A suitable methodology structure is also essential for an efficient and successful design process. Currently used methodology is the one which naturally evolved over the time. Some of the identified problems can be corrected by changing the structure of the methodology.

When designing, what could be called semi-standard equipment for dredging in the Marine Design and Engineering Department, the process is largely dependant on past designs and the experience of an expert designer. New designs are produced by finding older ones and modifying them accordingly, mostly based on the past experiences with the object’s type designs. What is produced after the first iterative design phase is a CAD model which is completely finished, with bearings, bolts, shafts, pins, cylinders, and all of the detailed elements and dimensions set up. However, these elements are not fully calculated but are selected by the expert based on past experience or minor hand calculations. Only after that, the design is being checked and analysis is performed according to the standards, with minimal interference in the structure being encouraged. Therefore, finishing the whole design apart from the checks without a proper foundation in calculations and limiting the agency of the FEA engineer is the usual procedure. Any, more significant changes in geometry could require correcting the CAD model and associated with it elements of detailed design. However, this is sometimes unavoidable, and depending on the accuracy of predictions during the early phases, it might happen that large amount of parts in the object have to be changed.

By choosing to perform calculations first, these redesign phases in CAD may be avoided. However, this does not mean forgoing to use past designs as a base for new ones. It is advantageous to have the possibility of using past knowledge and experience as a foundation for new creations. Although, it might be a good practice to first use simplified models and simple parametric models to perform preliminary calculations in FEA before redesigning the CAD model. Thanks to that, the choices made for the detailed design parts can be more accurate and some might not even be required to be recalculated again.

To perform the calculations at early phases of design while utilising the advantage of the design reuse, the following course of action can be taken:

1. state the requirements for the design.
2. Define the object's functionalities and work characteristics.
3. Choose the applicable standard or standards for the design and determine all of the needed checks and calculations.
4. Based on the previous designs, define the critical parts of the object.
5. Calculate the loads and safety coefficients based on standards.
6. Calculate and retrieve the critical dimensions.
7. Based on the results and previous design's prepare a new CAD model.

Thanks to this approach, it is possible to perform calculations before the almost complete design is completed in CAD, while still utilizing the previously acquired knowledge about the object type. Moreover, the risk of changing critical dimensions after hand checks at the last phases of design is minimized. Additionally, choosing all of the standards at the beginning prevents choosing them based on the tools rather than what is recommended in the rules.

4.2.4. Changes to the approach to standards

For the equipment and structures developed by the Marine Design and Engineering Department to be safe and classifiable, it is of an upmost importance that the standards are followed. Some of the problems which were identified did come up because of the approach to following the standards in case of the dredging equipment. By changing this approach to more closely following rules and taking fewer shortcuts could help with the clarity of the design and as a result, make it safer.

Firstly, standards should not be mixed. Standards are designed to be the guidelines based on which the produced object can be operated safely. Whenever an engineer deviates from the rules presented in the standard, there is a possibility that the choices made by him can cause the object to be dangerous. Then it could cause damages to property or in the worst case it can cause injuries or fatalities due to some occurrence unforeseen by an engineer, that might have been considered during the standard preparation. Since, some of the guarantees that the design is safe come from not only explicit safety factors but also from the interaction between all of the choices and calculations in the standard, mixing them freely can prove to be dangerous.

By not mixing different standards, which were not explicitly advised to be used by the rules authors, the problem of determining the safety factors is omitted. When the standards are mixed, especially between different classification societies' rules, it can be hard to determine what safety factors should be used during the calculations. There is no certainty whether the approach is not conservative enough or too conservative. Therefore, all of the decisions must be made in a manner which ensures that a conservative option is chosen every time. This might cause the finished design to be significantly heavier and over-designed or it could still not be safe despite the engineer's presumption that all of the choices made were conservative.

Secondly, it is important to fully follow the chosen standards. Although, it is tempting to take a shortcut and select only the cases and positions which seem to be the most critical, sometimes it might cause unsuspected omission of a few configurations and load cases which might be critical for some parts of an object. Therefore, it is important not to omit the calculations required by standards, even though it might seem that these are not critical. Additionally, it is important to perform all of the calculations according to the standards. For example, the buckling check should not be performed in a manner which is not presented or accepted in the rules.

4.2.5. Improvements in communication

Insufficient communication can frequently make the cooperation between the teams not efficient. Some of the identified problems could be an effect of the issues in communication between the general design department and the engineers who perform the FEA calculations.

The basis of design, loads, load cases and checking criteria for yield calculations are prepared by the general design department. Once these are finished, they are handed over to the engineers preparing the FEA and the CAD modelers. Only then, they receive the information about what type of machine is needed and what are the requirements for it. Therefore, a large amount of information is contained within the team preparing the input data during the most important phases of preparation. Moreover, since neither the modeler nor the FEA calculation team are part of this process, their needs might be not considered. This is especially important for the finite element analysis and calculations of the object in accordance with standards.

Since the input is prepared only with yield check in mind, the criteria for other calculations have to be gathered by the engineers who are performing them. This may lead to a situation in which certain inputs are missing, which are required to check whether the design satisfies newly developed criteria. For example, additional data containing the information of work characteristics of the object, which are relevant for fatigue calculations. Wherever the engineer has to develop the new required input or additional criteria under time pressure, shortcuts might be taken to ensure the timely finish of the project. Therefore, lack of cooperation in the early phases of design and exclusion of the FEA engineers from the input and criteria preparation process may be a contributing factor to the basis of the design missing important input data, containing prescriptions of limited calculations and the final design is created based of a mix of standards.

Additionally, since load cases used as inputs for calculations are supplied as a set of critical conditions with all of the relevant factors are already included, they should be altered for some of the calculations. The currently provided load cases can be described as "ready to go", theoretically the engineer who is performing the FEA could copy them directly into the software and obtain the required results for the yield check. Although, this is the only one of the usually larger array of necessary calculations Bureau Veritas, 2014; De Norske Veritas, 2020, 2021. Different, additional checks might require the engineer to use loads without or with other factors than the supplied (De Norske Veritas, 2020). Then in order for the design to be compliant with the standard, an engineer might have to modify certain load cases, which with the current state of supplied data may be challenging and prone to errors task. Therefore, supplying the loads and factors for load cases separately should be considered. Or an input for the FEA Engineer should consist of all of the required criteria and loads prepared.

4.2.6. Changes in the tool preparation

There are also issues in the tool preparation process that should be addressed. Despite attempts at creating semi-standardised tools, without explicit rules on their creation and documentation requirements, these attempts might be not as successful as anticipated.

Currently, an identified approach to the tool generation is partly standardised, although it is still lacking in terms of the tool documentation. Whenever a standardised tool is being developed it is important that satisfactory amount of documentation is provided with it. Although, it does not have to be as elaborate as in a commercial product. A manual with an explanation of how tools should be used, what is the reasoning behind some of the choices, how are certain values calculated and for which cases should they be used or not with sufficient reasoning, could help to resolve a multitude of problems.

Firstly, by providing a sufficient manual, some risk of errors caused by improper use of the tool by another engineer can be alleviated. Moreover, providing a manual should also resolve the problem of using the tool for some tasks despite the statements that it should not be used for them. This is an important issue, because without sufficient reasoning supporting such statements, some can be tempted to use the tool improperly as a shortcut. A proper explanation of why it should not be done could be a deterring such behaviors.

Secondly, providing documentation explaining the choices and equations which are embedded in the tool could help with its ambiguity. When additional descriptions are not provided, some tools may become a sort of black box which makes it harder to assess the results and interpret them. Moreover, it may cause an engineer to be hesitant to use it. Then they prepare their own tools and use them instead, which is rendering the already prepared tools useless and therefore they become wasted resources.

Additionally, a good documentation allows for the mistakes and errors to be spotted easier. All of the tools which are going to become standard in the department, have to be approved and therefore checked. However, it seems that the current approach is not sufficient to prevent errors and some of the approved tools are not completely correct after the approval. It could be beneficial that the person who is approving the tool for wider use to be supplied also with an additional document. It should be describing the choices which were made during the development and a manual on how to use the tool correctly.

In summary, in order to ensure proper standardisation and efficient use of internally developed standard tools, these should be always provided with documentation. To fulfill its purpose it should include the following:

- general description of the tool - its purpose, functionalities, standards on which it is based,
- explanation of intended uses - what it can and cannot be used for,
- manual - explanation of how it should be used,

- reasoning - explanation of choices, structure and code or calculations.

4.3. Incorporation of FEA post-processing software

Incorporating new tools which offer new functions into any process requires adjustments. Tasks can be approached differently and solutions can be reached dissimilarly from the usual course of action. Therefore, in order to incorporate a new tool in a manner that allows for taking full advantage of its functions, the approach to tasks in several areas of the design and calculation process has to be adjusted. That topic is discussed based on an example of SDC Verifier and current state of the art of design at JDN Marine Design and Engineering Department as an example in this section.

4.3.1. Preparation for calculations

To assess the structural strength of the structure frequently multiple load cases are suggested in the standard. An example of that could be standards for offshore handling appliances prepared by De Norske Veritas (DNV) and Bureau Veritas (BV) (Bureau Veritas, 2014; De Norske Veritas, 2020). Load cases may vary in terms of the type of loads which are applied, the safety factors for the case overall and each individual load, as well as the checking criteria for structural checks. In the aforementioned standard prepared by DNV in Section 4 Table 4-3 safety factor used for the buckling check varies for each of the load cases.

Currently, in the Marine Design and Engineering Department, the combined load cases are prepared by the general design department. In these, all of the loads are already multiplied by the safety factors and individual load factors. These are also structured in a manner which allows for them to be directly transferred into the Ansys Mechanical software with ease. Additionally, the number of load cases is lowered by selecting only some of them, which are considered critical for the yield strength calculations. However, this could be causing problems in incidents such as the aforementioned differences in safety factors specified for buckling calculations. While performing the analysis, each of the time steps in the FEA is one of the load cases. An example of the format of supplied load cases is presented in Figure 4.6, presented table is part of the load cases used for one of the projects.

ULS	Design LC	Description				F_X [kN]	F_Y [kN]	F_Z [kN]	M_X [kNm]	M_Y [kNm]	F_Z* [kN]
ULS-a, SM-01 (G loads dominant)	LC01-A	$+F_X$	$+F_Y$	$-F_Z$	$+F_Z$*	50.490	10.397	-524.181	-8.922	4.036	-472.084
	LC02-A	$-F_X$	$+F_Y$	$-F_Z$	$+F_Z$*	-50.490	10.397	-524.181	-8.922	-4.036	-472.084
	LC03-A	$+F_X$	$-F_Y$	$-F_Z$	$+F_Z$*	50.490	-10.397	-524.181	8.922	4.036	-472.084
	LC04-A	$-F_X$	$-F_Y$	$-F_Z$	$+F_Z$*	-50.490	-10.397	-524.181	8.922	-4.036	-472.084
ULS-a, SM-02 (G loads dominant)	LC05-A	$+F_X$	$+F_Y$	$-F_Z$	$+F_Z$*	14.860	17.069	-524.181	-8.922	4.036	-472.084
	LC06-A	$-F_X$	$+F_Y$	$-F_Z$	$+F_Z$*	-14.860	17.069	-524.181	-8.922	-4.036	-472.084
	LC07-A	$+F_X$	$-F_Y$	$-F_Z$	$+F_Z$*	14.860	-17.069	-524.181	8.922	4.036	-472.084
	LC08-A	$-F_X$	$-F_Y$	$-F_Z$	$+F_Z$*	-14.860	-17.069	-524.181	8.922	-4.036	-472.084

Figure 4.6: Sample of the current format in which the load cases are supplied.

When using SDC Verifier, individual loads without any factors can be applied in Ansys Mechanical. Then these can be combined into the load cases in the post-processing software, where all of the safety factors and load factors can be applied directly. Then, if needed, after the first calculations the "Governing Loads" function can be used to lower the number of the considered load cases for each of the relevant checks. The direct access to the load factors allows for their easier tracking and modifying if needed.

Although, with this approach the structure of the data provided to the FEA Engineers would have to be changed, to resemble the setup of the calculations in SDC Verifier if this tool were to be used. An example simple setup of three different load cases for two configurations of one model is presented in Figure 4.7.

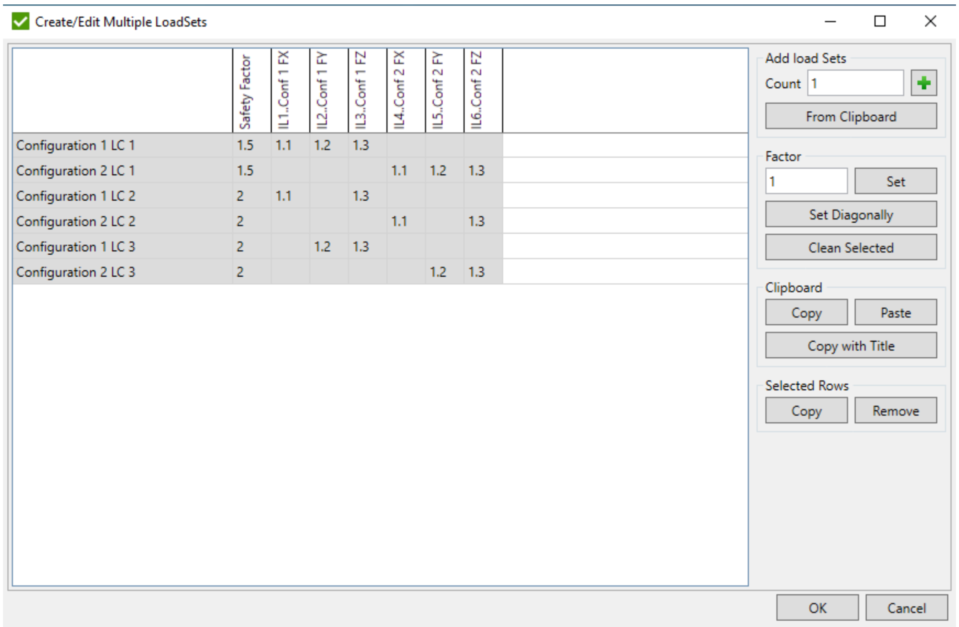

Figure 4.7: Sample setup of few load cases with different loads and safety factors applied in SDC Verifier.

The load cases and load factors could be provided in a spreadsheet as presented in Figure 4.7, since the software offers the possibility of copying the data between spreadsheets and itself. The loads applied to the object would have to be provided separately and ordered accordingly to the load cases and factors. Or they should be linked accordingly to allow the FEA Engineers to easily use them. As mentioned before, if all of the load cases are provided then, tools are available to reduce their number. Otherwise, the number of load cases can still be reduced beforehand but the load cases with factors should still be supplied separately from the loads themselves. Alternatively, it is also possible to continue the current approach with regard to the data supplied by the general design department. Then, however, when is connected to the Ansys Mechanical and the setup of the calculation is performed without changes, the individual loads in the post-processor can be treated as separate load cases. Although, then the tool is not used as efficiently as it could be.

4.3.2. Automatic recognition

One of the largest benefits of using a post-processor or any additional modern tool are its modules and functions which can improve the current process to obtain better results. For the design process, these sometimes also require a specific approach to modeling in order to fully take advantage of them. As an example in SDC Verifier the recognition tools give the user ability to quickly recognise characteristic parts of the meshed model, such as welds, joints, beam sections and members, plate panels. Although, to use them, the early phases of model development should be conducted accordingly.

In order to automate the calculations of one of the aforementioned parts, the model should be prepared with that consideration. This is due to the fact, that software does not support the recognition of characteristic parts between every type of element and every type of contact. As an example, automatic weld recognition capabilities are presented in Figure 4.8 for a model built with shell and solid elements.

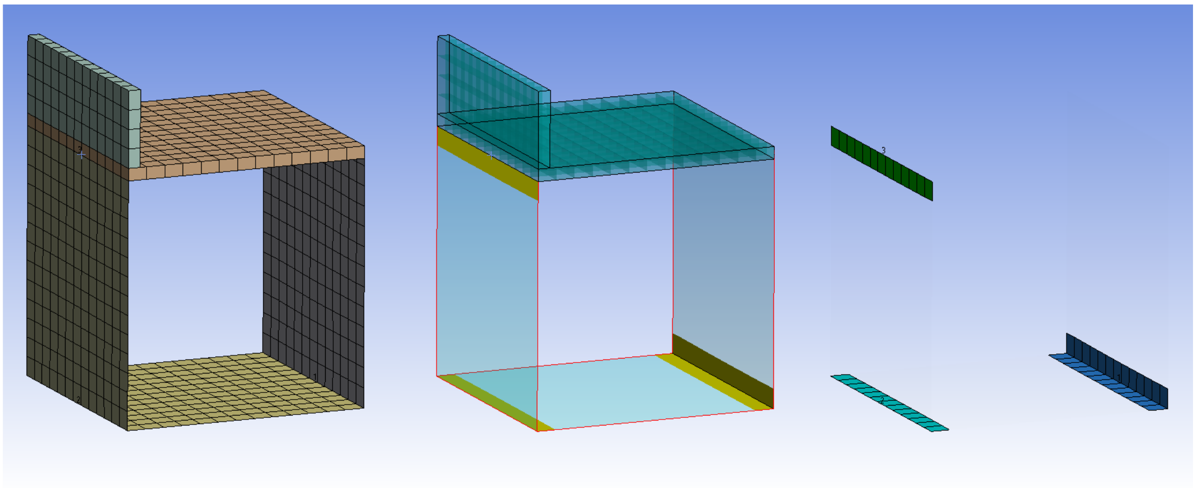

Figure 4.8: Weld recognition with respect to the modeling approach for shell and solid elements.

In this simple model four types of “Bonded Contact” in the Ansys Mechanical and one “Shared Topology” in Space Claim are defined. The three recognised welds are the ones which consist of at least one surface and are appropriately defined. The full results of this test are presented in the Table 4.1. As can be noticed, not all of the ways in which the model is set up allow for recognition of the welds between the elements.

Table 4.1: Automatic weld recognition for model with solid and shell elements in SDC Verifier post processor.

Type of Contact	Contact	Target	Recognition
Bonded	Shell	Solid	Contact elements
Bonded	Shell	Shell	Contact elements
Bonded	Solid	Shell	No
Bonded	Solid	Solid	No
Shared topology	Surface	Surface	All elements of the weld

Moreover, for other recognition processes th3 order of the elements might matter. For example, it is possible to manually add welds which include solid elements to the list of welds in SDC Verifier. However, it is required that the solid elements used to model the object are linear in order if an automatic “Weld Force Summation” tool is to be used. Hence, in order to use some functions of a new integrated software it might be also necessary to adjust the mesh generated for the FEA.

Furthermore, when automatic functions of tools are used, it is essential for the quality of the model to be sufficient. The results of the recognition process may be polluted when there are areas in the model which are poorly modeled. Although, the developers of post-processing software adjust it to the needs of consumers. Sometimes it might not be possible to prepare a perfect model due to time constraints or other issues, then it is possible to adjust the recognition process to omit some results. As an example, “Panel Finder Recognition Settings” window for SDC Verifier is presented in the Figure 4.9. Multiple options are available to filter the results of recognition according to the user’s needs. However, a higher quality model will lead not only to better results for the post-processing tools, but will also produce more reliable results in the FEA analysis.

In conclusion, in order to include a post-processor’s recognition module into the methodology of design it is important to also consider aspects such as the state of a model. The functionalities of the software can be affected by the FEA model which is prepared for the calculations. Not only does the quality of it matters, but also the type of used elements and their order. If in the project at hand the

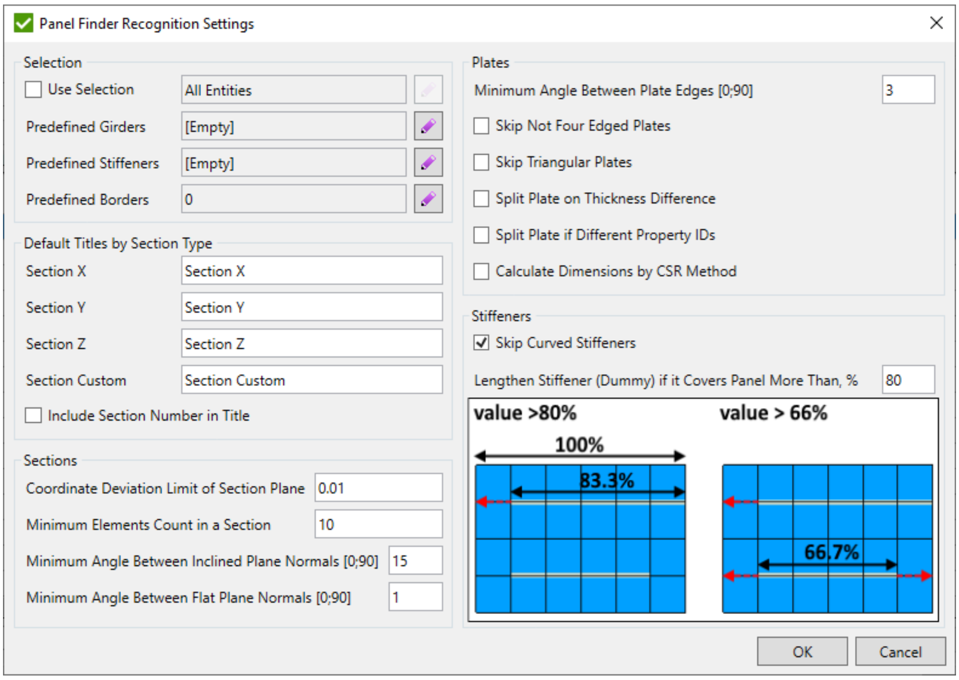

Figure 4.9: Example settings window for an automatic recognition tool.

code checking is supposed to be performed using a post-processor, it should be considered early in the process so that models could be prepared accordingly.

4.3.3. Calculation setup

Another advantage of using a finite element analysis post-processor is the possibility of creating and using templates. As previously, these will be discussed based on an example of SDC Verifier post-processing software. Creating and using templates generates higher potential for creating standard tools and approaches for the design process and FEA calculations in particular. Moreover, these may allow for modifications of the design methodology structure due to the new possibilities of reusing parts or whole previously prepared templates.

For objects for which finite element analysis is involving multiple checks on different levels of detail, or checking multiple concepts for which the setup is similar it is possible to reuse a whole project setup. This is also possible for semi-standard or standard objects for which FEA calculations are performed using the same standards and load cases with different models or concepts of an object. When working with such designs a previously prepared project can be opened parts of the setup may need to be adjusted, these could be the parts of calculations which rely on recognition modules such as, for example, fatigue calculations. In case of fatigue, frequently model details have to be classified based on their effect on fatigue lifetime (De Norske Veritas, 2010b). When the required adjustments are made, the setup can be calculated fully automatically and produce a final report. In this manner, a minimal intervention from an engineer is required to prepare calculations or reporting and their focus can be set on optimizing the design. Thanks to that more optimized designs can be achieved in the lead time which is the same or lower than for the previously produced objects. This type of template use might be highly beneficial for design departments in which partly standardised designs are produced.

Similarly, templates of user prepared calculations, which are not included in the post-processing software can be reused in a design process of multiple different objects. It is possible to prepare standardised calculations, which can be used for checking elements of design in the FEA without a need to transfer the results to a spreadsheet. Moreover, the results of these checks can be directly transferred to an automatically generated report. Thanks to that, time could be saved during the generation of results and reporting compared to the manual approach currently used in Marine Design and Engineering Department. Moreover, whenever changes in requirements occur after the report generation, it is possible to recalculate and generate results for these checks automatically.

Preparation and usage of templates for calculation or whole object design are similar to the development of any other tool. Hence, it should be treated as such. Therefore, sufficient documentation should be prepared for each standardised template in order to make its use more error-proof as suggested in previous sections.

The possibility of using the same model setup for analysis with different levels of detail makes it possible to incorporate a high level of detail early into the design. Thanks to that it might be advantageous to produce all of the loads and load cases for a given machine at the conceptual stage of design since these will be used throughout the whole process. Moreover, no additional setup time will be lost, since all of the data generated for the simplified model can be used for a detailed model. This allows for an increased use of FEA during the concept phase of the design.

4.3.4. Reporting

Reporting is one of the most important phases of the design process. Based on the calculation report and the drawings the classification society decides whether the design will be classified and could be used on a vessel. Therefore, it is important that not only the calculations were correctly performed but also that these are convincing to the engineers verifying the design.

Depending on the post-processor the possibility to explain the structure and reasoning of the calculation may vary. As an example, the options provided by SDC Verifier will be presented and discussed. A full report automatically generated by the post-processor report contains the following elements:

- title page.
- Table of contents.
- Preface - information about the used software, model and project files, report generation time and unit system which is used.
- Model information - mass and bounding coordinates of a model.
- FEM Model Description - summary of materials, summary of properties and summary of FEM Loads.
- Results - results of equivalent stress and displacement for each of the individual loads, loads set and load group. Summary with maximum and minimum values of stress, displacement and reaction forces over the loads and load sets. Additionally, any user-defined results, which were added in the post-processor including standard check results.
- Appendix:
  - Information about each analysis - FEM information, settings and solution information, contents of each individual load, load set and load group.
  - Information about each standard and user defined check - information regarding all of the inputs used for the calculations, all of the formulas used for calculations.

Apart from these, every element which can be defined in the post-processor can be added to a report. These include for example the results produced by post-processing tools such as the peak finder tool or results produced by the recognition modules. However, one of the biggest advantages of a post-processor is the ability to easily assess the designs according to the standards. Therefore, it is important that the information provided in the appendix, regarding the calculations are sufficient to convince the engineer verifying them that they are correct. An example short user-defined calculation code is presented in Figure 4.10.

1..Example standard

This is an example description for this check.

Unit System

Current Unit System = Custom. It is used in calculations for the following standards: API RP 2A, ISO 19902, Norsok N004, DIN 15018, FEM 1.001 and Eurocode3.

Safety Factors

The following checks (1..Static Stress Check) use safety factors from Individual Loads and Load Sets. Overview of safety factors are shown for Load Groups: if all items in Load Group have same factor - single value is shown, otherwise list of factors.

Load Group	Safety Factor
LG1..Envelope (IL)	1

Checks

This paragraph contains checks descriptions with their results.

1..Static Stress Check

Property	Value
Category	Elemental Custom Check
Selection	All Entities
Parameters	3
Alias (Parameter)	**Stress (Stress)**
Description	Parameter used to retrieve stress results
All	S
Alias (Parameter)	**Sallow (Allowable Stress)**
Description	Calculation of allowable stress
All	min(Yield, 0.7 * Tensile) / Load.Sf
XY/YZ/ZX	min(Yield, 0.7 * Tensile) / sqrt(3) / Load.Sf
Alias (Parameter)	**Uf (Utilization Factor)**
Description	Utilization factor calculation
All	Abs(Stress / Sallow)
Overall	Max(me.x, me.y, me.z, me.xy, me.yz, me.zx, me.eqv)

Figure 4.10: Exemplary calculation code summary from a post-processor report.

As it is presented in the figure, the calculations are presented as a table. Each of the calculated parameters has an alias, which is used in the code and a parameter name. Moreover, each calculation can be described according to the user's needs. These could be descriptions explaining the calculations and containing the information on what standard and which equation these are based on. Moreover, for each of the standards, user-defined or provided by the developer, description regarding the safety factors, unit systems and an additional description can be included. Apart from the calculation code, all of the inputs in form of constants, characteristic-based constants, classification-based constants and tables with constants, can be included in the report with their own descriptions.

When provided with sufficient descriptions regarding the calculations and their base, a code report represented in this form could be also used as part of the tool documentation. Thanks to that, time can be saved on providing the reasoning part, general description and explanation of intended uses parts of documentation. Hence, the developer of such tool should only provide an additional manual explaining how to use the tool, if the descriptions were written during the development process.

In comparison to this type of calculation code report, normally the Marine Design and Engineering Department usually presents the calculation report in form of a spreadsheet with parameter titles, values and reference or equations for each of the calculated parts. This is a similar approach to the post-processing software reporting only that the equations and the results are not presented together in the report prepared by the latter. However, this is partly caused by the extensive nature of the calculations. The results can be presented in tables or mapped onto a model in form of a chart. Hence, the code or calculations have to be presented separately.

It should also be considered that the exemple code provided in Figure 4.10 resembles closely basic mathematical equations. Hence, a trained engineer should not have significant problems with following these calculations, especially if sufficient descriptions are provided by the tool developer.

4.4. Structure of the design methodology

The new methodology structure is based on the VDI 2221 design methodology. However, it was modified to incorporate the concepts of integrated design and modern CAE software explicitly in the design process. Moreover, past experience and previous designs are also an important part of the methodology. Its schematic is presented in Figure 4.11.

The new proposed methodology of design is consisting of ten steps and four phases. The phases are following:

- I - Clarification
- II - Conceptual phase
- III - Detailed design
- IV - Production preparation

Each of the phases are comprised of steps. Steps and the results, which should be achieved through them are presented below:

- clarify and define task.
  - Specification.
- Determine functions and their structures.
  - Type of main conversions.
  - Type of auxiliary conversions.
  - Overall function.
  - Sub-functions.
- Select standards.
  - Research standards, find required calculations, loads and load cases.
  - Choose an approach for each calculation.
  - Prepare loads and load cases.
- Search for solution principles and their combinations.

    - Select solutions available in-house and commercially.
    - Type of energy, physical effects and the auxiliary conversions necessary.
    - Active motions, active surfaces, active spaces, type of material.
- Divide into realizable modules.
- Develop concepts with beam model.
    - Simplified model: calculations (hand and FEA), main dimensions, standard, bought and repeat parts, manufacturing methods, joining and fastening procedures.
- Develop detailed assembly.
    - Detailed assembly and part models: individual parts, assemblies, connecting parts, parts list, detailed FEA calculations, hand calculations.
- Final model development.
    - Final assembly, calculation report.
- Production and operation preparation.
    - Production drawings and assemblies.
    - Instructions for commissioning, operation, maintenance, decommissioning.

An important part of the methodology is the fulfillment and adaptation of the requirements. After each of the steps, a meeting should be held between the general design section, the FEA engineer and the CAD engineer to review the results, the requirements and the current state of the project. This approach should cause the cooperation to be more clear since the team members working on the design are up to date at every step of the process. Moreover, they can react early if some aspect of the project needs to be revised for later steps to be performed successfully.

At the end of the design process its assessment should be performed. The performance of methods and the process as a whole need to be evaluated. Based on that, necessary changes can be incorporated into the work for the next design. Thanks to this a feedback loop is created and the methodology may be tuned to the individual needs of an engineer or a company. Moreover, a constant improvement of the process is expected, as it can evolve with factors such as new methods or software, as well as changes in the company policy. Thanks, to the feedback the design process can be always adjusted to the work environment.

As it is illustrated by the arrows, all of the steps can be repeated if needed. Moreover, the inclusion of previous experience, designs and known concepts at each of the design steps allows for a more robust methodology. It is possible to skip a step or greatly shorten the time needed to finish it, by using parts of a previous design or older specifications. Designers, could for example skip parts of the concept development phase if a semi-standard or a standard solution to their problem already exists and it is only necessary to tune it to the specific case. On the other hand, it is also possible to go through a whole design process and develop completely new designs, only based on the engineer's experience.

Additionally, the experiences and relevant parts of the design should be stored for future use. This can be done by creating and maintaining a database where data gathered during previous projects can be accessed by designers. However, it is essential that the data is stored in an efficient and structured manner. Information should be easily accessible and provide sufficient meta information to be understandable and readily available for use.

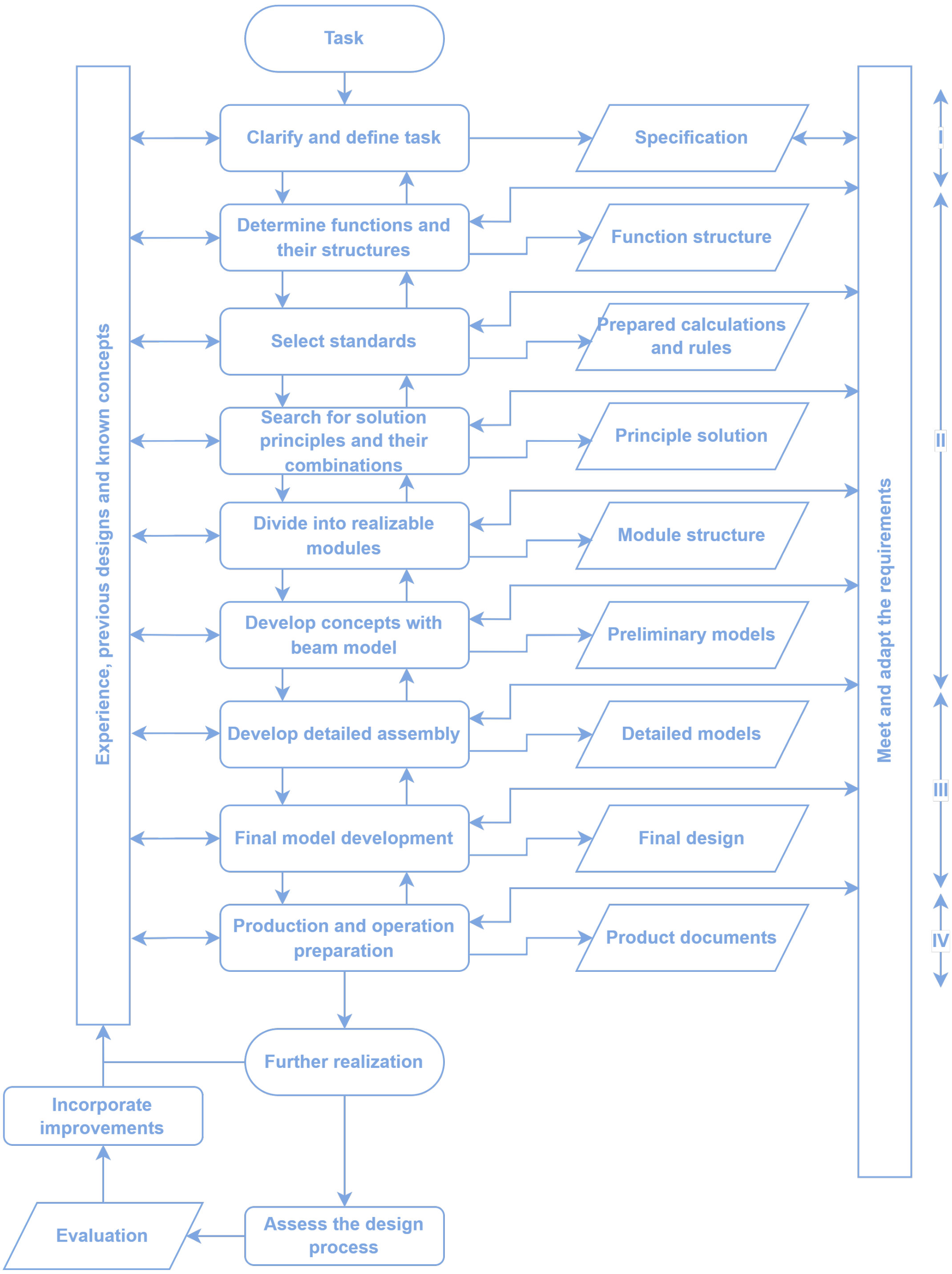

Figure 4.11: Proposed overall structure of the new methodology of design.

5

New design of a draghead gantry

5.1. Introduction

In this chapter the design process of a draghead gantry according to the new methodology of design is presented. First, the input and requirements are presented. Next, each section corresponds to the design process phase as it is presented in the previous chapter. Lastly, the results of the two designs are compared with regard to their mass and safety factors for governing load cases.

It is important to note that the presented verification of methodology ends at the point at which the full calculation report is generated. The 3D modelling of the detailed finished model with all additional parts is not included in either of the designs prepared in this research. This is due to the fact that finite element analysis, calculations and post-processing are the main focus of the study. Preparing the final detailed 3D model would be the same process for both designs and is not relevant to their assessment.

5.2. Input

At the beginning of a design, the methodology states that the task of a new machine should be clarified and defined. As a result, specification is obtained, which can be followed throughout the process. Technical requirements for a draghead gantry are presented in Table 5.1.

Table 5.1: Technical requirements for the draghead gantry.

Requirement	Value
Safe working load	44 tonnes
Reach	$\pm$ 6673 mm
Tumbler range of motion	36^o
Design life	40 years
Number of work cycles per day	5
Predicted down time per year	20%
Steel	S355

The safe working load is the marking on the gantry and corresponds to the reaction force that is exerted on the front sheave wheel by the empty suction pipe hanging above the water. Reach is a distance between the vertical wire rope supporting the pipe and the pivot point of the crane in the out position. The horizontal range of motion is double the angle between the wire rope and the vertical axis normal to the deck of the vessel while the suction pipe is in the lowest dredging position. Predicted design life is 40 years of continuous operation with 5 cycles of work per day, with 20% down time each year.

Additionally, for the design to be compatible with the hopper dredger, vessel's characteristics should be considered. Vessel's main dimensions are presented in Table 5.2.

Table 5.2: Vessel's parameters.

Parameter	Value
Length overall	139 m
Length waterline	128.4 m
Depth	11.3 m
Moulded waterline breadth	33 m
Draught "15 miles"	7.5 m
Draught "8 miles"	8.15 m
Draught "International"	6.10 m

5.2.1. Function structure

The second task, which should be performed is the determination of functions and their structures for the machine. In this design, the knowledge from previous experiences and past designs is used and the step is essentially skipped. This is due to the fact that an already finished design of this type of equipment is available and that large changes in the functionalities or the overall structure is not needed at the moment. Therefore, the conceptual part of the design process is limited in this case.

5.3. Standards Selection

Next, according to the new methodology of design, standards are selected to suit the classification needs and the design characteristics. A list of standards used in the design process is presented in Table 5.3.

Table 5.3: Standards used in the design process.

Standard	Title
DNVGL-ST-0378	Offshore and platform lifting appliances
DNV-RP-N201	Lifting appliances used in subsea operations
DNVGL-RU-SHIP Pt.3 Ch.4	Rules for the Classification: Ships
DNVGL-CG-0127	Finite Element Analysis
F.E.M. 1.001	Rules for the design of hoisting appliances
EN 1993	Design of steel structures
EN 13001-3-1	Cranes - General Design - Part 3-1: Limit States and proof competence of steel structure

The main standard used for the design is the "DNVGL-ST-0378 Offshore and platform lifting appliances" with supporting "DNV-RP-N201 Lifting appliances used in subsea operations". The rest of the standards are either allowed to be used or suggested to be used directly by these standards. Hence, the finished design should be safe, since the classification rules are followed strictly.

5.3.1. Loads acting on the gantry

The design of the gantry is based on the DNVGL-ST-0378 standard. The loads which are considered according to the standard are the following:

- Loads due to dead weight of the components (S_G).
- Loads due to working load (S_L).
- Loads due to prestressing.
- Loads due to operational motions.
- Loads due to motion of the vessel (S_M).
- Loads due to wind (S_W).

Loads due to dead weight of the components
Loads due to the dead weight of the components are taken into account in the FEA model. The density of material is adjusted to incorporate the mass of the missing equipment.

Loads due to working load
The load due to working loads is the static load exerted on the structure by the weight of all of the lifted weight, including any additional equipment. This load is taken as equal to the safe working load of 43 tonnes. The safe working load has been developed based on the vertical reaction force of the suction pipe acting on the gantry in positions under and above the water. Therefore it complies with the requirements presented in DNV-RP-N201.

Loads due to prestressing
Loads due to prestressing in this design are only applicable to bolt connections. Prestressing loads are applied to bolts in FEA software according to the requirements stated in F.E.M. 1.001 standard, as suggested in DNVGL-ST-0378.

Loads due to operational motions
Vertical loads due to the operational motions are taken into account by multiplying the static vertical working load by the dynamic amplification factor φ. The dynamic factor is taken as $\varphi = 1.7$ according to rules presented in DNV-RP-N201 for lifting appliances used in subsea operations in the simplified approach.

Loads due to motions of the vessel
Loads due to motions of the vessel are calculated according to DNVGL-RU-SHIP Pt. 3 Ch. 4 Sec. 3 as required by DNVGL-ST-0378. Loads for three different draught depths were calculated. Moreover, in coherence with the design reuse philosophy, an older design was used to find the centre of mass of a draghead gantry required for calculations. The loads considered in this case are accidental and appear with a probability of 10^{-8}.

Loads due to wind
Load due to the wind is calculated according to the Appendix A of DNVGL-ST-0378. Out of service load wind pressure is considered for the critical condition when the gantry is in the upwards position and the hopper of the vessel is empty. The same conditions are applied to the working load wind pressure calculation.

5.3.2. Load Cases

Loads are arranged into three load cases, which are the following:

- Case I - crane working without wind.
- Case II - crane working with wind.
- Case III - crane subjected to exceptional loading.

Case I

In this case, loads which occur during normal operation are applied to the crane. In this design these are the crane's weight, the working load and the loads due to vertical operational motions:

$$S_G + \varphi \cdot S_L.$$

Moreover, since the crane is to be mounted on a vessel, trim and heel are taken into account for the weight and working load components. The safety factor for loads in this load case is 1.5.

Case II

In this case loads which occur during the normal operation with wind are applied to the crane. In this design these are the crane's weight, the working load, the loads due to vertical motion and the wind loads:

$$S_G + \varphi \cdot S_L + S_W.$$

Due to wind, the S_G and S_L are corrected to adjust for increased values of trim and heel of the vessel in these conditions. The safety factor for loads in this load case is 1.33.

Case III

In this case accidental and occasional loads are considered apart from the usual ones. In this design these are loads due to the weight of the crane, the loads due to motions of the vessel and the out of operation wind load. Two cases presented in the standard are considered:

- IIIa:

$$S_G + S_L,$$

- IIIb:

$$S_G + S_M + S_{Wmax}.$$

The loads S_G and S_L are considered for the maximum rolling and pitching angles, with inclusion of initial trim and list of the vessel. The safety factor for loads in this load case is 1.10.

For each of the presented load cases, multiple load combinations have to be applied to the model. These are permutations of loads acting in various directions or with various intensity.

5.3.3. Calculated Loads

The gantry calculations are supposed to be performed in the most critical position. However, this can be different for different parts of the machine. Hence, the calculations are performed for multiple positions of the crane, to account for that. This also has an effect on the load calculations, since it is necessary to consider more loading scenarios. Based on standards, requirements and gantry positions the loads are calculated.

In this design, it is possible to do this early, when the structure of the machine is known at this stage. However, for other designs, where the simple or approximate structure is not known beforehand, it might be necessary to first perform tasks further down the methodology structure and come back to this step later.

The results of load calculations are presented in the tables in Appendix G. The loads presented in the appendix are presented without the safety factors, which are set in the SDC Verifier.

5.4. Principle solution and the realisable modules

The next two steps are also influenced by the use of previous designs and knowledge. Since the drag-head gantry crane is a semi-standardised type of equipment, the principle solution which was going to be used was known from the start. Hence, it is not required to redo this step of the methodology. The solution which is universally used on the dredging ships in the company has the following characteristics:

- the main structure of a gantry is an A-frame,
- the suction pipe is lifted and lowered with a winch and steel cable,
- the main motion of an A-frame is partial rotation around the pivot point,
- the rotation is caused by a linear motion of a hydraulic cylinder,
- the outer sheave of a gantry is mounted on a tumbler which can rotate.

The principle solution is therefore known from the beginning. Regarding the division into the realisable modules, the beam model will only consider the A-frame, while later the final model will consist of the whole gantry without the standard equipment parts, such as bearings, sheaves, pins, axles and detailed cylinder model. For this project, the calculations are divided into four parts, with specific results expected after each of them. These are the following:

- Hand Calculations I - the parts in a direct load path,
  - wire rope,
  - sheaves,
  - sheave axles,
  - tumbler axle.
- FEA Calculations I - beam model of an A-frame,
  - A-frame geometry design - static stress check, cripple check, fatigue check,
  - cylinder design - force retrieval,
  - pivot design - force retrieval.
- Hand Calculations II - calculations based on the beam model,
  - cylinder and its mounting points design,
  - pivot design.
- FEA Calculations II - detailed model calculations of the whole gantry,

- static stress check,
- plate buckling check,
- fatigue check,
- weld strength check,
- bolt check.

At the beginning the parts which are affected by the working load directly, and which can be therefore easily calculated at the beginning. First, wire rope is calculated and based on dimensions, the sheaves can be chosen from a catalogue. Then the sheave axles and their mounting points can be calculated and dimensioned to comply with standards. Based on the sheaves and pins dimensions, it is then possible to redesign the tumbler to fit these newly chosen parts. Based on the new geometry and the loads, the tumbler axle and its mounting points can be calculated and dimensioned in compliance with the rules. Based on the new geometry of the tumbler and the sheaves dimensions, the geometry of the A-frame and positioning of the sheave in the fixed part and the cylinder is defined. Moreover, the cylinder lengths at different gantry positions are checked against the possible options in the catalogues.

Then, a beam model of an A-frame is modelled and iterative design is performed to find the base for the geometry of the A-frame in the detailed model. Several checks are performed using the FEA software and the post processor to optimize the design according to the standards. Additionally, the reaction forces in the cylinder and the pivot are retrieved. Once the beam model is optimised and the aforementioned reaction force values are retrieved, a second part of hand calculations is performed.

The second hand calculations part is based on the information obtained from the beam model. The cylinder is chosen from the catalogue to match the required specifications of length and operating forces. Moreover, the eye plates and pins used to mount the cylinder are calculated according to the standard. Similarly, the dimensions of the pivot shaft, the bearings and the bearing housing are designed to suit the requirements. For this design, it was stated that for the pivot plain bearings should be used, and replacement parts should not be costly. Therefore, this part of a design was optimised for cost rather than weight.

After, that the detailed FEA model of a gantry is created based on all of the previous calculations and previous designs. Next, the final calculations can be performed and the gantry is iteratively designed and recalculated to comply with the requirements stated in the standards.

5.5. Developing concept

First, the required wire rope is chosen from the catalogue according to the requirements stated in the Based on that, a 6x36 IWRC galvanised steel wire rope with a breaking load of 2510 kN is chosen.

The rope is chosen based on the criteria presented in the DNVGL-ST-0378 Section 5.2.5. (De Norske Veritas, 2020). The breaking load of the rope should fulfill the following criteria:

$$B > S \cdot S_F, \tag{5.1}$$

where, S is the working load and S_F is a safety factor, which was calculated to be 4.38 in this case.

For sheaves the criteria regarding the relation between the wire rope diameter and the sheave diameter are specified in DNVGL-ST-0378 Section 5.2.7.1. According to the rules sheaves diameter must satisfy the following criteria:

$$D > 18 \cdot d, \tag{5.2}$$

where d is the wire rope diameter. Based on that relation, a welded sheave with a diameter of 1380 mm is chosen from the catalogue.

Then, the sheave axles and the eye plates in which they fit are calculated according to the EN 13001-3-1 Section 5. Based on the obtained axle dimensions and the required eye plate dimensions, the tumbler's geometry is modified to fit the new sheave. The resulting model is presented in Figure 5.1.

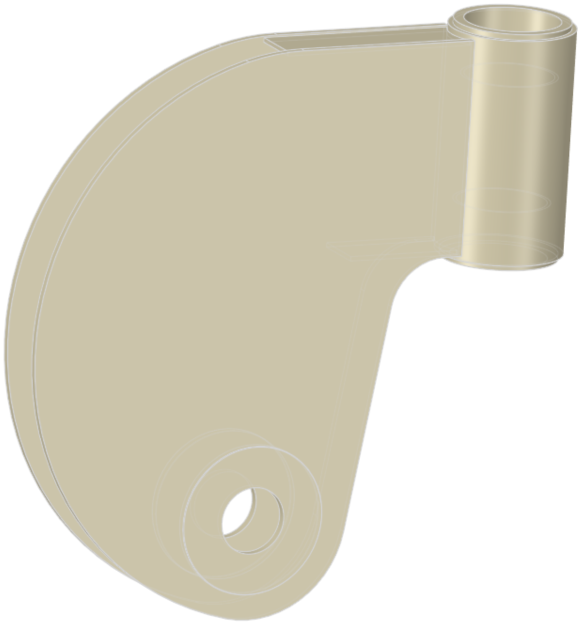

Figure 5.1: The new tumbler modelled according to the calculated and chosen dimensions.

Based on this design, the position of the tumbler axle in relation to the sheave mounting points can be determined. Thanks to that the required axle diameter is calculated by hand to the EN 13001-3-1. Then plain bearings on which the tumbler is mounted on the axle are chosen according to the required dimensions and the force that has to be transmitted from the tumbler to the axle.

Then, a beam model of an A-frame is prepared which suits the required geometry. The model is based both on the current requirements and the previous designs. In order to prepare the geometry, find the angles at which the working load will be acting on the sheaves and what are the required lengths of the cylinder at each position, a simple 2D parametric drawing was prepared. Two of eight of the positions prepared are presented in Figures 5.2 and 5.3.

After developing this simple 2D geometry, a beam model is developed based of it. The following calculations are performed for all of the load cases for the crane in eight different positions:

- static stress check according to DNVGL-ST-0378,
- cripple check according to NEN 2018 and NEN 2019,
- conservative fatigue check according to FEM 1.001.

The calculations of the cripple check require using the beam member finder tool included in the package. The recognised beams could then be used for calculating the crippling force of the A-frame parts, according to the NEN 2018 and NEN 2019 which calculation is included in SDC Verifier's library. While,

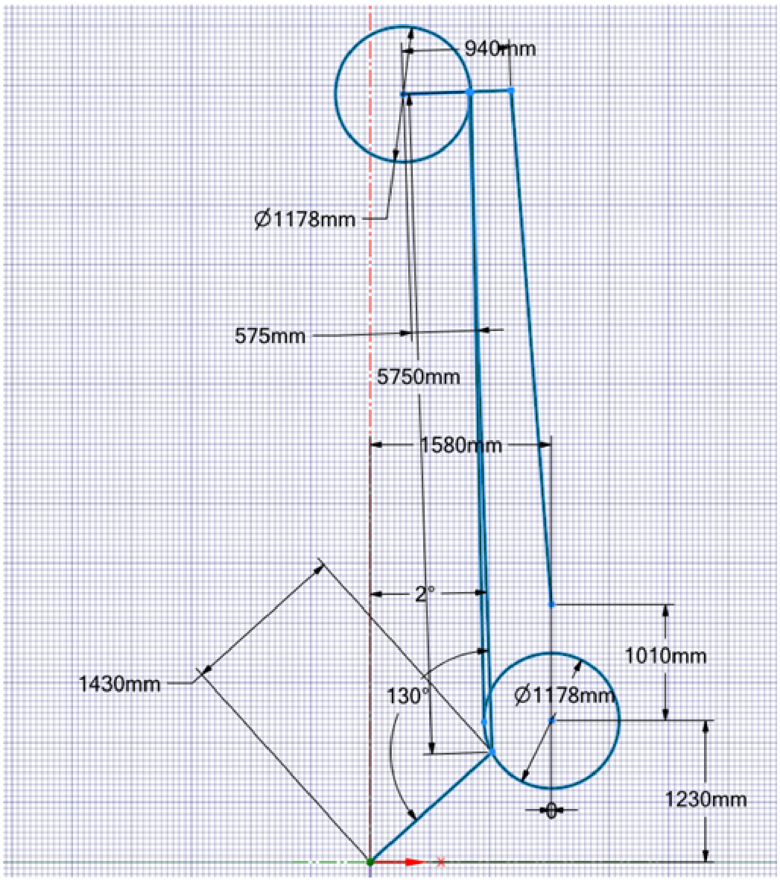

Figure 5.2: The upright position of the gantry schematic.

the static stress check has to be manually programmed, since DNVGL-ST-0378 is not available as a pre-set standard in this software.

However, before calculations can be performed any additional input required by standards, which is not recognised automatically by the software has to be manually chosen. For example, for cripple check calculations, the length and cross-sections of the beams are automatically recognised. On the other hand, in order to perform fatigue calculations according to FEM 1.001, information such as the class of utilization of a machine and the class of welds used to have to be provided manually to the software based on the engineer's assessment and the structure characteristics.

The positioning of a gantry was managed using a modified thermal expansion coefficient of the cylinder beam. By changing this coefficient and applying specific temperature conditions to the beam all of the calculations could be performed using only one model, which position can change during the simulation.

Additionally, the results of the axial force in the cylinder and the reaction force acting on the pivot are retrieved. The calculations are preformed using previously calculated loads. The mass of the A-frame is adjusted to account for the components which are missing from the model. The beam model geometry is optimised according to the used standards and then a report is generated. The sample of results of the three aforementioned checks are presented in Figures 5.4, 5.5 and 5.6, the results of cripple check and the static stress check are presented only for load case 2, since it is the governing condition. The fatigue damage is calculated for the Load Case 1 according to the DNVGL-ST-0378 and FEM 1.001. The result plots are prepared, and the results of the checks are calculated using

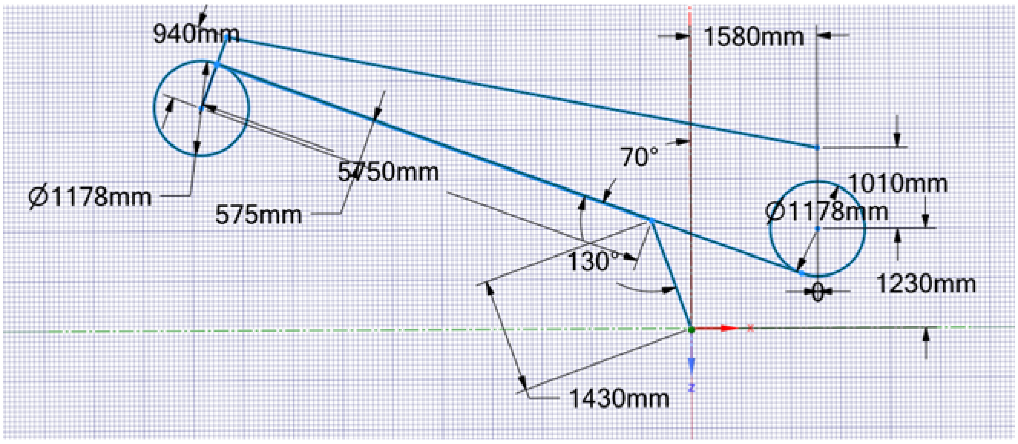

Figure 5.3: The out-most position of the gantry schematic.

SDC Verifier post processor and Ansys Mechanical. In Ansys Mechanical, only one individual load is applied to the model at each step, then these are composed into load sets with applicable factors in SDC Verifier.

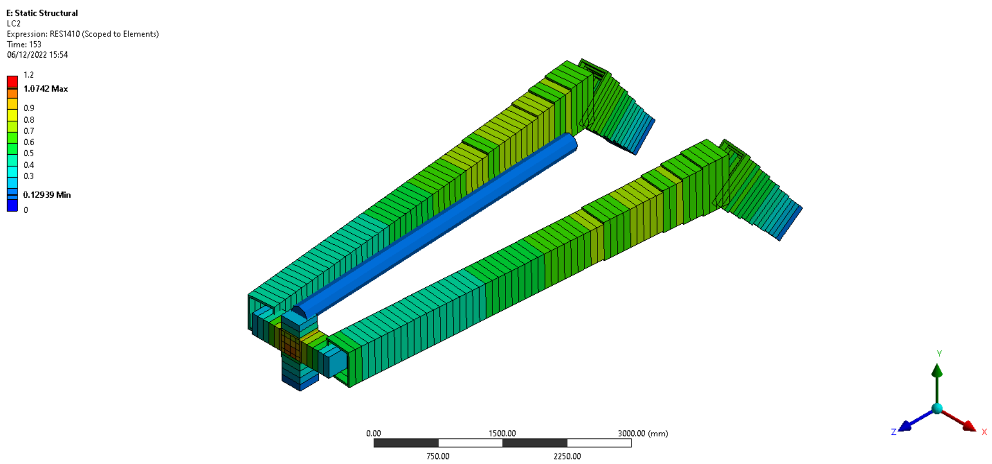

Figure 5.4: The results of static stress check for load case 2.

Based on the retrieved force results, the cylinder is chosen from the catalogue. The cylinder is Rexroth Bosch luffing cylinder Rexroth, Retrieved 2022 with a 450 mm bore diameter and 250 mm piston rod diameter, operating with a pressure of 350 bar. Based on this choice and the axial force, the mounting eye plates and pins were calculated according to EN 13001-3-1 Section 5 standard.

The pivot shaft and the bearing housings from a previous design are modified in order for the bearing pressure to be lowered to the value at which plain wrapped bronze bearing can be used. The values of pressure for the bearings are based on the information from THN company bearings catalogue (THN, Retrieved 2022).

To sum up, the following elements are redesigned in this phase:

- the A-frame geometry,
- the tumbler,
- the eye plates,

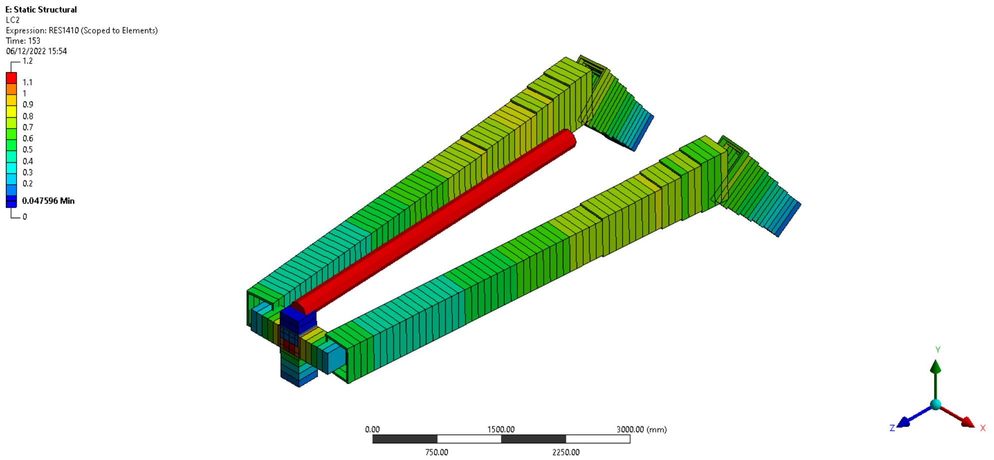

Figure 5.5: The results of cripple check for load case 2.

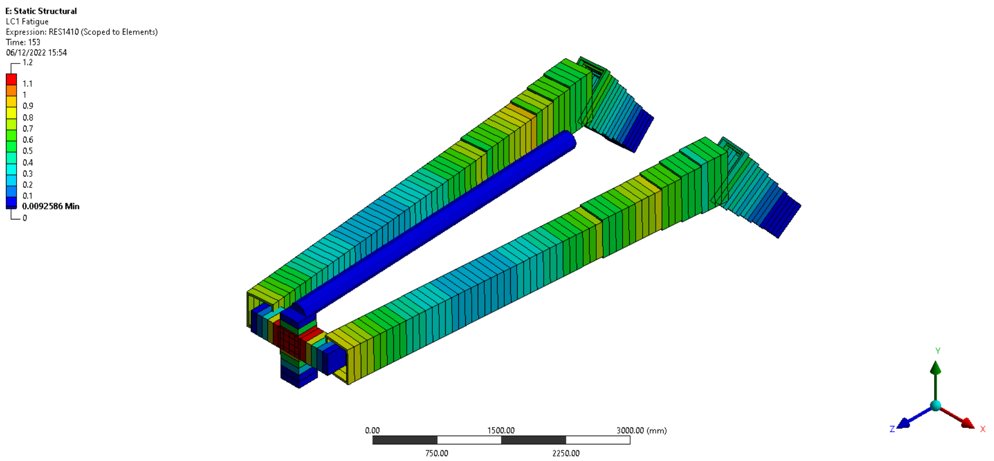

Figure 5.6: The results of fatigue check.

- the pivot shaft with cooperating parts,
- the cylinder,
- all of the pins and axles.

The knowledge of the dimensions and shape of these elements, with the use of an older similar design can be now used to produce a detailed FEA model. First, a 3D model of the gantry is modified to incorporate all of the required changes in geometry. This 3D model is presented in Figure 5.7.

5.6. Developing detailed assembly

The 3D solid model developed in the previous phase is now converted to a shell model using the SpaceClaim software integrated in Ansys Workbench. Although, some parts are kept solid to better represent their behaviour during the FEA calculations. Additionally, the cylinder and all of the bolts are modelled as beams. These include the bolts in the deck mount and the bolts which are used to connect the pivot bearing housings. Moreover, a plate simulating part of the deck is added for a better representation of the flange to deck connection. The Figures 5.8,5.9 and 5.10 present the surface model as prepared in Space Claim and the aforementioned bolts and cylinder.

After this preparation the model is transferred to Ansys Mechanical, where the model is meshed and the individual loads are applied. Since the model is more detailed than the beam model, the number of positions in which the calculations are performed is lowered to five to lower the calculation times. The meshed model is presented in Figure 5.11.

To complete the model, revolute joints are defined between the pivot shaft and the bearing housings and between the cylinder mounts and the cylinder. Moreover, a special joint is defined between the tumbler and the two plates used to lock the axle. The tumbler is normally, rotating around the axle, and its translation in the rotation axis locked by the lower plate. Therefore, the joint between the upper plate and the tumbler is defined as a fixed joint with free translation in one axis, while the joint between the lower plate and the tumbler is a fixed joint. Moreover, due to problems with calculations, the cylinder is split into two beams and translational joint is introduced instead of the previously used thermal expansion method to allow for calculations in multiple positions. All of the joints in the model are presented in Figure 5.12.

After, setting up the model for calculations in Ansys Mechanical, a first small analysis is performed to check if the model behaves as intended. Next, the mistakes are corrected.

Before, the first full calculation, all of the checks required by standards are set up using SDC Verifier. These are the following:

- static stress check according to DNVGL-ST-0378,
- plate buckling check according to DNVGL-ST-0378,
- fatigue check according to FEM 1.001,
- weld strength check according to EN 1993-1-8,
- bolt check according to EN 1993-1-8.

After, the setup for all of these calculations is completed, the full Ansys Mechanical and SDC Verifier calculations are run.

The bolt check is important due to the need to modify and re-mesh the model every time the bolt diameter is changed. Therefore, a priority is set on optimising the bolt connections first, because every time the mesh is updated, welds have to be recognised again and both fatigue calculation and the weld strength calculation setup have to be updated. In the second iteration of calculations all of the bolts were fulfilling the requirements stated in the standard, this allowed for some additional time savings during this phase of design.

Setting up calculations is different depending on the check which is supposed to be calculated and depends both on the requirements set in the specific rules and the characteristics of SDC Verifier. For the weld check, the setup involves using the recognition module to recognise the welds in the model, then the recognised welds are inspected and all of the wrongly recognised welds are corrected. After that, the throat size of each weld fillet weld is set according to the requirements presented in Table 5.4, based on the company's design method.

For fatigue check, in this case according to FEM 1.001, the class of utilization for the machine and weld types has to be set. For this design considering the number of cycles and the load spectrum, the class of utilization is set to E2. The weld types in the model are presented in Figure 5.13.

After multiple iterations of calculations in Ansys Mechanical and SDC Verifier, the final optimised model is reached. The results of calculations can be found in Appendix C. Most of the plots and tables are presenting utilization factor values, these are calculated as actual force or stress divided by the

Table 5.4: Weld throat size for double sided continuous fillet welds depending on the abutting plate's thickness.

Plate thickness [mm]	Throat size [mm]
≤5	3
≤8	3.5
≤10	4
≤12	5
≤15	6
≤16	7
≤20	8
≤25	10

allowable value calculated according to the standard. For Load Case 2 in the buckling check, one of the elements is not fulfilling this condition, however it is treated as a local outlier and was not considered in the final analysis. The final weight of the new gantry, after optimization is 21657.5 kg.

When the optimization is finished and the final optimized model is produced, a calculation report is generated. First, it is prepared to be generated automatically by SDC Verifier and then it is generated and assessed. Mistakes in the setup are corrected and the final report can be generated. This project has been finished at that step. However, during the normal development process, based on the calculation report and the already prepared 3D model, a final CAD model and drawings should be prepared to finish the design.

5.7. Results Comparison

To compare the two designs, one produced using the old methodology of design and one using the new one, mass of both is compared. However, since different standards and parameters were used for the calculations, the safety factors on the working load are going to be assessed for the governing cases. For both designs, the governing case is Load Case 2 and the load combinations which are included in it. The comparison between the mass of the models and the factors is presented in Table 5.5.

Table 5.5: Design results comparison.

	Old design methodology	New design methodology	Ratio
Safety factor	0.96 (very fine mesh)	1.33	-
Dynamic amplification factor	1.35	1.70	-
Duty factor	1.06	-	-
Factors overall	1.37	2.26	1.65
Mass [t]	13.3	21.7	1.62

Based on the results presented in the table, it can be noticed that the design which was produced using the new methodology is heavier. However, factors applied to the main working load are 1.65 times higher than in case of the first design, while the ratio between the mass is equal to 1.62. Therefore, using the new methodology, a slightly more efficient structure was obtained. On the other hand, the dynamic factor of 1.7 is very high compared to the previously used factor of 1.35. It might be beneficial to perform research or calculations to find the real dynamic factor which should be used for trailing suction hopper dredger gantries.

Figure 5.7: Detailed 3D model of the new gantry.

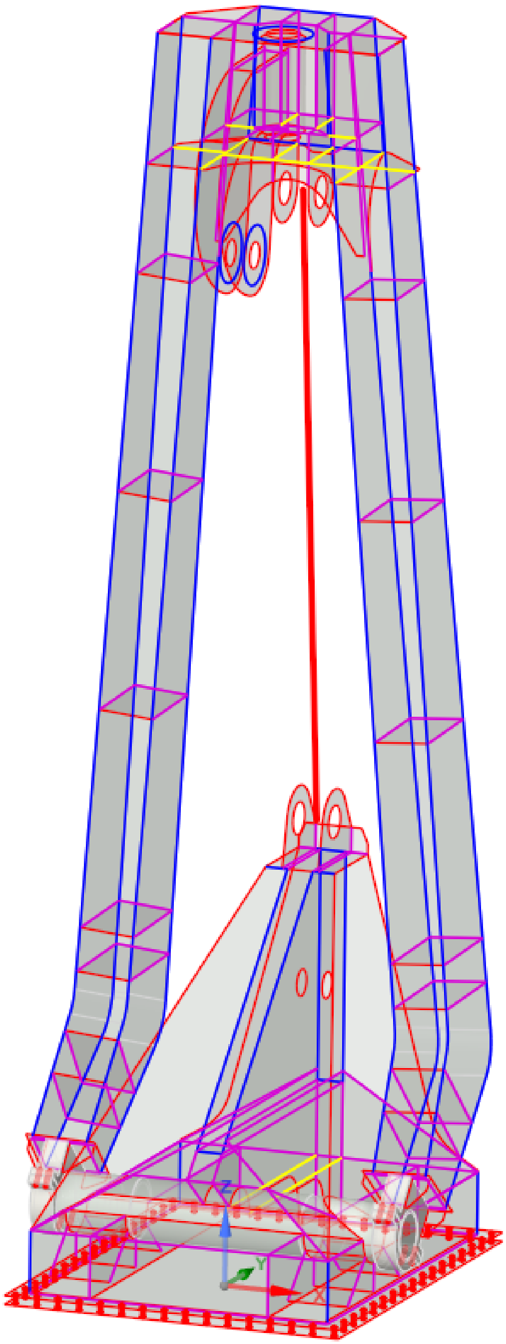

Figure 5.8: The surface model prepared in Space Claim software using the new 3D model.

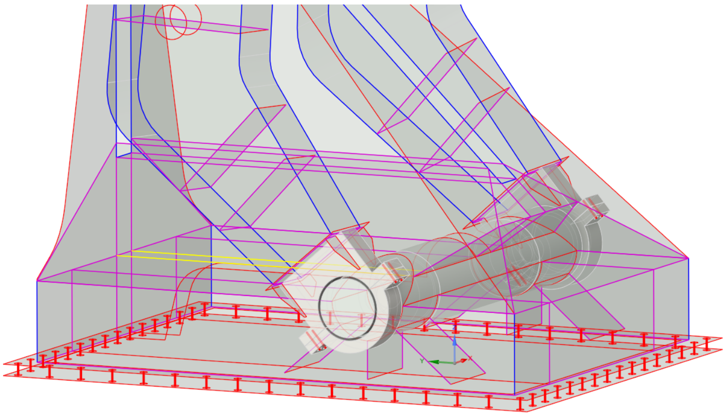

Figure 5.9: Fixed part of a gantry with flange to deck connection.

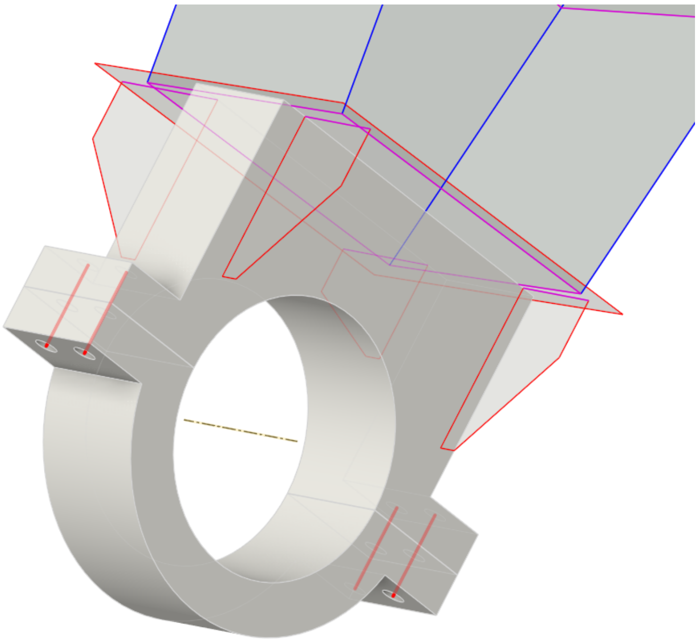

Figure 5.10: Pivot bearing housing connected by bolts, modelled as beams.

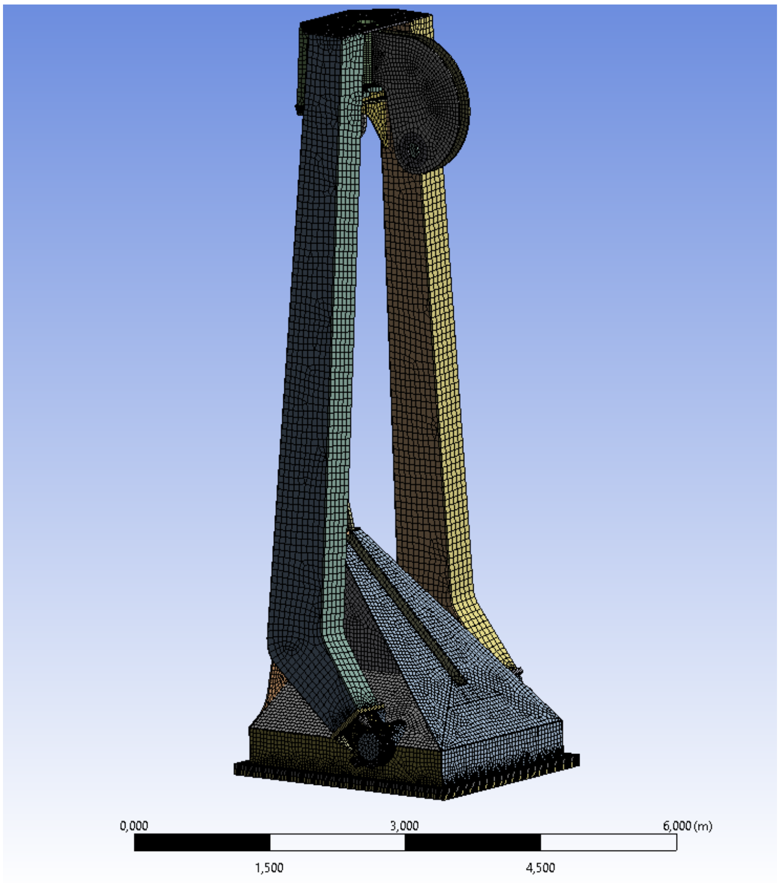

Figure 5.11: Meshed model of the draghead gantry, used in FEA.

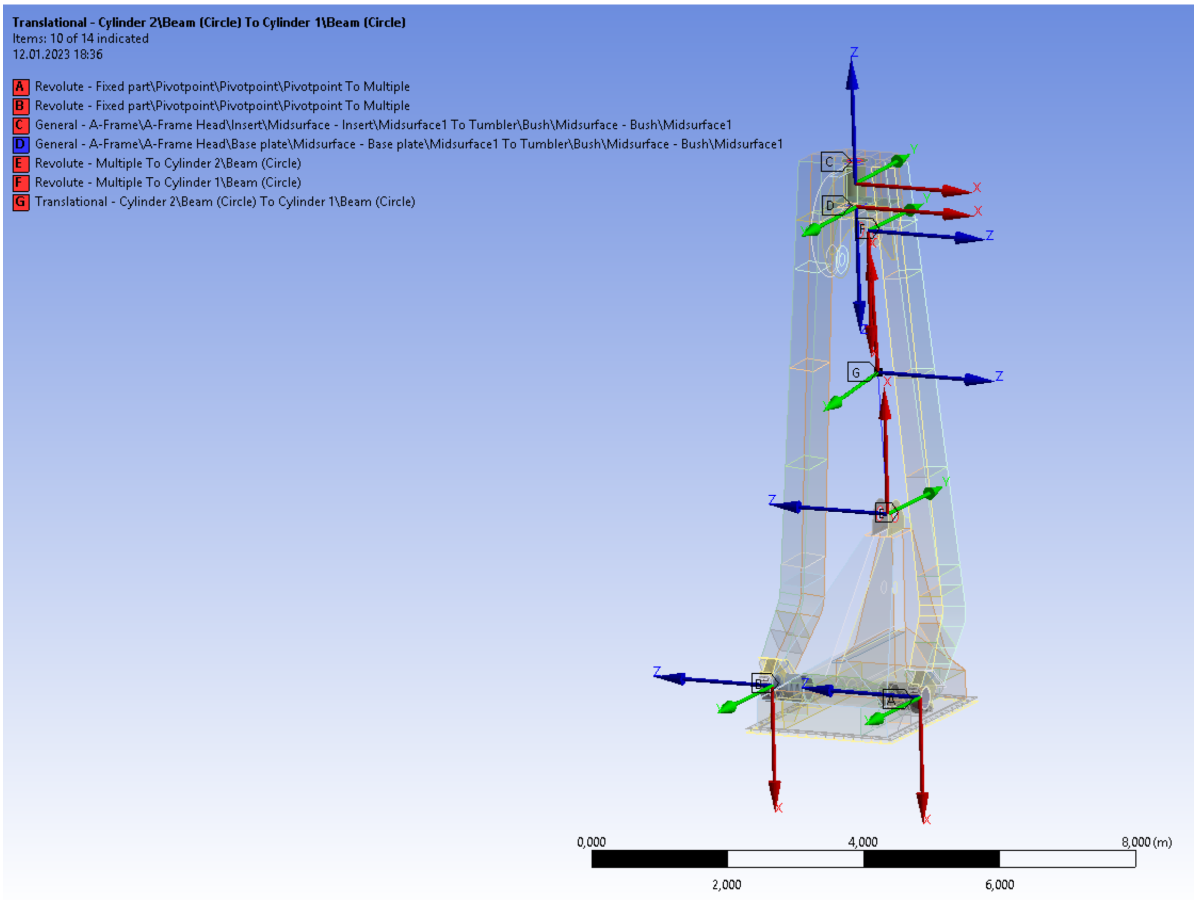

Figure 5.12: Joints in the model.

Property	Value
Type	**Classification**
Alias	**Weld Type**
Selections	**4**
All Entities	**W0**
Component '1..Full Penetration Welds'	**K1 (All Directions)**
Component '2..Fillet Welds'	**K3 (All Directions)**
Named Selection '1823..Fixed Part Flange'	**W1 (All Directions)**

Figure 5.13: Weld types set for fatigue calculations.

6

Evaluation of the new methodology

6.1. Introduction

In this chapter the effects of the new methodology on the design process are presented. First, the time summaries for both methodologies of design are presented. Then, the effectiveness of the post-processing software is assessed in comparison to hand calculations. Next, the benefits and drawbacks of using post-processing software are presented. Lastly, the benefits and drawbacks of the new methodology of design are discussed.

6.2. Assessment of the new design process effectiveness

The effectiveness of the new methodology is measured against the baseline, which is the old methodology of design at Jan De Nul Marine Design and Engineering Department. Figure 6.1, presents the distribution of time in a project realized using the old methodology of design. While in Figure 6.2 the distribution of time in the process performed with the new methodology of design is presented. The values are summarised times of each category of work performed during the design process.

The largest amount of time during the work with the old methodology was spent on performing the hand calculations. These included:

- cylinder,
- pins,
- wire rope and sheaves,
- bolts,
- hinges and pad eyes.

A considerable portion of the time was spent on trying to use the pre-prepared calculation sheets which were normally used for the calculations, checking if the results are correct and preparing new ones. This is due to the fact that some of them would be prepared without sufficient explanations or intrinsic assumptions with parts of the required calculations left out. Therefore, a lot of time was spent on researching and altering the already existing solutions.

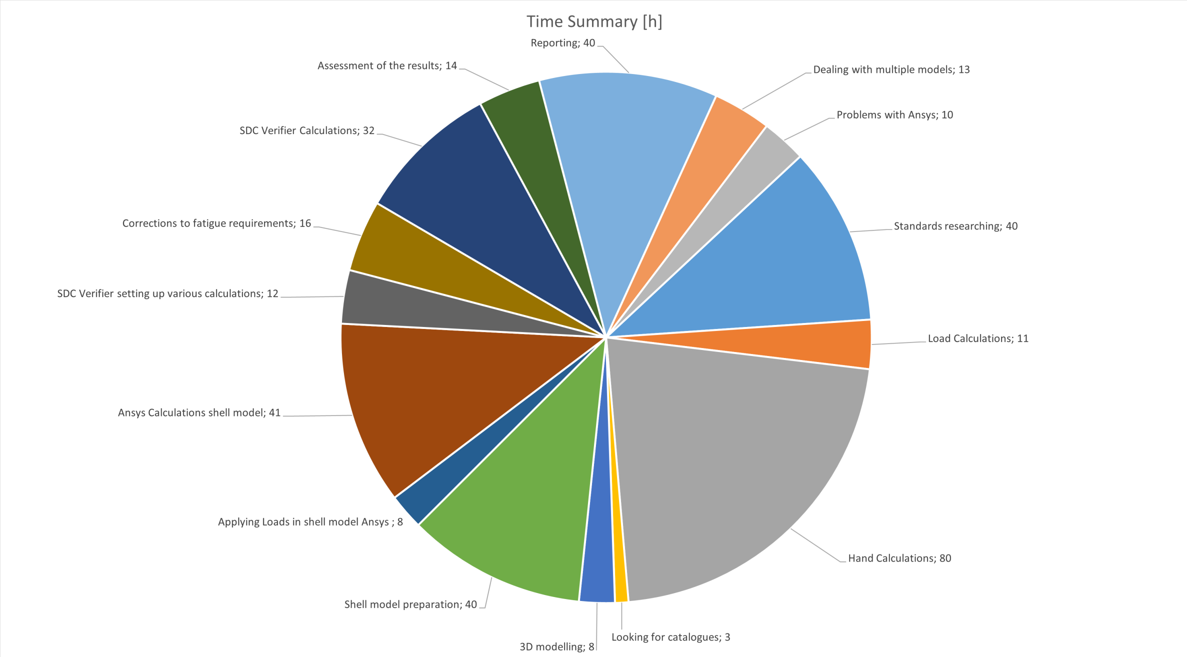

Figure 6.1: The time distribution among tasks in the design process using the old methodology of design.

The second biggest section of the chart is time of Ansys calculations. Both FEA and the SDC Verifier calculations also took considerable time during the first design. This is partly caused by working with multiple models but is also affected by the change of the requirements with regard to fatigue late into the design process. Apart from additional calculations, sixteen hours were spent on finding out the correct fatigue requirements for the gantry and trial calculations. However, a limited experience of an author might have also affected these results. The setup time for SDC Verifier calculations in summary is twelve hours, although it can be attributed to the same reasons.

Another large portion of the pie chart is the summary of time spent researching the standards. This type of activities took a considerable amount of time due to several reasons. Firstly, the basis of design did not specify the standards which should be used for further calculations. Secondly, after the standards for further checks were specified comparisons between the safety factors had to be made in order to try to ensure the safety of the design.

Significant portion of time was also spent preparing the shell model of a gantry. This involves converting the 3D model to the surface model, meshing and defining the constraints in the model. However, this time is prolonged due to the initial unfamiliarity with the draghead gantry model and its design characteristics. Moreover, as in the case with the summed calculation times, this may have been affected by the limited experience the author had with the software.

Other part of the design process on which a large portion of time was spent, was reporting. For the report the results were generated using SDC Verifier module but the report itself was manually wrote basing of a sample report for a different design.

Some time was also lost due to working with three separate models. This is due to the fact that these needed to be updated and checked if all of the dimensions and parameters are matching, between each iteration of the calculations. Moreover, it also had an effect on the time spent on assessment of the results since multiple models had to be analysed. Similarly, loads had to be applied to multiple models, however time spent on that was also affected by the inexperience of the author with the software.

The problems with Ansys, these refer to the crashes, software not updating the results after calculations even when inputs were changed, problems with joints and contacts definitions and other software bugs. The problems with SDC Verifier software did not appear during the first design.

Lastly, the load calculations category includes the calculations of the loads on the gantry in different positions due to the working load and the loads due to motions of the vessel. While, the 3D modelling refers to the summed time of changing the minor parts in the model throughout the project.

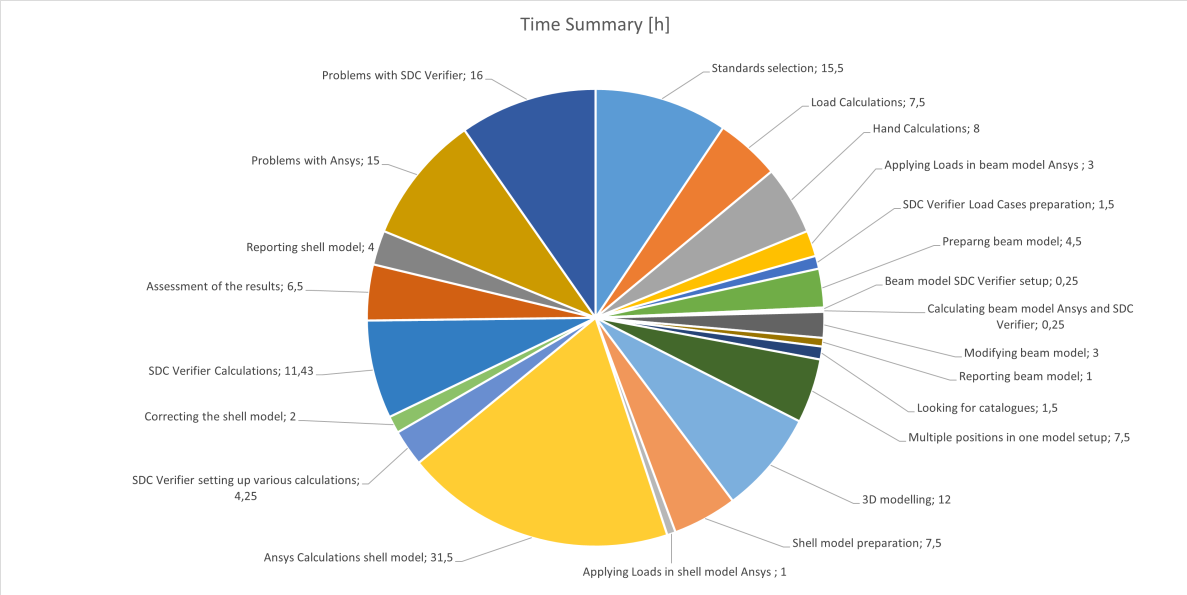

Figure 6.2: The time distribution among tasks in the design process using the new methodology of design.

In comparison, for the new methodology, the largest amount of time was spent as calculation time in Ansys Mechanical for the shell model. This is largely due to the relative complexity of the design, in comparison all of the calculations for a simple beam model took only a quarter of an hour. Even though, each analysis consisted of 153 load steps for a beam model and only 93 load steps for a shell model.

Two of the four largest sections on the chart are referring to the problems with software, which were encountered during the calculations. For Ansys, these are the same problems, which were encountered during the first design. In case of SDC Verifier one problem occurred during this project, the software could not find the results produced by Ansys Mechanical after one of the crashes of Ansys Workbench. To solve this problem an older backup version of the project had to be used and brought up to date. However, author's limited experience with both Ansys Mechanical and SDC Verifier, might have also been a factor causing some of the problems.

The time spent on standards selection and research is also a large contributor to the overall time spent on the project. This involves the search for an applicable base standard and then researching the requirements and other standards which are suggested to be followed by it. Time spent on this task may be greatly shortened for subsequent projects thanks to the experience gathered during the first design and research.

In comparison to the old methodology the reporting for the final shell model took significantly less time. Since SDC Verifier offers an automatic report generation, after setting it up it is possible to generate a new report without additional work even if the results change.

Summed up, 9 hours were spent on working strictly with beam model. However, it might have indirectly caused time savings, since there was no need to perform significant changes to the A-frame structure modelled after the beam model. Additionally, loads and load cases prepared for the beam model were reused for the shell model.

When comparing the two charts it is also visible that a significant amount of time was saved on the hand calculations. This is due to the fact that a strict set of standards was set at the beginning of the project and all of the calculation sheets for hand calculations were prepared from the very beginning, based only on standards. Therefore, no time was spent researching already prepared tools.

Moreover, assessment of the results also took significantly less time in the second project. This result may be caused by the need to assess only one model but also thanks to larger experience with the designed machine after finishing the previous design. This is also valid for the SDC Verifier calculations setup time.

Overall, it is clearly visible, that the project in which the work was structured according to the new methodology, took significantly less time. The first design took in summary 368 hours, while the second one took only 165 hours. This can be largely attributed to the new work structure and more efficient use of tools, however it is important to note that experience gained throughout both projects might have also affected the results.

In the Figure 6.3 a direct comparison of time spent on various tasks is presented. For this figure an attempt was made to adjust the results for the effect of experience. Therefore, in categories such as load calculations, applying loads, SDC Verifier setup time and FEA model preparation the values of time spent are adjusted to be equal. At the same time, the time spent on problems with fatigue requirements was excluded from the analysis. In that case the sum of time spent during the design using new methodology is still 165 hours, while the adjusted time for the design process using the old methodology is 309 hours. The largest differences between the two approaches can be noticed in the hand calculations category, reporting and working with standards.

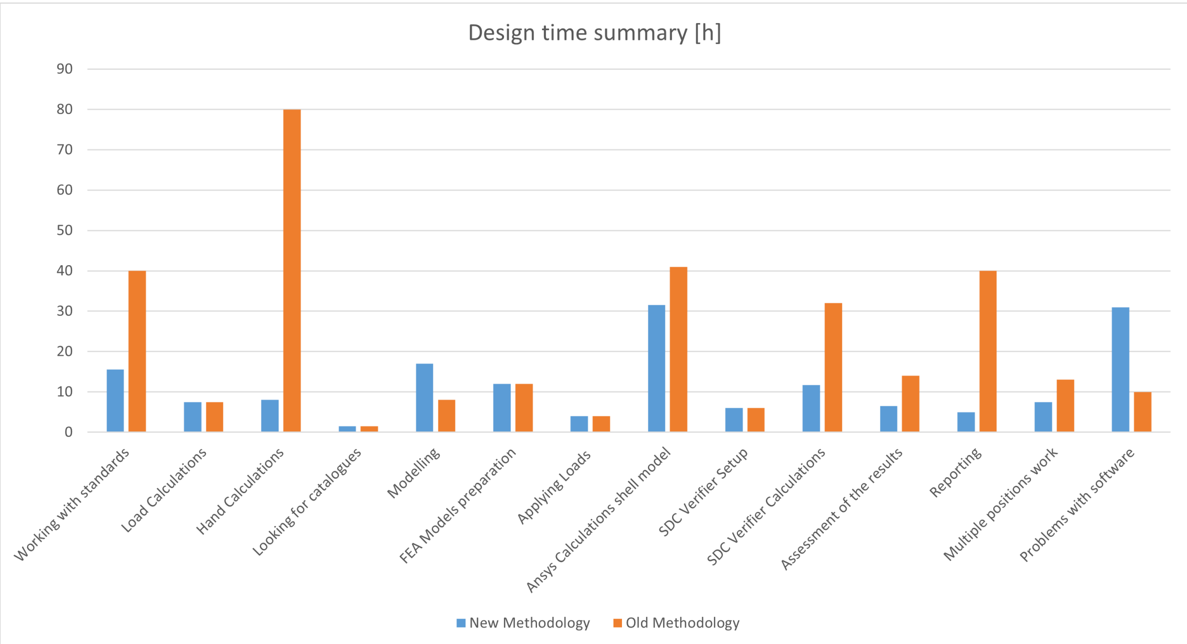

Figure 6.3: The time distribution among tasks in the design process - direct comparison adjusted for experience.

6.2.1. Effectiveness of post-processing software

The post-processing software was used for both of the projects. However, it was used to the varying extent and additional tests of the existing tools were performed to find the differences between them and the ones offered by the post-processing software.

The effectiveness of the standard check calculations using post-processing software were measured against the time spent on calculations performed by hand using the existing calculations sheets and methods in the company. The comparison is made between four different standard checks, which are frequently performed for many of the machine designs in Jan De Nul Marine Design and Engineering Department. These are:

- weld strength check,
- fatigue check,
- buckling check.

The tests were performed in different capacities due to the different characteristics of work with the hand calculation calculation sheets and the tools available in the post-processing software.

Weld Strength Check

In order to compare the efficiency of the weld strength check the following test was performed. The comparison is made between calculation of fillet welds according to DNV-ST-N001 and DNV-OS-C101 standards. For hand calculations ten welds were calculated using the company's method and for the post-processor 85 welds were calculated using SDC Verifier. Test was performed based on the first project models and calculations.

For each weld check performed via hand calculation, first a bonded contact is created in Ansys Mechanical between the edge of the welded plate and the other part. This was done for all of parts during one iteration, since it is necessary to run analysis again after such change to the model setup. After, that it is possible to retrieve the results of force and moments in each of the welds. Apart from that measurements of the weld length have to be performed in the 3D model or have to be retrieved from a drawing if it exists at this point in the design process. In this test, the weld dimensions were retrieved from a 3D model of the gantry crane. Then all of the information was input into the company's weld calculation sheet and the time was measured. The results of this test are presented in Table 6.1.

Table 6.1: Time needed to calculate 10 welds by hand using the hand calculation method.

	Time [min.]
Model preparations and recalculation	25
Measurements and calculations	83
Sum	108
Average time per weld	10.8

For the weld check performed using SDC Verifier, the weld recognition tool was used to find all of the welds in Ansys Mechanical. The weld length is automatically recognised based on the dimensions in the shell model. Apart from that it might be necessary to check how well did the recognition process perform, if required, the corrections are made. Similarly, to the hand calculations the throat dimensions were input by hand. After that, calculation is run according to the standard. The results of this test are presented in Table 6.2.

Table 6.2: Time needed to calculate 85 welds by hand using the post-processor method.

	Time [min.]
SDC Verifier welds setup	122
SDC Verifier and FEA Calculation	20
Sum	142
Average time per weld	1.67

The sum of time spent on hand calculations is lower, however, the number of checked welds is also lower and on average the post-processor calculation is faster. Moreover, it should also be considered that the preparatory time for the hand calculation method is lower than for the second method. However, in the first case it is only 10 parts which have to be modified in the shell model. With more parts and larger models both, the calculation time and the preparation time might significantly increase for hand calculations. This is due to the larger amounts of time that might be spent searching for a certain weld in the model or making errors due to the large amount of information, which needs to be tracked by an engineer.

Fatigue Check

In order to compare the efficiency of the fatigue checks, the following test was performed. One iteration of fatigue calculations was performed using the pre-existing calculation sheet and for comparison the same calculation was performed using SDC Verifier post-processor. The test was performed based on the first project models and calculations according to DNV-RP-C203.

For the hand calculations the check was performed in the following manner. First, the hot spot were identified in the model, then the equivalent von Mises stress results from the most stressed element were read out from the results in Ansys Mechanical. Next, an applicable S-N curve from the standard and other required information was input into the calculation sheet to obtain results. This approach was followed for all 33 identified hot-spots.

For the second method, first, the welds were recognised in the model using the weld recognition tool of the post-processor. Next, the applicable S-N curves were applied to all of the elements according to the standard. After that, a calculation was run in SDC Verifier for the whole model. The summarised time of one iteration of calculations for both approaches is presented in Table 6.3.

Table 6.3: Time summary comparison between two approaches to calculating fatigue.

	Time [min.]
Hand calculations of fatigue	960
Post-processor calculated fatigue	193

Realizing the calculations using post-processor is certainly quicker for larger number of hot-spots. However, even for designs, where there are no apparent hot-spot regions in the results it might be useful to perform the full analysis. By calculating the fatigue damage for all of the elements rather than for few areas of the model, risk of missing a region which is not fulfilling requirements of the standard is mitigated. This is especially important for designs in which allowable values of fatigue damage might differ depending on the specific areas of the model.

Buckling Check

In order to compare the efficiency of the buckling check the following test was performed. The plate buckling calculations were performed using the pre-existing calculation sheet and the method currently used in the department and the second calculation was performed using SDC Verifier post-processor.

Test was performed based on the first project models, the standard used for the second calculation is DNV RP-C201.

For the first method the model was analysed using the Eigenvalue Buckling analysis in Ansys Workbench. First five buckling modes of the model were checked, then if the load multiplier was smaller than 5 the deformed plate was checked via hand calculations according to DNV-ST-N001 standard. If required it was stiffened or thickened and then, another analysis was run to find the next deforming plate, or if the load multiplier was higher than 5, the design was approved. The time summary results for this approach are presented in Table 6.4.

Table 6.4: Time summary of hand calculated plate buckling check.

	Time [min.]
Setting up eigenvalue buckling analysis	15
Eigenvalue buckling calculations	5
Converting plate to an equivalent plate	15
Stresses in plate retrieval	10
Hand calculations	8
Sum	53

For the second method, first plates were found in SDC Verifier using the plate recognition tool. Then, after checking the correctness of recognition process and additional input required by the standard, the calculations are run. The time summary results for this approach are presented in Table 6.5.

Table 6.5: Time summary of automated calculation of plate buckling check.

	Time [min.]
SDC Verifier calculation setup	25
Ansys calculations	5
SDC Verifier calculations	15
Sum	45

For both methods, one iteration of the plate buckling check was performed. The post-processing method was faster but not as much as for the previously analysed checks, however there are few important points to consider, regarding the efficiency of these checks. On one hand, the first method allows only to check one plate at once and after each one another eigenvalue buckling analysis is required. This means that for larger models the time required to perform calculations in this manner might be significantly larger. On the other hand, using the automatised method it is possible to perform a check for all of the plates in the model all at once. While, the calculation and most likely the setup times will be longer for larger models, this approach should become more and more efficient when compared to the hand calculations.

6.3. Benefits and drawbacks of implementing finite element analysis post-processing software

Based on the results presented in the previous section, the post-processing software undoubtedly allows to perform tested the checks in a more efficient manner. Although, an additional setup is required for each of the calculations, which might take considerable time especially for larger models. On the other hand, tools provided in the post-processing software allow for automatic detection and maintenance of data. This includes, lists of plates, welds, beams etc. with the automatically recognised dimensions but also with parameters assigned by the user. Which, otherwise has to be done by hand separately from the FEA software, in case of the old methodology. Therefore, although additional setup time is required in order to use some of the post-processor's features, it alleviates other problems such as the database maintenance. Which otherwise might also cause the time spent on calculations as a whole to be larger.

Another large benefit of using post-processor is the automatic reporting feature. Large benefits in terms of efficiency are gained through the automated generation of charts and tables. The old methods of work in the Marine Design and Engineering Department required every chart to be screenshot manually from the results presented in Ansys Mechanical Workbench. Not only is this a time consuming task but whenever the requirements of the project would change, it had to be repeated. The same point is also valid for manually constructed tables. However, if an automated reporting is used a report, once setup one time does not have to be changed if the inputs are altered. The only requirement is to run the calculations again and generate the report anew. Thanks to that, the projects can also be reused easily, if the design only requires minor changes.

Moreover, another benefit is the possibility of using the calculations from different standards which are implemented in the software. Thanks, to that a significant portion of time can saved on preparing the tools for calculations depending on the project. In case of the draghead gantry design, only the structural check and the buckling check had to be implemented separately by hand.

On the other hand, using post-processing software may require adaptation of methodology. As it is presented in Section 6.2, large differences in the process overall effectiveness might occur if the design methodology is specifically intended for working with FEA and post-processor. Without these changes there are still benefits in terms of more efficient standard check calculations. However, a big part of the potential of additional software is lost.

Additionally, the post-processing software in this case favours shell and beam models over solid models. The recognition tools are large part of a functionality of the application and they work mostly with such models. Therefore, it is best to adapt the approach to modelling to reflect that to be able to benefit from the all functions provided by the software.

Lastly, as it is the case with adaptation of all software, it requires experience to be used efficiently. Therefore, additional training is required, if this post-processor is to be adapted in a company.

6.4. Benefits and drawbacks of the new methodology

The new methodology of design has its benefits and drawbacks. Firstly, the design produced using this methodology should be safe. This is due to the fact that selection of all standards is a separate explicit step. Moreover, it is embeded early in the methodology structure, therefore it allows for more rules oriented design in the subsequent steps.

Moreover, the new methodology increased the efficiency of the design process. The second project was finished faster than the first one by a large margin. Although, undoubtedly the effect of experience gained during the first project is non-negligible and should be considered. However, the new methodology offers a more streamlined approach to design of heavy machinery. Its structure is focused more on producing new designs through calculation and reuse of previous models and experience, rather than modelling and checking the finished design through finite element analysis. Therefore, detailed model is produced only once and does not have to be changed after finished calculations, as it might happen for objects designed using the old methodology.

Additionally, the new methodology includes evaluation of methods at the end of each project. Therefore, it is incentivised to judge each design process and to improve it. Thanks to that, for each consecutive project the performance of work should be improved, either in terms of quality or efficiency.

Another benefit and simultaneously a drawback is that, the new methodology was specifically prepared for working with post-processing software. Thanks, to that it results in increased efficiency while working with such. However, it is not intended and has not been tested for projects, where such software is not going to be used. Additionally, the methodology is intended specifically for use in heavy machinery design, which narrows the possibility of its use.

Moreover, implementation of the methodology might require changes to the work structure between the departments. This is due to the need for larger cooperation between the general design section and the FEA engineers from the beginning and throughout the project. Cooperation at all stages is intended to avoid problems in all stages of design. An example of that could be the basis of design and requirements not containing all of the information necessary for calculations.

7 Conclusions

The main research question and the objective of this report is to find the effects of using the modern Computer Aided Engineering tools on the design process of heavy equipment. In order to do that several research questions have been answered.

The literature study shown that, over the years, one of the most popular developed theories of design is what the researches call the consensus model. The approach of Systematic Approach design theory and VDI 2221. The fact that it is the official recommendation of The Association of German Engineers for few decades and is also taught at some universities is a large positive as it proves that the theory is proven to be useful and helpful during the design process. Moreover, research indicates that it also could partly work as a predictive model. However, in context of a broader product design, at the company level, the other popular approach are various forms of integrated design. The methodologies presented by researchers working on this type of approach tend to have more abstract structure and allow form more freedom. On the other hand, these gravitate towards development of innovative artifacts rather than proved mechanical structures. Although, the holistic concepts of integration presented in various research can be useful for all types of designs. Very few approaches were found which are concerned with explicit reuse of previous designs. These tend to be very abstract and present a broader idea on what mindset should be incorporated into the design methodology to efficiently reuse previously gained knowledge, experience and resources. The research regarding the post-processing software is limited. Many studies are concerned with optimization of results, rather than increasing the efficiency of the finite element analysis. However, commercial post-processing software offers many advantages while performing the calculations.

The design methodology in Jan De Nul Marine Design and Engineering Department was not codified. The overall approach to design is an effect of natural evolution happening in the workplace through cooperation rather than an explicit set of rules. The methodology had to be first codified based of an example in order to be able to efficiently incorporate the post-processing software into the work structure. The resulting structure of the methodology and the methods which are currently used are exhibiting many problems. The overall mindset, based on the exemplary work which was performed, is to design and calculate rather than calculate to design. Moreover, mixing standards or taking shortcuts in the calculation as it is the case with buckling calculations, sometimes occur. Additionally, methods used for checking accordance to standards frequently rely on hand calculations and pre-prepared calculation sheets. These include, fatigue calculations, buckling calculations, weld checks, bolt calculations, pin and pad eye design. Part of these as presented in this report can be performed using automatized post-processing software.

In order to develop the new methodology of design, solutions to the found problems are proposed in various forms. Some can be addressed by changing the tools and methods which are currently used during the design. Large number of problems can be addressed by improvements in communication and inclusion of the post-processing software into the work structure in an efficient manner. The potential changes resulting form the this change are also presented. Lastly, the new design methodology structure is proposed. The base for this new structure is the consensus model, although it has been modified. The modifications in the structure are oriented towards efficient use of the capabilities offered by the post-processing software. The design process is based on calculations and using simplified models first and detailed calculations later. With the use of post-processing software the setup needed for simplified calculation, such as loads and safety factors can be easily used again for the detailed model. However, the modifications also encourage the design reuse mindset, which in an industrial setting may prove to largely increase the efficiency of work. In order for the methodology and methods used during the design process not to become obstacles at some point in time, an assessment step has been added at the end of the process. This, adheres to the mindset of constant improvement and if its implemented, the resulting feedback loop can help increase the efficiency and quality in the future.

The design process during the work on the gantry crane produced using the new methodology of design was successful. When comparing the results of the two gantries designed during this study, if factors applied to the working load are considered, the resulting design is of a similar weight ratio to the safety factors ratio. Therefore, it can be concluded that the new methodology did not cause an issue of producing an overly heavy design. Although, it is important to note that the sample size is only two designs.

The performance of design process was improved when using the newly proposed methodology. The time needed to perform the second design was greatly shortened. Although, more different tasks were performed overall, many of the newly proposed methods resulted in the shorter time needed to perform other tasks later in the design process. However, the effect of experience on the time needed for the new design are certainly non-negligible. Additionally, comparison tests were performed to compare the time of calculations between the currently used methods in Jan De Nul Marine Design and Engineering Department and the tools provided in the post-processing software. These proved that the efficiency of performing the calculations with the post-processor is greatly increased, as the time per iteration or per part is reduced significantly. Considering the benefits and drawbacks of using the new methodology and post-processing software, it seems that these could enhance the design process significantly.

However, the study presented in this report is limited to only one case study, the gantry crane design for a specific application. The results, prove that the new methodology of design is an improvement on the previously used methods, but it is tested only on this one case with a sample size limited to one engineer and two designs. Therefore, it is still not researched enough to be implemented in an industrial setting as a base methodology for heavy equipment design. It would either have to be tested more extensively by the company, to ensure that it is viable choice or it would have to be researched more extensively in the academia. Changes in methodology and shifting the work structure in a design office would most likely introduce additional costs and period of lowered efficiency, due to the resources shifted towards testing and transition to the new work standard. Therefore it is unlikely that at this stage of the research, the new methodology is going to be introduced in its whole extent. However, with more research the risk involved in such transition could be lowered and become more attractive for the industry.

In conclusion, the CAE software can have large impact on the design process. Based of the example presented in this report, the efficiency of design can be greatly increased with the use of post-processing software. However, in order to use its full potential, changes have to be incorporated into the methodology of design. Therefore, use of modern CAE tools can greatly increase the efficiency of design, however it also requires adjusting the work structure to use it to its full potential.

7.1. Research recommendations

In this research the effects of using modern CAE tools on the design process have been discussed. Although, the study is limited, the designs were performed by one engineer, therefore the sample size is small. Moreover, due to the fact that the design process of the second gantry crane was performed after the first one, the experience change between the two is a significant factor affecting the results. An interesting research could be conducted on a larger scale, where engineers design the same structure using two different methodologies and tools. Then, the comparison between the results of these two approaches, if the sample size was sufficiently large, would be largely free from the effects that the experience and the knowledge of the specific design have on them.

Moreover, since the study presented in this report is only based on one type of design, studies could be conducted that show performance of the post-processor and the presented methodology of design for other machines. Since different types of heavy equipment might require varied approach to design, the performance of presented approach could be tested. If proven reliable also for other designs, it could incentivise its use in an industry.

A

Research Paper

Effects of modern Computer Aided Engineering (CAE) software on the design process

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Over the years the introduction of new Computer Aided Engineering software into the design process allowed engineers to significantly shorten the time necessary to produce finished designs. Researchers seem to agree that CAE tools have positive impact on the efficiency of the process and the quality of finished products. However, oftentimes the studies are limited and the benefits are measured through questionnaires filled out by the management, rather than measurements. In this article, the effects of introduction of a finite element analysis post-processing software on a design methodology are assessed based on a case study conducted in an industrial setting - Jan De Nul Marine Design and Engineering Department. Literature connected to the design methods is researched. The current methodology of design in the company is researched and a new methodology based on the needs and concepts from the literature is proposed, which is created to suit the design process with the specific CAE tool. Comparison is made between the effects of work with the two different methodologies.

I. Introduction

NOWADAYS, the design of various machines and structures is conducted by groups of engineers working with computerised tools on a scale that was never possible before. The increase in computational speeds, allows for more and more complex calculations and software to be developed. Over the years, the tools of an engineer changed from "pencil and paper" into machines which allow, them to quickly calculate increasingly complex problems and visualise them with one click of a button.

This shift also caused changes to the ways in which the designing is performed [1]. With the aid of various new tools, such as for example finite element analysis or computer aided design software, the engineers are now able to create more elaborate and better optimized artifacts.

The Computer Aided Engineering (CAE) software is also being incorporated into the design methodologies[2]. In the field of integrated design, there are four fundamentals[3]:

- humans,
- methodology,
- organization,
- technology.

The technology aspect is in this context among others, representing the efficient integration of software and computerisation. Researches, seem to agree that there is large potential in computerised methods of design and using the computer aided engineering tools can greatly enhance the process of design.

However, there are not many studies which are researching the topics of implementation of CAE in an industrial setting and their effects. The verification of the results is rarely a direct comparison between the effects of work before the implementation of a new tool and afterwards. The studies researching the effects of new improvements in the industry, frequently rely on the perceived benefits. The comparison is made between the current status and the improvement that could be made, relying on data gathered through questionnaires [4].

This research aims to find what is the effect of using modern Computer Aided Engineering (CAE) tools on the design process of heavy equipment. To achieve this goal a case study is performed at Jan De Nul Marine Design and Engineering Department. Currently, the department is in process of implementation of new post-processing software[5] for finite element analysis, which could enhance the effectiveness of the design process. In order to find the improvements, the following research questions have been developed:

- What is the state of the art regarding design methods in scientific literature?
- What are the characteristics of the current methodology of design in Jan De Nul Marine Design and Engineering Department based on the example of draghead gantry design?
- What could be the methodology of heavy equipment design?
- What is the performance of the proposed new method on the design proces of a draghead gantry crane?

Wrocław, March 14, 2023

II. Methods

In order to find the current design methodology and methods used in Jan de Nul Marine Design and Engineering Department, mechanical design of a chosen heavy machinery is performed. The structure, which was chosen as a good example of a typical design is a draghead gantry for a trailing suction hopper dredger vessel. During the design, time spent on tasks is measured using a clock. The current design methodology is defined based on the design and all of the discussions with other engineers, which happen during that process.

After the first design is finished, a new methodology is developed based on the first methodology, the researched literature and the functionalities of the new post-processing software. Then a second design is prepared, according to the developed methodology. Similarly, the time spent on various tasks is measured and summarised.

Since the machine is intended to be used in marine environment, the designs are performed according to the classification societies rules. It is an important factor because checking the design accordance to standards is a large part in the methodology.

Based on these two approaches a comparison is made, regarding the effects of the work and its efficiency. Additionally, a direct comparison in the time needed to perform standard calculation checks according to the classification society rules using spreadsheets and using the post-processing software. These are:

- weld check,
- plate buckling check,
- fatigue check.

In order to compare the efficiency of the weld strength check the following test was performed. The comparison is made between calculation of fillet welds according to DNV-ST-N001[6] and DNV-OS-C101[7] standards. For hand calculations ten welds were calculated using the company's method and for the post-processor 85 welds were calculated using SDC Verifier. Test was performed based on the first project models and calculations.

In order to compare the efficiency of the fatigue check the following test was performed. One iteration of fatigue calculations was performed using the pre-existing calculation sheet and for comparison the same calculation was performed using SDC Verifier post-processor. Test was performed based on the first project models and calculations according to DNV-RP-C203[8].

In order to compare the efficiency of the buckling check the following test was performed. Plate buckling calculations were performed using the pre-existing calculation sheet and the method currently used in the department and the second calculation was performed using SDC Verifier post-processor. Test was performed based on the first project models, the standard used for the second calculation is DNV RP-C201[9].

Additionally, to compare the two designs, one produced using the old methodology of design and one using the new one, mass of both is compared. However, different standards and parameters were used for the calculations in the designs, the safety factors on the working load are going to be assessed for the governing cases.

The software used during the FEA calculations and 3D model preparation are Ansys Workbench and SDC Verifier post-processor. For hand calculations Microsoft Excel has been used. The base 3D model for the gantry design is supplied by the company.

Although, the new methodology is developed specifically with them in mind, it was deemed unnecessary to list the post-processors capabilities in this paper. The list of capabilities of SDC Verifier can be found on the developer's website.

III. Literature

There are many different approaches to the mechanical engineering design process that were proposed by researchers over the years. One of the most prominent and influential model is the Systematic Approach described by Pahl and Beitz [10]. Or a consensus model as it is called by Roozenburg and Cross[11]. The slightly altered version of that model is also an approach recommended by The Association German Engineers [12]. This theoretical model is supposed to be an aid during the design, it proposes an easy to follow structure and certain tasks, which should be completed on each stage of the design process. The overall approach is similar to the generic stages in different procedural approaches, which can be found in literature [13]. These are: performance specification, function structure, principal solution, module structure, preliminary layout, definitive layout and documentation.

One of the proofs of the popularity and usefulness of this approach is the fact that it is taught in academia in many countries[14]. However, there are also certain criticisms. Roozenburg and Cross state that the model is focused on the early stages of design too much. The strong emphasis is put on the conceptual phase, despite the fact that frequently designs and their parts can be based of already proven solutions without the need to "reinvent the wheel". The second criticism is that the procedural approach of the consensus model does not provide much guidance in the latter stages of design. Lastly, in the industrial setting, the road from a conceptual model to the finished design is frequently highly iterative, recursive and relies on the anticipated solutions to the problems[11].

One of the solutions to the problems of classical approach to engineering is explored by Konda et al. [15], who advocate a concept of shared memory. The shared memory is defined as codified knowledge, experience, models and techniques shared within a group of professionals. The weaknesses that authors describe are:

- During the design of an artifact, the process demands knowledge of realisation of subsequent stages of development, which is held by stakeholders involved in these stages.
- When the knowledge of subsequent stages is not accessible for stakeholders involved in early stages, a redesign might be necessary when the process crosses between these stages.
- The differences between the knowledge an capabilities of stakeholders involved in subsequent stages of design might cause professionals from an earlier stage to overstep their duties into a later phase, causing a mismatch and consequently a need to redesign.
- The design process itself might be not sufficiently versatile to adapt to sudden changes in the design environment.

The shared memory advocated by the authors should help alleviate these through effective integrated engineering. To gain competitive edge authors suggest departure from classical approach to engineering and bring up points made by Clark[16]. Who proposes transition to integrated engineering through integration of software, hardware and professionals.

However, study by Kannengiesser[14] suggests that the consensus model, so the classical approach, could be the more natural approach to design. In this study a group of students were tasked with design work. Although, the Systematic Approach was not explicitly taught to students, it seems that reasonable predictions for parts of the design process can be made based of it. Moreover, the differences in model and behavior of the students seem to match the criticisms of Roozenburg and Cross[11], such as early solution anticipation and therefore solution fixation at the early stages.

Currently, the more recently developed methodologies, seem to be more abstract and engage with the design problem in less detail, with a more idealistic view. The research is, similarly to the older studies, based on personal expertise rather than empirical studies[17].

An important part of the design process is incorporation of prior knowledge. In the study by Oxman [18], it is stated that structured prior knowledge of the concepts, prototypes and precedents, on which future works can be based is an inherent part of design. Although, this statement is related to architecture, it is also true in the context of mechanical engineering. After all the engineering studies and academia do exist.

In their study Duffy et. al. explored the perceived benefits of using a design reuse model[4]. According to the study, applying design reuse model[19], offers significant improvements in areas of the costs of design, time of design and performance. If the organisational strategy is focused on improving and reusing the knowledge resources, large gains can be achieved, apparently it could save up to 23% in costs.

A more abstract and holistic approach to design than the classical model is offered by the integrated design, first developed in research by Olsson [20]. The idea behind it is integrating multiple domains of an organisation in subsequent phases of product development to enhance this process. The integrated design model is presented in Figure 1. In the field

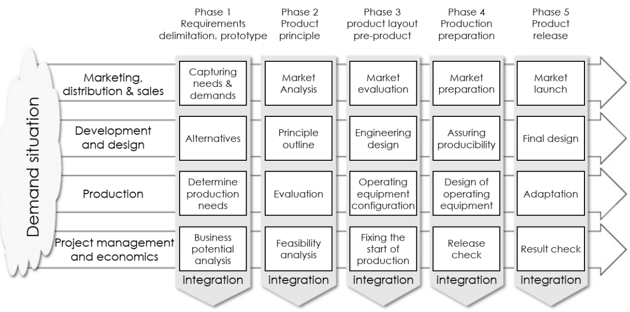


Fig. 1: The IPD Model by Olsson [21] from [2].

of integrated design large emphasis is put on integration of people, information and organisations. These core ideas are present in multiple studies [22], [3], [2].

Although, the core ideas behind integrated design are useful, the very abstract look that the methodology offers for the design process is not best suited for heavy machinery design. Integrated design seems to be more applicable to innovative products intended for serial production.

In terms of technology, Computer Aided Design and Computer Aided Engineering tools are valuable assets during the design process. Currently, a multitude of CAD software developers provide the market with a wide array of software solutions. CAD tools can be used to create 3 dimensional models of all kinds of products, for example ships, buildings or steel structures ([23]). Moreover, it is also possible to integrate CAD tools with CAE tools, such as finite element analysis software ([2], [24], [25]).

Structural analysis performed with FEA is a valuable tool for the design process of various machines and structures. However, there are more requirements that most of the designs have to fulfill, which are required by standards or for example classification societies rules in case of ships and ship equipment. These additional requirements are for example buckling checks, weld strength checks or fatigue checks, which can be calculated based on the results obtained in the finite element analysis manually by hand or in integrated manner in the FEA software if it allows for that. However, there has also been a development of FEA post processing software, which can extract the results from the analysis and perform calculations automatically. Some of these programs have been developed by researchers and some are commercially available. The tools developed by researchers, usually can be used to calculate one specific case for which an example of optimization is provided. These solutions are not very robust and they could be quite unwieldy to use in the industry. On the other hand, commercially available software provides multitude of options and capabilities which could be used to enhance the design process ([26], [27], [28], [29], [5]).

In summary, the older research of design theory is usually presenting a more detailed approach to methodology. In recent studies the researchers propose more holistic and abstract look. Moreover, integrated design methodologies similar to, for example a methodology developed by Vajna ([2]) are more suited to be used in creation of new products which are supposed to be sold on the market. In case of methodologies which are taking more detailed approach to the design process like the consensus model, it seems that these are more suited not only for marketable product but also for an in-house design. Moreover, the consensus model seems to be better suited for heavy machinery design.

IV. Current Methodology of Design Structure

Based on the first design of a draghead gantry, a current methodology of design at Jan De Nul Marine and Design Engineering Department is identified. The structure of said methodology is presented in figure 2. The current design process structure is consisting of for phases:

- I - preparation,
- II - detailed design,
- III - calculations,
- IV - corrections and reporting

During the first phase, the General Design Department, based on the needs regarding the design, form basic requirements and select basic standards. These are the standards used to calculate loads and prepare basis of design. The basis of design include loads and the requirements for basic structural check.

After that, the second phase in which the detailed design is prepared by CAD Engineer under the supervision of Expert Engineer based on previous designs and experience. After a detailed 3D model is prepared, it is passed to the FEA Engineer.

Since the basis of design do not contain information on any additional checks, FEA Engineer has to first conduct research on which standards to use and what checks should be performed for the design to be approved. Sometimes, it is also required to find additional information regarding the design if supplied data is insufficient to perform all of the calculations. After the yield strength check is performed and FEA model is updated, any additional calculations are performed. These include calculations of:

- welds,
- plate buckling,
- fatigue,
- pins,
- shafts and axles,
- bolts,
- cylinder buckling.

After all of the calculations are finished, the fourth phase begins. During which the report is created. All of the charts with results of calculations are screenshot by hand form the FEA software. Similarly, all of the tables and other results are prepared in manual fashion. Simultaneously the 3D CAD model is updated and the final drawings are prepared. Then the design can be sent for classification.

There are obvious inefficiencies in this approach. The problems recognised in the methodology are listed below:

- missing input or limited calculations,
- disconnect between the needs of the engineer performing the FEA and criteria provided by the general design department,
- hand checks, which are performed at the end of the design process, may cause critical dimensions to change significantly,
- performing buckling, fatigue and weld checks by hand, individually for large structures may prove to be a very time consuming task,
- identifying and manually keeping track of all of the elements such as plates, welds and hot-spots is prone to errors,
- bolt connections can be checked in FEA software,
- relying on manual report generation, manually taken screenshots, manual calculations and manual updating of the report,
- finishing the detailed design before any significant FEA calculation is performed,
- heavily relying on the experience of the expert designer to produce practically finished design at the start of the design process.

V. New methodology of design

Based on the consensus approach [12], the capabilities of the post-processor and the old methodology, the new methodology structure is developed. Moreover, the design reuse [19] mindset is implemented. The methodology structure is presented in Figure 3.

The new proposed methodology of design is consisting of ten steps and four phases. The phases are following:

- I - Clarification
- II - Conceptual phase
- III - Detailed design
- IV - Production preparation

Each of the phases are comprised of steps. Steps and the results, which should be achieved through them are presented below:

- clarify and define task.
  - Specification.
- Determine functions and their structures.
  - Type of main conversions.
  - Type of auxiliary conversions.
  - Overall function.
  - Sub-functions.
- Select standards.
  - Research standards, find required calculations, loads and load cases.
  - Choose an approach for each calculation.
  - Prepare loads and load cases.
- Search for solution principles and their combinations.
  - Select solutions available in-house and commercially.
  - Type of energy, physical effects and the auxiliary conversions necessary.
  - Active motions, active surfaces, active spaces, type of material.
- Divide into realizable modules.
- Develop concepts with beam model.
  - Simplified model: calculations (hand and FEA), main dimensions, standard, bought and repeat parts, manufacturing methods, joining and fastening procedures.
- Develop detailed assembly.
  - Detailed assembly and part models: individual parts, assemblies, connecting parts, parts list, detailed FEA calculations, hand calculations.
- Final model development.
  - Final assembly, calculation report.
- Production and operation preparation.
  - Production drawings and assemblies.
  - Instructions for commissioning, operation, maintenance, decommissioning.

An important part of the methodology is the fulfillment and adaptation of the requirements. After each of the steps, a meeting should be held between the general design section, the FEA engineer and the CAD engineer to review the results, the requirements and the current state of the project. This approach should cause the cooperation to be more clear, since the team members working on the design are up to date at every step of the process. Moreover, they can react early if some aspect of the project needs to be revised for later steps to be performed successfully.

At the end of the design process its assessment should be performed. The performance of methods and the process as a whole needs to be evaluated. Based on that, necessary changes can be incorporated into the work for the next design. Thanks to this a feedback loop is created and the methodology may be tuned to the individual needs of an engineer or a company. Moreover, a constant improvement of the process is expected, as it can evolve with factors such as new methods or software, as well as changes in the company policy. Thanks, to the feedback the design process can be always adjusted to the work environment.

As it is illustrated by the arrows, all of the steps can be repeated if needed. Moreover, inclusion of previous experience, designs and known concepts at each of the design steps allows for a more robust methodology. It is possible to skip a step or greatly shorten the time needed to finish it, by using parts of a previous design or older specifications. Designers, could for example skip parts of the concept development phase if a semi-standard or a standard solution to their problem already exists and it is only necessary to tune it to the specific case. On the other hand, it is also possible to go through a whole design process and develop completely new designs, only basing on engineer's experience.

Additionally, the experiences and relevant parts of design should be stored for future use. This can be done by creating and maintaining a database where data gathered during previous projects can be accessed by designers. However, it is essential that the data is stored in an efficient and structured manner. Information should be easily accessible and provide sufficient meta information to be understandable and readily available for use.

VI. Results

A. Methodologies time summary results

The time summary comparison results are presented in Figure 4. The results have been adjusted for the effects of experience gained during the design process for the first gantry crane. Therefore, in categories such as load calculations, applying loads, SDC Verifier setup time and FEA model preparation the values of time spent are adjusted to be equal.

In that case the sum of time spent during the design using new methodology is 165 hours, while the adjusted time for the design process using the old methodology is 309 hours. The largest differences between the two approaches can be noticed in the hand calculations category, reporting and working with standards.

B. Weld check time summary results

The time summary results for hand calculated weld strength check are presented in Table I.

TABLE I: Time needed to calculate 10 welds by hand using the hand calculation method.

	Time [min.]
Model preparations and recalculation	25
Measurements and calculations	83
Sum	108
Average time per weld	10.8

The time summary results for calculation performed with post-processor are presented in Table II. The improvement in efficiency between the hand calculation approach and the automated calculation is equal to 646.7%.

TABLE II: Time needed to calculate 85 welds by hand using the post-processor method.

	Time [min.]
SDC Verifier welds setup	122
SDC Verifier and FEA Calculation	20
Sum	142
Average time per weld	1.67

C. Fatigue check time summary results

The summarised time of one iteration of calculations for both approaches to fatigue check is presented in Table III. The improvement in efficiency between the hand calculation approach and the automated calculation is equal to 497.4%.

TABLE III: Time summary comparison between two approaches to calculating fatigue.

	Time [min.]
Hand calculations of fatigue	960
Post-processor calculated fatigue	193

D. Buckling check time summary results

The time summary results for hand calculated buckling check are presented in Table IV. The time summary for calculation performed with post-processor are presented in Table V. The improvement in efficiency between the hand calculation approach and the automated calculation is equal to 117.8%. Although, it should be noted that in one iteration of plate buckling calculations using the standard methods used at the department, the check is performed only for one plate. On the other hand, one iteration of automated calculations in this instance allows to check all of the plates in one model.

TABLE IV: Time summary of hand calculated plate buckling check.

	Time [min.]
Setting up eigenvalue buckling analysis	15
Eigenvalue buckling calculations	5
Converting plate to an equivalent plate	15
Stresses in plate retrieval	10
Hand calculations	8
Sum	53

TABLE V: Time summary of automated calculation of plate buckling check.

	Time [min.]
SDC Verifier calculation setup	25
Ansys calculations	5
SDC Verifier calculations	15
Sum	45

E. Methodologies mass results comparison.

The comparison between the mass of the models and the factors is presented in Table VI.

TABLE VI: Design results comparison.

	Old design methodology	New design methodology	Ratio
Safety factor	0.96 (very fine mesh)	1.33	-
Dynamic amplification factor	1.35	1.70	-
Duty factor	1.06	-	-
Factors overall	1.37	2.26	1.65
Mass [t]	13.3	21.7	1.62

VII. Discussion

The results of time comparison between the two methodologies show that the design process conducted using the new methodology of design is significantly faster. In comparison to the old methodology the reporting for the final shell model took significantly less time. Since SDC Verifier offers an automatic report generation, after setting it up it is possible to generate a new report without additional work even if the results change.

When comparing the results it is also visible that a significant amount of time was saved on the hand calculations. This is thanks to a strict set of standards which was prepared at the start of the project. All of the calculation sheets for hand calculations were prepared from the very beginning, based only on standards. Therefore, no time was spent researching the tools which were previously used for calculations in the company.

Standards' selection and research are also large contributors to the overall time spent on the first project. This involves the search for an applicable base standard, the requirements and other standards which are suggested by them, to be followed for a specific design. Time spent on this task may be greatly shortened, the experience gathered during the first design and the research performed then can be useful in new designs. However, new standards were chosen at the beginning of the project for the second design. During the project in which the old methodology was used, some of the standards were chosen at the beginning, but additional research had to be conducted to find applicable standards for other calculations. Due to this reason, and problems with the base set of rules provided for the first design, this task was prolonged.

During the work with old methodology three models for three different positions of the gantry were used for calculations. These are presented in figure 5. Therefore, the SDC Verifier setup and calculations had to be done for each of the models. Which is one of the causes of the difference in time spent on both tasks between the two approaches. Additionally, experience of the designer is certainly a factor in this case. However, there is no possibility of decoupling these two factors and therefore for these results it is impossible to adjust the time for experience.

On the other hand, the new methodology requires more work related to creating and modifying models. Additional, simplified models are advised to be prepared to save time on calculations later during the design process. For the design of a gantry with the new methodology, additional beam model was prepared. This helped with reducing the time required for preparation and calculations of a detailed model. Parts such as, cylinders and the A-frame pivot shaft were designed early to introduce more constraints into the detailed model.

With regard to the time required to perform hand calculations of plate buckling, fatigue and welds, it can be noticed that the post-processing software allows for a large decrease in time needed to perform them.

For the weld check, the sum of time spent on hand calculations is lower, however, the number of checked welds is also lower. On the other hand, if time spent for calculations per one weld on average is considered, the post-processor is faster. Moreover, it should also be considered that the time spent for preparation for hand calculation method is lower than for the other one. Although, For hand calculations the preparations had to be performed only for 10 welds in the shell model. With more parts and larger models both, the calculation time and the preparation time will likely be significantly increased for hand calculations. This is due to the larger amounts of time that might be spent searching for a certain weld in the model or making errors due to the large amount of information tracked by an engineer.

For fatigue calculations similar results were obtained. The post-processing software offers significant reduction in time required to perform one iteration of fatigue calculations. Moreover, hand calculations are performed only in areas of high stresses. However, since fatigue is dependant on stress amplitude and the number of cycles, some areas of the model might be missed. This is not the case, when post-processing software is used. During each iteration, the fatigue damage could be calculated for each of the elements in the model if its desired by the engineer.

Plate buckling check also requires less time to be performed when post-processing software is used. The difference is not as big as with the previous two cases, however an important point should be considered. The first method of calculation is performing the Eigenvalue Buckling analysis in Ansys Workbench in the manner that was used in the company. First five buckling modes of the gantry were checked using the model, then if the load multiplier was smaller than 5 the deformed plate was checked via hand calculations according to DNV-ST-N001 standard. The plate was modified if needed and the process was repeated until the load multiplier of 5 was reached during an analysis. While for the other method, first plates were recognised in SDC Verifier, then, after checking the correctness of recognised parts and additional input required by the standard, the calculations are run. The model is optimised and the process is repeated until final design is reached. On one hand, the first method allows only to check one plate at once and after each one another eigenvalue buckling analysis is required. This means that for larger models the time required to perform calculations in this manner may be larger. On the other hand, using the automatised method it is possible to perform a check for all of the plates in the model all at once.

While, the calculation and most likely the setup times will be longer for larger models, this approach should become more and more efficient when compared to the hand calculations.

Due to the extent of work which is required to be performed while designing a machine, presented research is quite limited. Work was performed by one engineer and only for one specific machine. Therefore, it can be assessed that the presented methodology is useful in this specific case. However, further research might be required in order for it to be introduced in an industrial setting as a rule of design. This would require conducting studies similar to this, but on different designs and with more samples, where, statistically significant results could be obtained.

VIII. Conclusion

In conclusion, the CAE software can have large impact on the design process. Based of the example presented in this report, the efficiency of design can be greatly increased with the use of post-processing software. However, in order to use its full potential, changes have to be incorporated into the methodology of design. Therefore, use of modern CAE tools can greatly increase the efficiency of design, although it also requires adjusting the work structure to use it to its full potential.

References

[1] M. J. Legaz, "Computer aided ship design: a brief overview," *SeMA Journal*, vol. 72, no. 1, pp. 47–59, Oct. 2015. [Online]. Available: https://doi.org/10.1007/s40324-015-0048-7
[2] S. Vajna, Ed., *Integrated Design Engineering*. Springer International Publishing, 2020. [Online]. Available: https://doi.org/10.1007/978-3-030-19357-7
[3] H. Meerkamm, "Integrierte produktentwicklung im spannungsfeld von kosten-, zeit-und qualitatsmanagement," *VDI Berichte-Verein Deutscher Ingenieure*, no. 1136, pp. 1–14, 1994.
[4] A. H. Duffy and A. Ferns, "An analysis of design reuse benefits," 1998.
[5] SDC Verifier, 9 2022. [Online]. Available: https://sdcverifier.com
[6] De Norske Veritas, "Dnv-st-n001 marine operations and marine warranty," 9 2021.
[7] ——, "Dnv-os-c101 structural design of offshore units (lfrd method)," 7 2019.
[8] ——, "Dnv-rp-c203 fatigue design of offshore steel structures," 4 2010.
[9] ——, "Dnv-os-c201 structural design of offshore units (wsd method)," 4 2011.
[10] G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, *Engineering Design*. Springer London, 2007. [Online]. Available: https://doi.org/10.1007/978-1-84628-319-2
[11] N. Roozenburg and N. Cross, "Models of the design process: integrating across the disciplines," *Design Studies*, vol. 12, no. 4, pp. 215–220, Oct. 1991. [Online]. Available: https://doi.org/10.1016/0142-694x(91)90034-t
[12] VDI, *VDI 2221: Systematic Approach to the Design of Technical Systems and Products*, ser. VDI guidelines. Beuth Verlag, 1993.
[13] K. Gericke and L. Blessing, "Comparisons of design methodologies and process models across disciplines: A literature review," vol. 1, 01 2011, pp. 393–404.
[14] U. Kannengiesser and J. S. Gero, "Can pahl and beitz' systematic approach be a predictive model of designing?" *Design Science*, vol. 3, 2017. [Online]. Available: https://doi.org/10.1017/dsj.2017.24
[15] S. Konda, I. Monarch, P. Sargent, and E. Subrahmanian, "Shared memory in design: A unifying theme for research and practice," *Research in Engineering Design*, vol. 4, no. 1, pp. 23–42, mar 1992. [Online]. Available: https://doi.org/10.1007/bf02032390
[16] K. Clark, T. Fujimoto, and P. Fujimoto, *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*. Harvard Business School Press, 1991.
[17] P. Badke-Schaub and E. Voute, "DESIGN METHODOLOGY: WHERE DO YOU GO?" in *Proceedings of the DESIGN 2018 15th International Design Conference*. Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia, The Design Society, Glasgow, UK, 2018. [Online]. Available: https://doi.org/10.21278/idc.2018.0550
[18] R. Oxman, "Prior knowledge in design: a dynamic knowledge-based model of design and creativity," *Design Studies*, vol. 11, no. 1, pp. 17–28, Jan. 1990. [Online]. Available: https://doi.org/10.1016/0142-694x(90)90011-z
[19] J. S. Smith and A. H. B. Duffy, "Product structuring for design re-use," in *Design for Configuration*. Springer Berlin Heidelberg, 2001, pp. 83–100. [Online]. Available: https://doi.org/10.1007/978-3-642-56905-0-8
[20] K. Olsson, *Systematisk konstruktion: en studie med syfte att systematisera innehåll och metoder i samband med produktkonstruktion*. Institutionen för Maskinkonstruktion, 1976.
[21] F. Olsson, "Integrerad produktutveckling–arbetsmodel," *Series 21 Produktutveckling. Sveriges*, 1985.
[22] K. Ehrlenspiel, in *Integrierte Produktentwicklung*. München: Carl Hanser Verlag GmbH & Co. KG, Jun. 2009.
[23] M. José Legaz, "Computer aided ship design: a brief overview," *Bol. Soc. Esp. Mat. Apl. SeMA*, vol. 72, no. 1, pp. 47–59, Dec. 2015.
[24] J. Fuh and W. Li, "Advances in collaborative CAD: the-state-of-the art," *Computer-Aided Design*, vol. 37, no. 5, pp. 571–581, Apr. 2005. [Online]. Available: https://doi.org/10.1016/j.cad.2004.08.005
[25] R. Bernd, T. Alexander, and R. Frank, "Integrated finite element analysis (fea) in three-dimensional computer aided design programs (cad)-overview and comparison," *Guidelines for a Decision Support Method Adapted to NPD Processes*, 2007.
[26] G. Alencar, A. de Jesus, J. G. S. da Silva, and R. Calçada, "A finite element post-processor for fatigue assessment of welded structures based on the master s-n curve method," *International Journal of Fatigue*, vol. 153, p. 106482, Dec. 2021. [Online]. Available: https://doi.org/10.1016/j.ijfatigue.2021.106482
[27] A. K. Shojaei and A. R. Wedgewood, "An anisotropic cyclic plasticity, creep and fatigue predictive tool for unfilled polymers," *Mechanics of Materials*, vol. 106, pp. 20–34, Mar. 2017. [Online]. Available: https://doi.org/10.1016/j.mechmat.2017.01.003
[28] J. Abry, C. Mittelhaeuser, S. Wolf, and D. Turlier, "Enhanced fatigue structural stress analysis of a heavy vehicle seam welded steel chassis frame: FEA model preparation, weld model description, fatigue stress calculation and correlation with 10 year operating experience," *Procedia Engineering*, vol. 213, pp. 539–548, 2018. [Online]. Available: https://doi.org/10.1016/j.proeng.2018.02.050
[29] A. Alhajahmad and C. Mittelstedt, "Minimum weight design of curvilinearly grid-stiffened variable-stiffness composite fuselage panels considering buckling and manufacturing constraints," *Thin-Walled Structures*, vol. 161, p. 107526, Apr. 2021. [Online]. Available: https://doi.org/10.1016/j.tws.2021.107526

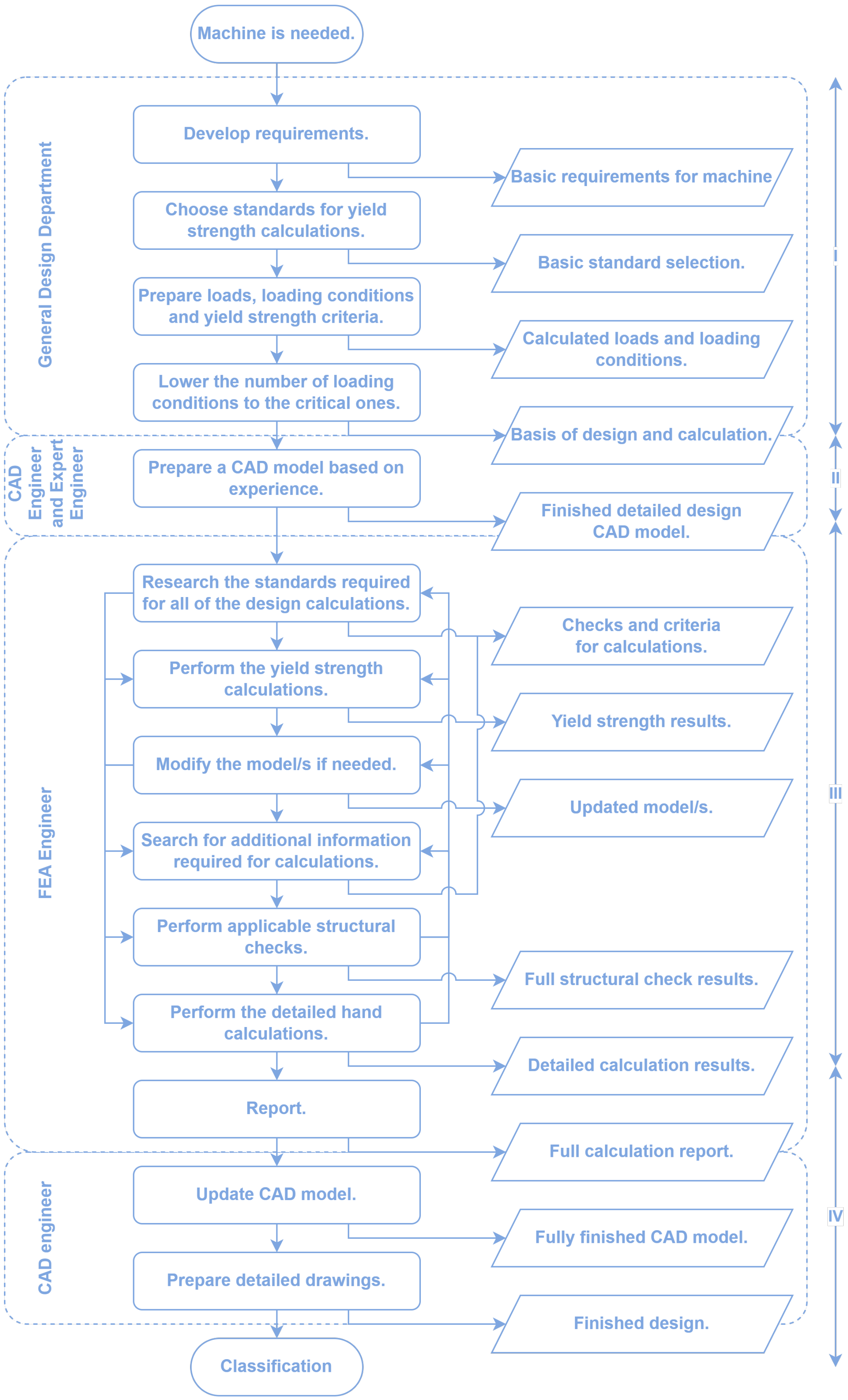


Fig. 2: Structure of the current methodology of design.

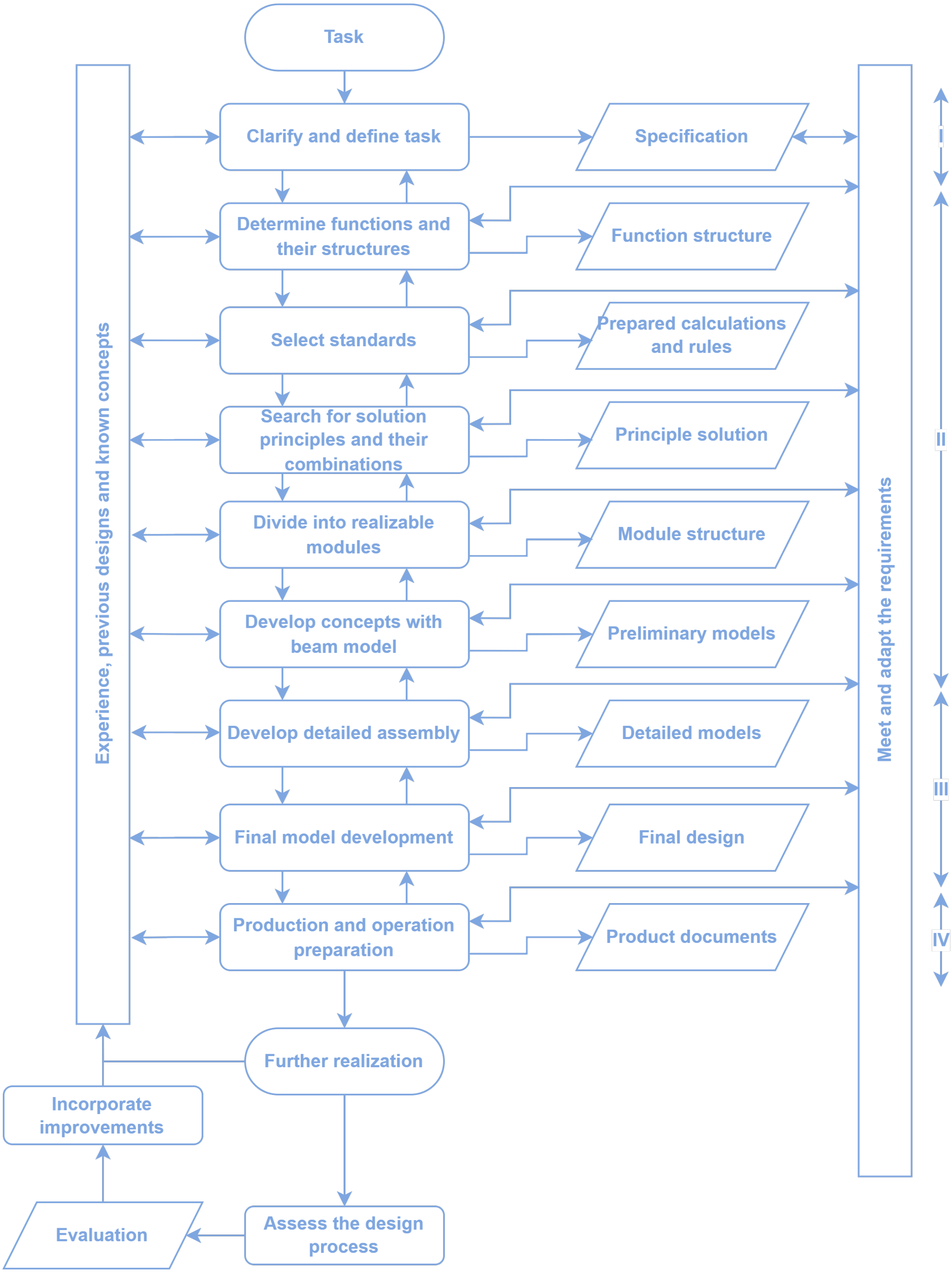


Fig. 3: Proposed overall structure of the new methodology of design.

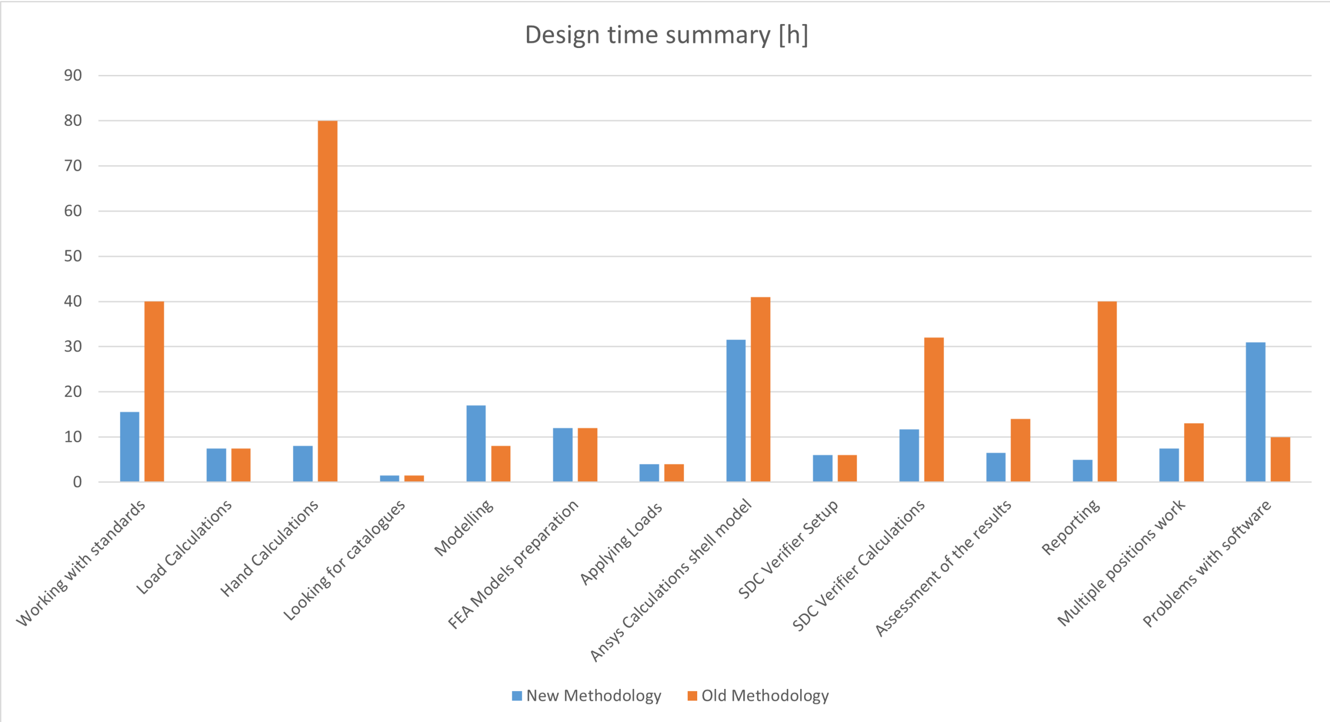


Fig. 4: The time distribution among tasks in the design process - direct comparison adjusted for experience.

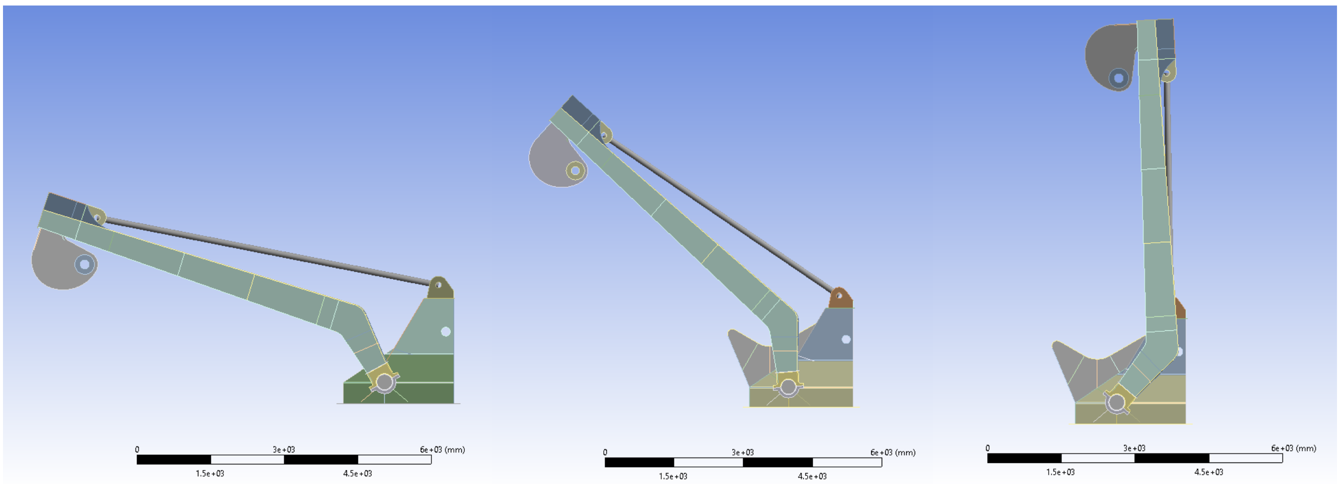


Fig. 5: Gantry crane in three positions.

B

FEA Capabilities Comparison

Table B.1: Comparison of FEA software integrated in CAD (Wasserman, Retrieved October 2022).

Simulation In-CAD: Structural/FEA					
Structural/FEA	Autodesk NASTRAN In-CAD/Inventor	Creo Simulate	IronCAD	Siemens Solid Edge NX Nastran	Solidworks Simulation Portfolio
Adaptive meshing	X	X	X		X
Automated mesh refinements	X	X	X		
Bolt pre-tension	X	X	X		X
Buckling/collapse	X	X	X	X	X
Cold working	X		X		
Composite components	X	X	X	X	X
Contact modeling	X	X	X		X
Cloud storage					
Cloud computing		X			
Cracks and fractures mechanics		X			
Democratized task-specific FEA tools	X		X		X
Digital materials	X		X		X
Drop test/impact	X	X	X	X	X
Durability analysis	X	X	X		X
Fatigue	X	X	X	X	X
Frequency response	X	X	X	X	X
Higher order elements	X	X	X		X
HPC compatibility	X	X	X		
Linear static	X	X	X	X	X
Modal	X	X	X	X	X
Non-linear (static/transient)	X	X	X	X	X
Normal modes	X	X	X		X
Pressure vessels	X	X	X	X	X
Residual stresses	X		X		X
Simulation app creation			X		
Simulation template creation		X	X		X
Shape/topology/optimization	X	X		X	X
Spot weld analysis	X	X	X		X
Transient stress	X	X	X	X	X
Vibration modes	X	X	X		X
User defined functions	X	X	X		X

Table B.2: Comparison of standalone FEA software (Wasserman, Retrieved October 2022).

Simulation Platforms/Solvers: Structural/FEA					
Structural/FEA	3DEXPERIENCE Simulation SIMULIA/Abaqus	Altair HyperWorks	ANSYS AIM	ANSYS Structural / Multiphysics	Autodesk Simulation 360
Adaptive meshing	X	X		X	X
Automated mesh refinements	X	X		X	X
Bolt pre-tension	X	X	X	X	X
Buckling/collapse	X	X	X	X	X
Cold working	X	X		X	X
Composite components	X	X		X	
Contact modeling	X	X	X	X	X
Cloud storage	X	X	X	X	X
Cloud computing	X	X	X	X	X
Cracks and fractures mechanics	X	X		X	
Democratized task-specific FEA tools	X	X	X	X	X
Digital materials	X	X		X	X
Drop test/impact	X	X		X	X
Durability analysis	X	X		X	X
Fatigue	X	X		X	
Frequency response	X	X		X	
Higher order elements	X	X	X	X	X
HPC compatibility	X	X	X	X	X
Linear static	X	X	X	X	X
Modal	X	X	X	X	X
Non-linear (static/transient)	X	X	X	X	X
Normal modes	X	X	X	X	X
Pressure vessels	X	X	X	X	X
Residual stresses	X	X		X	X
Simulation app creation	X		X	X	
Simulation template creation	X	X	X	X	
Shape/topology/optimization	X	X		X	X
Spot weld analysis	X	X		X	X
Transient stress	X	X	X	X	X
Vibration modes	X	X	X	X	X
User defined functions	X	X		X	

Table B.3: Comparison of standalone FEA software (Wasserman, Retrieved October 2022) cont.

Simulation Platforms/Solvers: Structural/FEA						
Structural/FEA	Autodesk Simulation Mechanical/ Nastran	COMSOL	Cervenka ATENA	Dynaform	ESI Virtual Performance Solution (VPS)	ESRD StressCheck
Adaptive meshing	X	X		X	X	
Automated mesh refinements	X	X		X	X	X
Bolt pre-tension	X	X	X			X
Buckling/collapse	X	X	X			X
Cold working	X	X	X	X		X
Composite components	X		X		X	X
Contact modeling	X	X	X	X	X	X
Cloud storage			X			
Cloud computing		X	X		X	
Cracks and fractures mechanics		X	X	X	X	X
Democratized task-specific FEA tools	X	X	X	X	X	X
Digital materials	X	X	X			
Drop test/impact	X		X		X	
Durability analysis	X	X	X		X	
Fatigue	X	X	X		X	X
Frequency response	X	X	X		X	X
Higher order elements	X	X	X	X		X
HPC compatibility	X	X	X	X	X	
Linear static	X	X	X		X	X
Modal	X	X			X	X
Non-linear (static/transient)	X	X	X	X	X	X
Normal modes	X	X	X		X	
Pressure vessels	X	X	X			
Residual stresses	X	X	X	X		X
Simulation app creation		X			X	X
Simulation template creation		X		X	X	X
Shape/topology/optimization	X	X				
Spot weld analysis	X				X	
Transient stress	X	X	X		X	
Vibration modes	X	X	X		X	X
User defined functions	X	X	X			X

Table B.4: Comparison of standalone FEA software (Wasserman, Retrieved October 2022) cont.

Simulation Platforms/Solvers: Structural/FEA							
Structural/FEA	INTES PERMAS	MSC Nastran	NISA	PreSys	Siemens' Simcenter Portfolio	Simscale	VPG
Adaptive meshing		X		X	X		
Automated mesh refinements		X		X	X		
Bolt pre-tension	X	X	X	X	X	X	
Buckling/collapse	X	X	X	X	X		X
Cold working				X	X	X	
Composite components	X	X	X	X	X		
Contact modeling	X	X	X	X	X	X	X
Cloud storage					X	X	
Cloud computing					X	X	
Cracks and fractures mechanics			X	X	X		
Democratized task-specific FEA tools	X				X	X	
Digital materials							
Drop test/impact	X	X		X	X	X	
Durability analysis	X		X	X	X		X
Fatigue	X	X	X		X		
Frequency response	X	X	X	X	X	X	X
Higher order elements	X		X	X	X		X
HPC compatibility	X			X	X	X	X
Linear static	X	X	X	X	X	X	
Modal	X	X	X	X	X	X	
Non-linear (static/transient)	X	X	X	X	X	X	X
Normal modes	X	X	X	X	X	X	
Pressure vessels	X		X	X	X	X	
Residual stresses	X		X	X	X	X	X
Simulation app creation					X		
Simulation template creation	X		X	X	X	X	X
Shape/topology/optimization	X	X	X		X		
Spot weld analysis	X	X		X	X		
Transient stress	X	X	X	X	X	X	X
Vibration modes	X	X	X	X	X	X	
User defined functions	X	X	X	X	X		

C

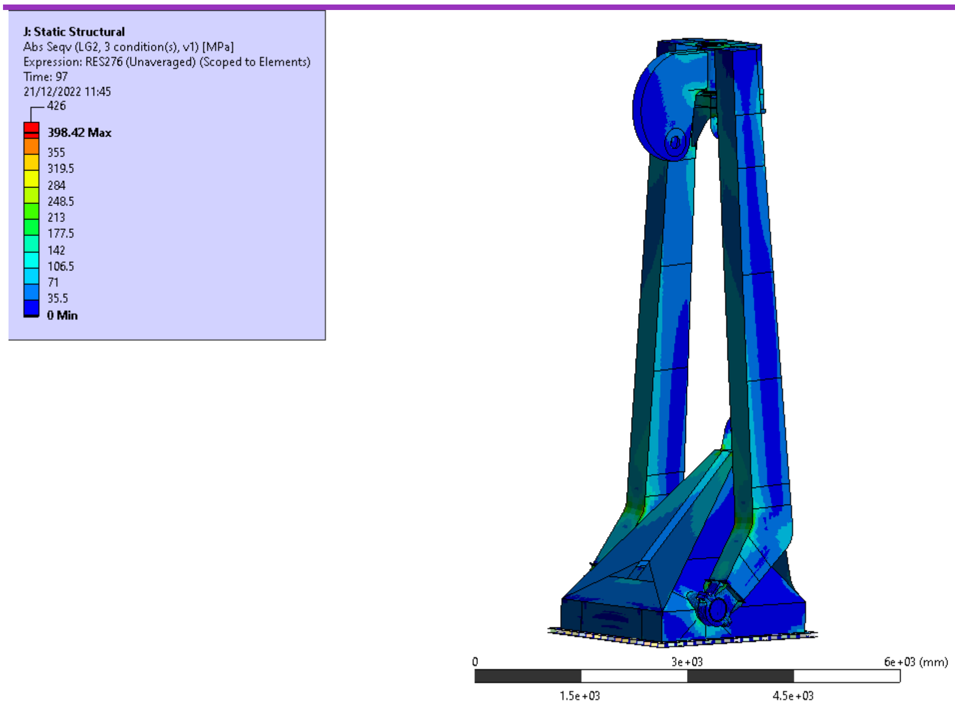
Results of the FEA - New Methodology

Results

Load Groups

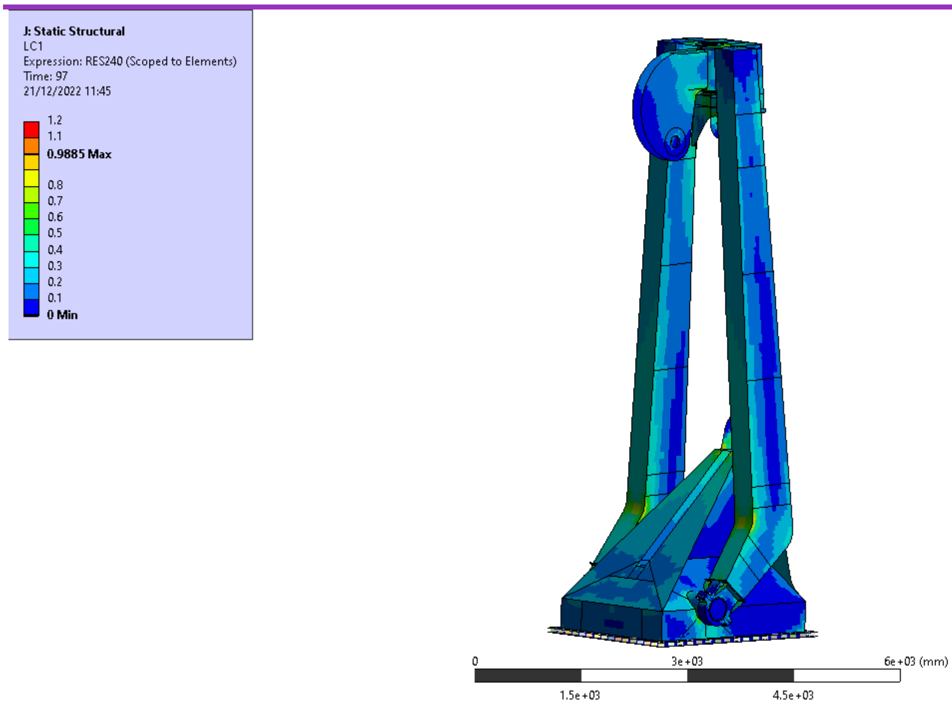
In this paragraph the influence of the different load groups is described. Load group represents extreme values (min, max, abs) among its items.

LG2..LC1

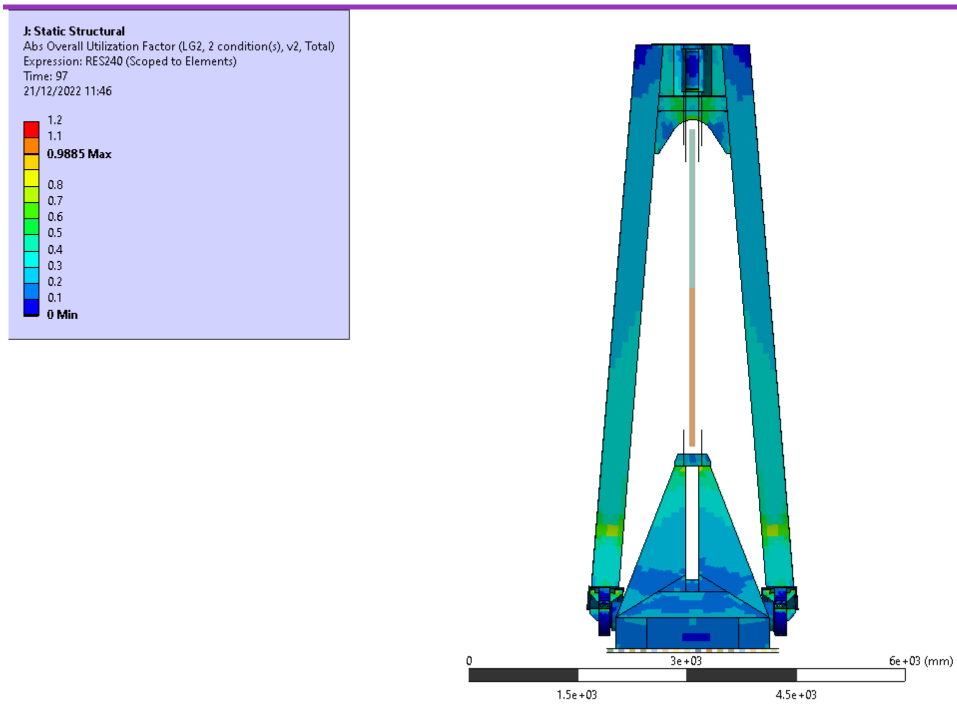


Load Group	LG2..LC1	**Parameter**	AbsoluteStress Equivalent
Selection	90397 element(s)	**View**	1..Default View
Data Conversion	No Averaging		

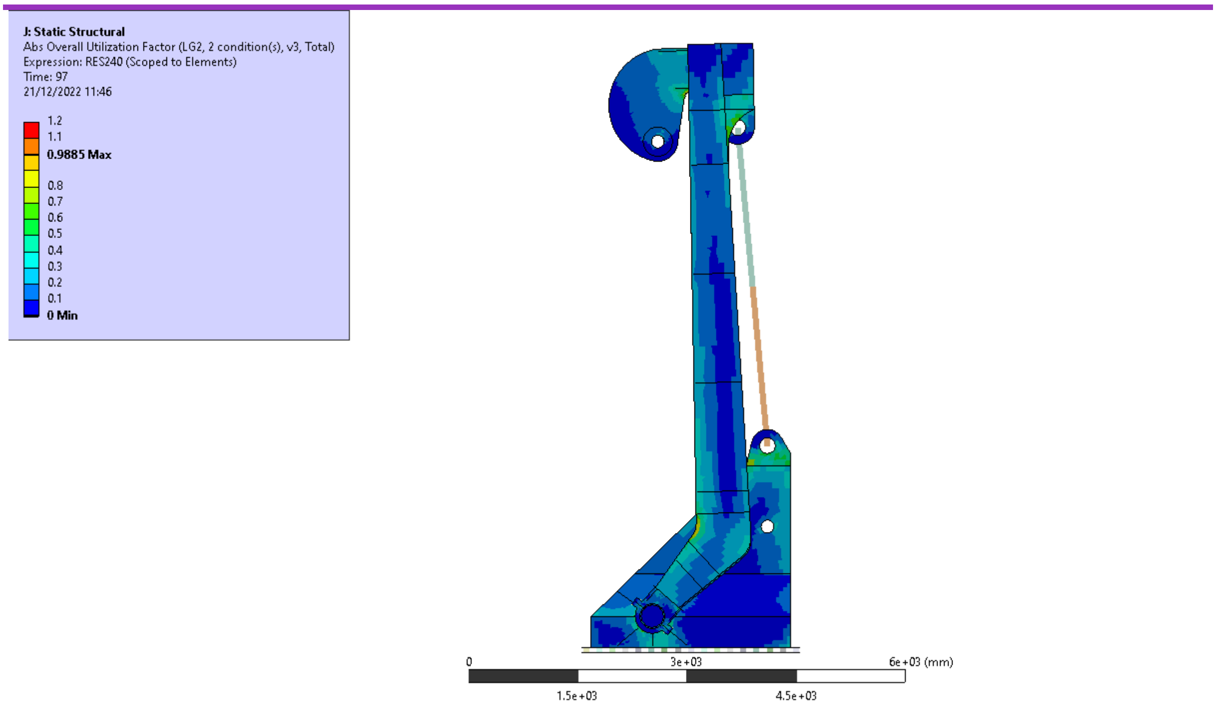
1..DNVGL-ST-0378 – Static Stress Check



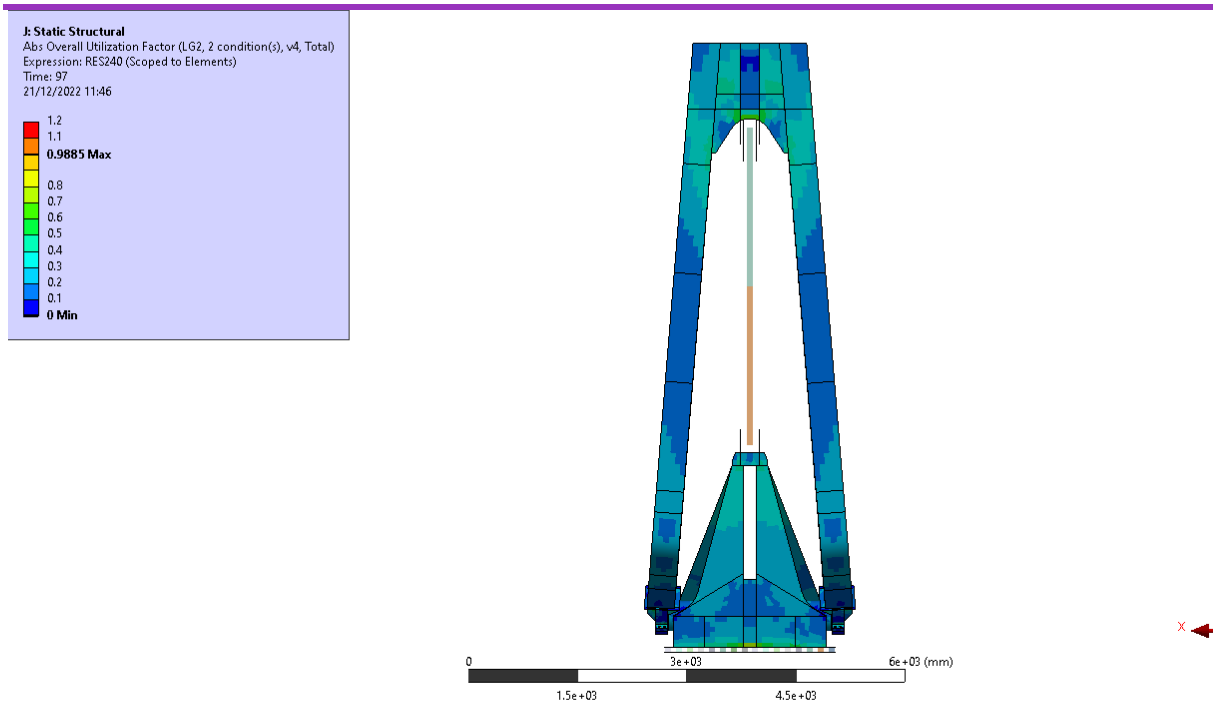
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	1..Default View



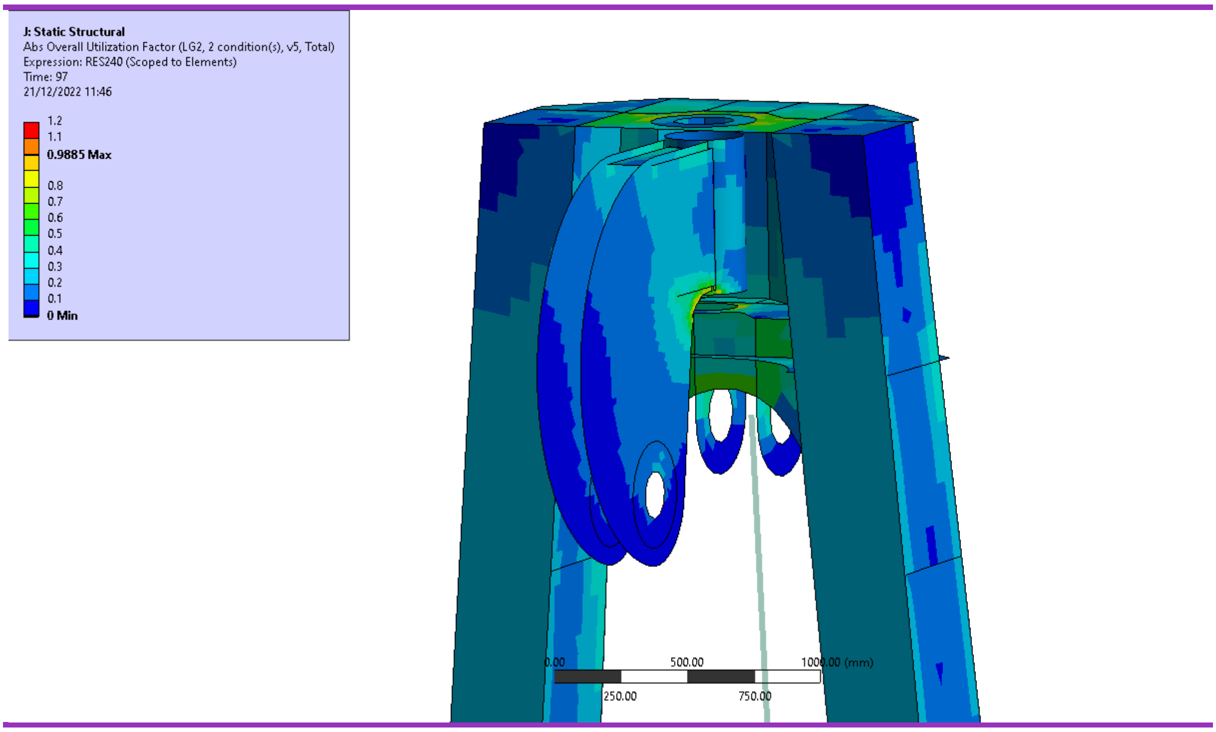
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	2..Front View



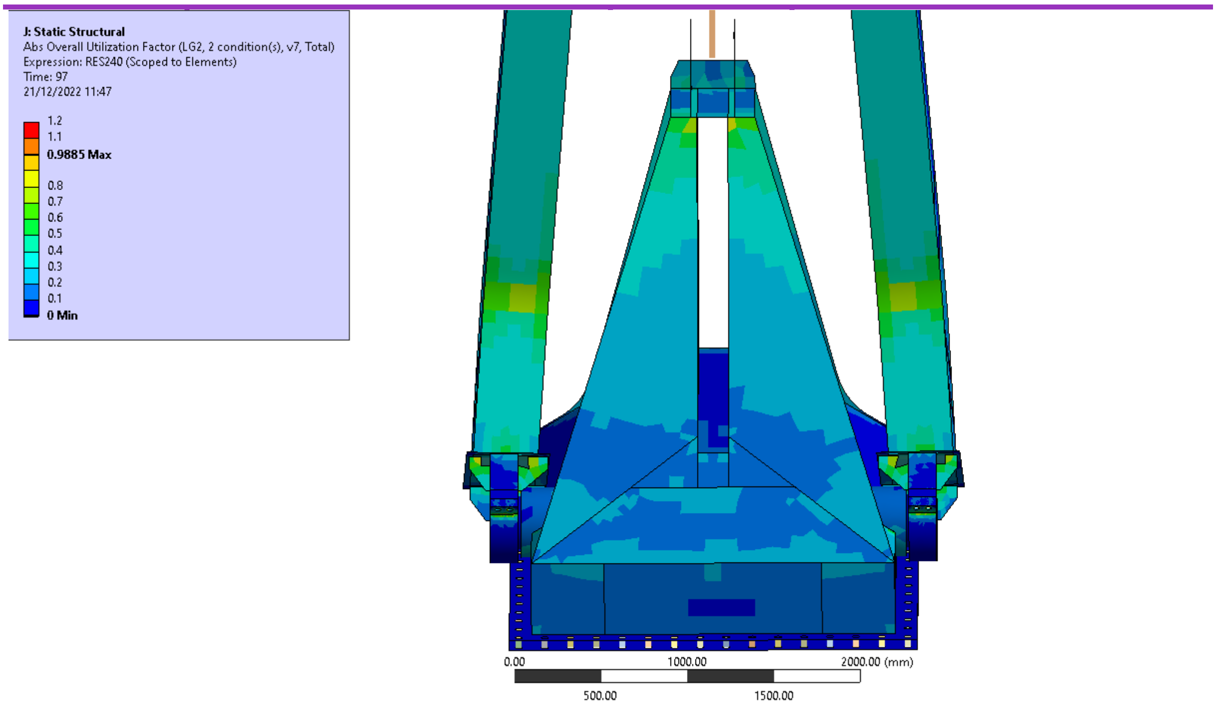
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	3..Side View



Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	4..Back View

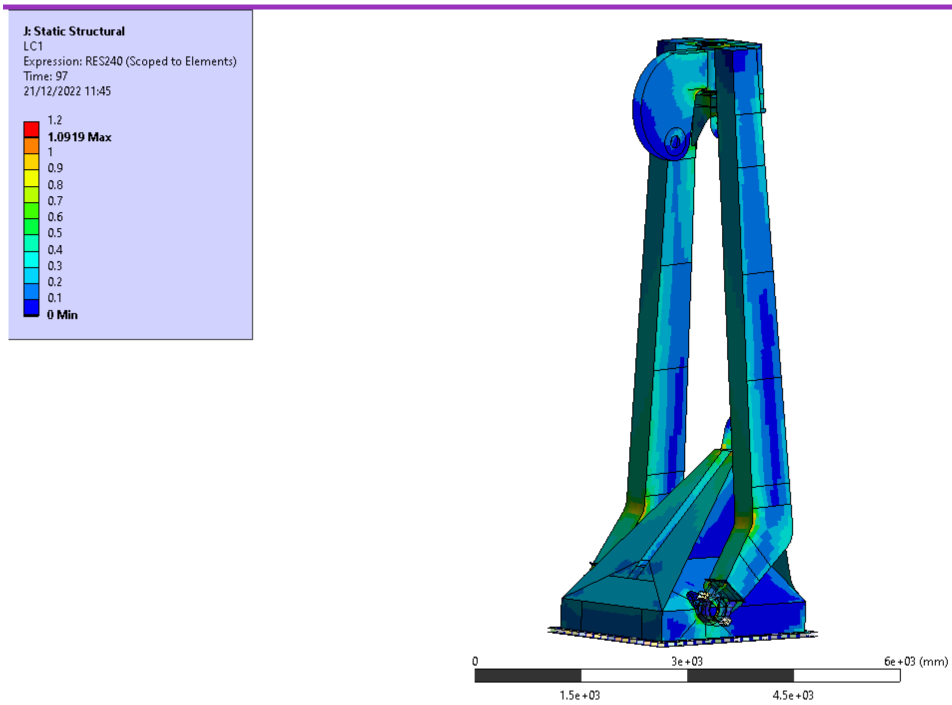


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	5..A-Frame Head and Tumbler Side

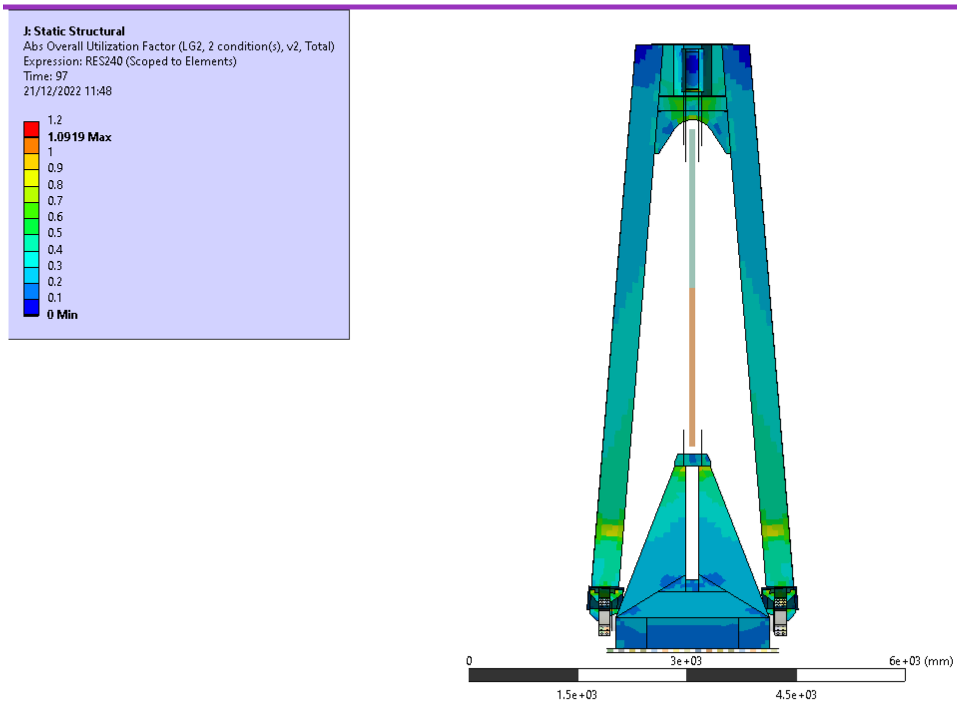


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	7..Fixed Part Front

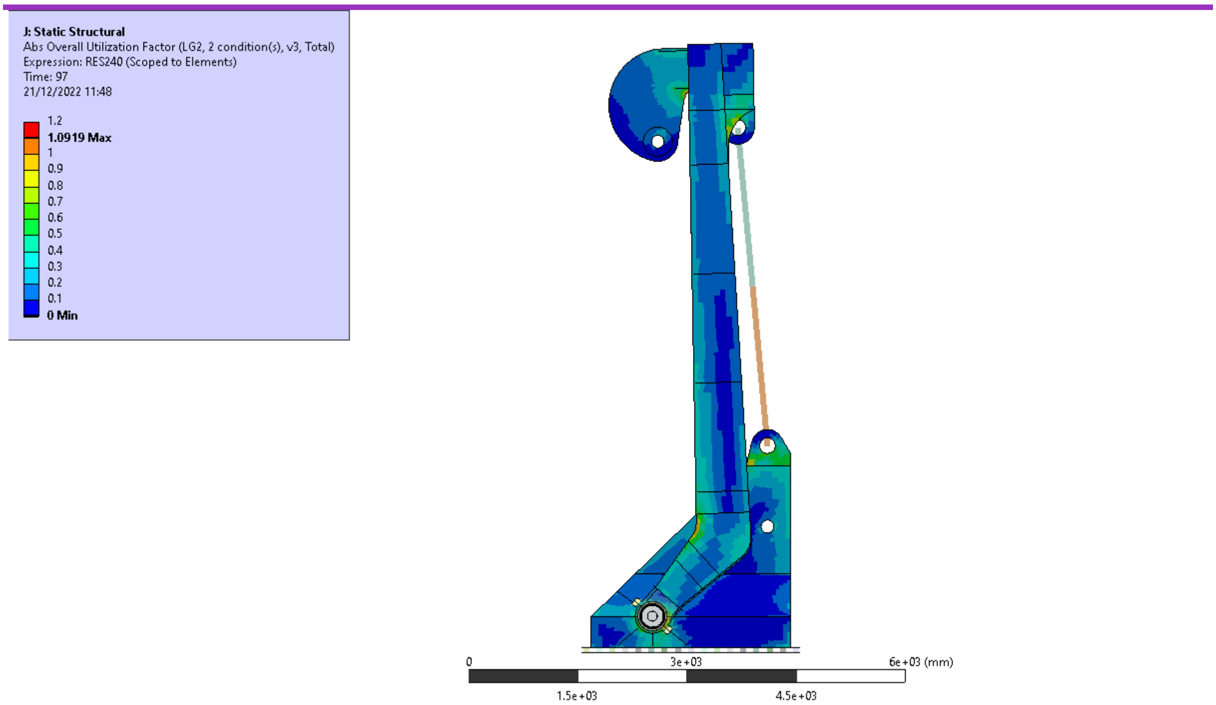
2..DNVGL-ST-0378 – Buckling check



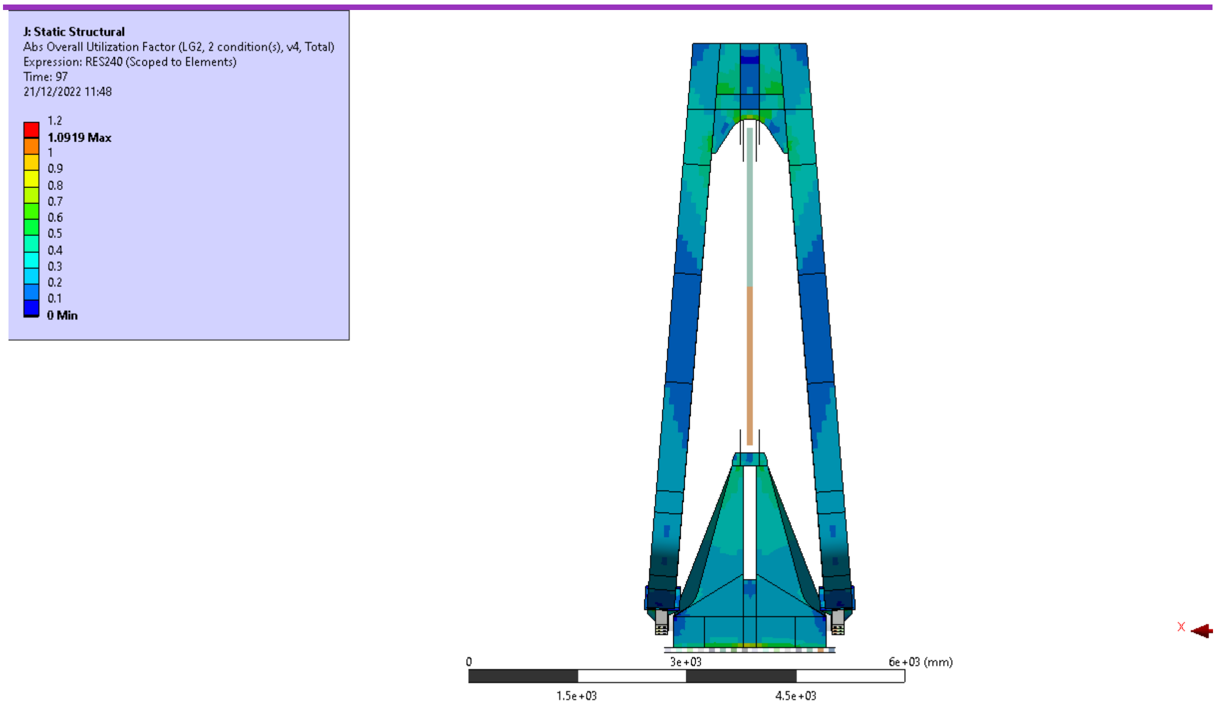
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	1..Default View



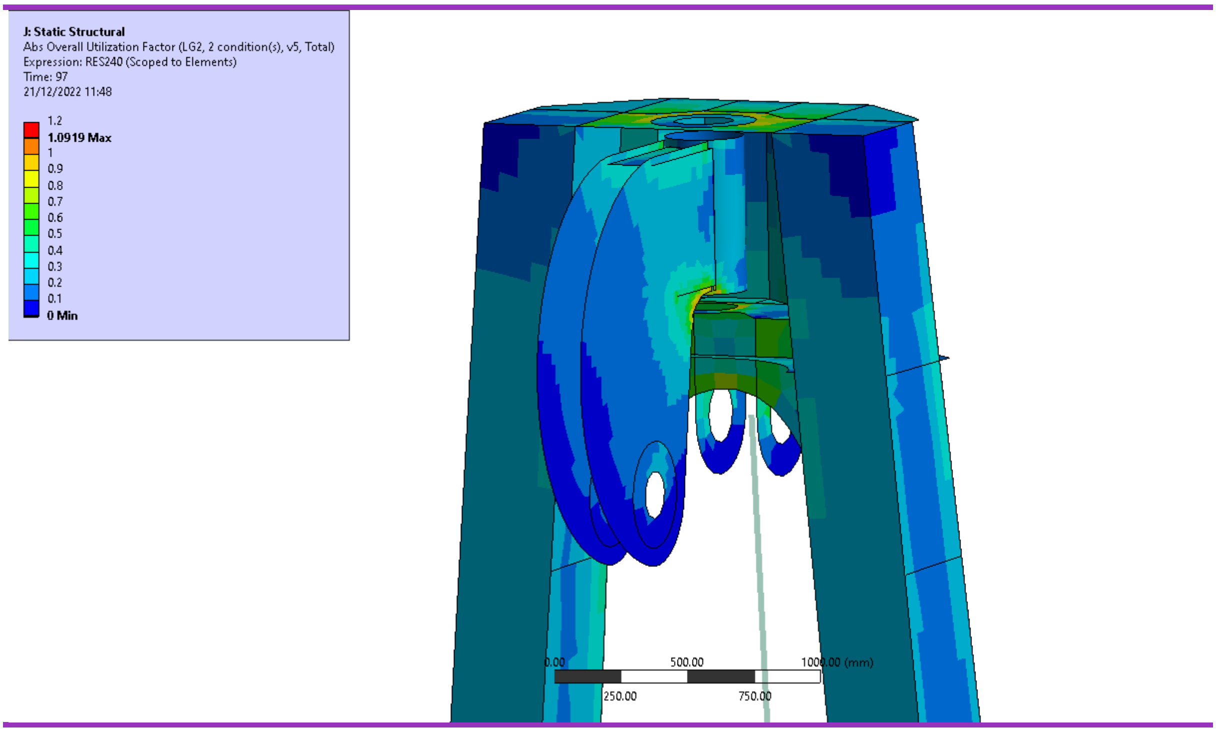
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	2..Front View



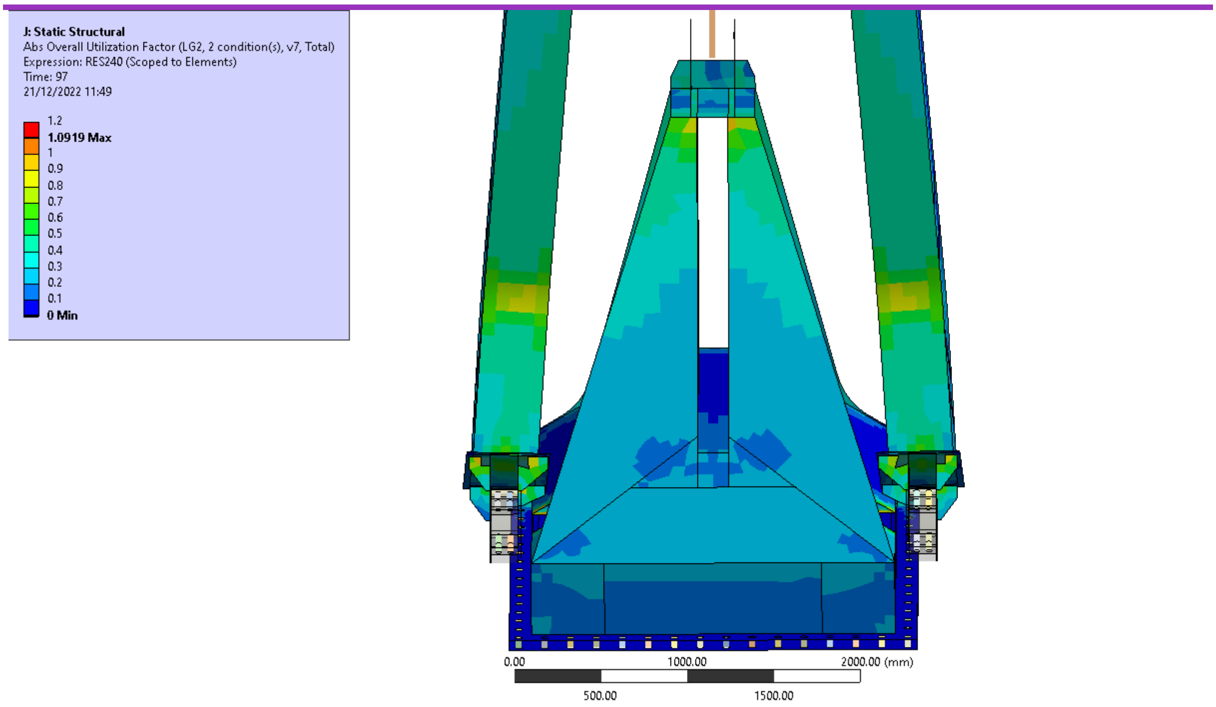
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	3..Side View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	4..Back View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	5..A-Frame Head and Tumbler Side



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG2..LC1	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	7..Fixed Part Front

3..Eurocode3 Weld (EN1993-1-8, 2005)

Standard	2..Eurocode3 Weld (EN1993-1-8, 2005)	**Check**	[S2] 15..Weld Check Total
Load Group	LG2..LC1	**Selection**	216 Welds

Title	Uf VM total	Uf N total	Uf material total	Uf Overall
133..Weld 133 [0.02; 1068.92; 7616.17]	0.83	0.30	0.78	0.83
66..Weld 66 [89; 486.24; 7704.11]	0.36	0.24	0.67	0.67
68..Weld 68 [-89; 486.23; 7704.11]	0.36	0.24	0.67	0.67
137..Weld 137 [-193.99; 1000.94; 7614.96]	0.65	0.35	0.67	0.67
140..Weld 140 [193.98; 1000.95; 7614.96]	0.65	0.34	0.67	0.67
100..Weld 100 [-1199.61; 51.75; 854.1]	0.35	0.36	0.65	0.65
55..Weld 55 [-126; 1602.19; 2530]	0.33	0.31	0.61	0.61
56..Weld 56 [126; 1601.57; 2530]	0.32	0.31	0.60	0.60
101..Weld 101 [-1350.01; 377.18; 570.92]	0.31	0.35	0.58	0.58
54..Weld 54 [-126; 1895; 2613.59]	0.28	0.25	0.53	0.53
53..Weld 53 [126; 1895; 2624.55]	0.27	0.20	0.51	0.51
319..Weld 319 [-324.59; 937.54; 7411.3]	0.26	0.30	0.49	0.49
321..Weld 321 [307.4; 937.54; 7411.3]	0.25	0.29	0.47	0.47
120..Weld 120 [541.22; 787.81; 6633.6]	0.44	0.18	0.41	0.44
86..Weld 86 [-541.22; 787.81; 6633.6]	0.42	0.17	0.40	0.42
122..Weld 122 [914.97; 786.85; 6664.22]	0.40	0.18	0.37	0.40
78..Weld 78 [-914.97; 786.85; 6664.22]	0.38	0.18	0.36	0.38
33..Weld 33 [1051; -523.44; 455.69]	0.19	0.18	0.36	0.36
35..Weld 35 [-1051; -523.44; 455.69]	0.19	0.17	0.36	0.36

52..Weld 52 [-0.07; -314.33; 970.77]	0.19	0.24	0.36	0.36
136..Weld 136 [-332.39; 921.43; 8316.66]	0.27	0.10	0.35	0.35
139..Weld 139 [332.39; 921.43; 8316.66]	0.26	0.09	0.35	0.35
57..Weld 57 [89.5; 1601.11; 2530]	0.17	0.15	0.33	0.33
67..Weld 67 [89; 366.33; 8220.3]	0.18	0.08	0.33	0.33
58..Weld 58 [-89.5; 1629.09; 2530]	0.16	0.13	0.31	0.31
17..Weld 17 [1051; 0; 160.77]	0.29	0.15	0.29	0.29
74..Weld 74 [-853.79; 757.41; 7408.1]	0.29	0.11	0.27	0.29
123..Weld 123 [853.94; 757.46; 7408.1]	0.29	0.11	0.28	0.29
142..Weld 142 [126; 1165.49; 7415.36]	0.28	0.17	0.27	0.28
19..Weld 19 [-1051; 0; 160.77]	0.27	0.15	0.27	0.27
95..Weld 95 [-666.06; 996.1; 7412.34]	0.27	0.10	0.27	0.27
143..Weld 143 [-126; 1165.54; 7415.36]	0.27	0.16	0.26	0.27
41..Weld 41 [1051; 525.5; 30]	0.14	0.17	0.26	0.26
50..Weld 50 [-629; -844; 243.64]	0.26	0.15	0.25	0.26
318..Weld 318 [308.72; 1397.47; 7419.48]	0.13	0.05	0.25	0.25
25..Weld 25 [-1051; -316.45; 199.47]	0.21	0.15	0.24	0.24
22..Weld 22 [1051; -316.45; 199.47]	0.18	0.14	0.20	0.20
93..Weld 93 [-728.08; 1042.16; 6658.92]	0.20	0.10	0.20	0.20
121..Weld 121 [728.08; 1042.16; 6658.92]	0.20	0.10	0.20	0.20
132..Weld 132 [-126; 1062.49; 7977.53]	0.17	0.13	0.20	0.20
134..Weld 134 [126; 1062.49; 7977.56]	0.17	0.13	0.20	0.20

308..Weld 308 [126; 1395.68; 7520.24]	0.11	0.13	0.20	0.20
20..Weld 20 [-1051; 316.45; 199.47]	0.18	0.12	0.19	0.19
26..Weld 26 [1051; 316.45; 199.46]	0.18	0.11	0.19	0.19
94..Weld 94 [-591.78; 940.81; 8317]	0.10	0.03	0.19	0.19
72..Weld 72 [-1088.51; 513.51; 4534.76]	0.09	0.12	0.18	0.18
105..Weld 105 [983.82; 711.97; 1227.38]	0.17	0.07	0.16	0.17
107..Weld 107 [1357.59; 711.67; 1257.76]	0.17	0.10	0.16	0.17
138..Weld 138 [-193.47; 988.95; 8317.86]	0.16	0.09	0.17	0.17
141..Weld 141 [193.47; 988.95; 8317.86]	0.15	0.09	0.17	0.17
320..Weld 320 [0; 937.54; 7411.3]	0.09	0.11	0.17	0.17
32..Weld 32 [629; -518.73; 455.69]	0.12	0.04	0.16	0.16
45..Weld 45 [662.65; -324.61; 693.54]	0.09	0.08	0.16	0.16
49..Weld 49 [-662.62; -324.62; 693.55]	0.08	0.08	0.16	0.16
75..Weld 75 [-1357.59; 711.65; 1257.77]	0.16	0.09	0.15	0.16
82..Weld 82 [-983.82; 711.97; 1227.38]	0.16	0.07	0.15	0.16
84..Weld 84 [-933.81; 976.58; 1848.4]	0.15	0.07	0.14	0.15
90..Weld 90 [-1120.63; 1334.41; 1877.77]	0.15	0.07	0.14	0.15
111..Weld 111 [1120.63; 1334.41; 1877.77]	0.15	0.07	0.14	0.15
112..Weld 112 [933.81; 976.58; 1848.4]	0.15	0.07	0.14	0.15
46..Weld 46 [89.5; 828.32; 1044.57]	0.07	0.08	0.14	0.14

97..Weld 97 [-1231.55; 373.73; 573.92]	0.08	0.08	0.14	0.14
113..Weld 113 [1307.56; 975.21; 1879]	0.14	0.08	0.13	0.14
37..Weld 37 [-1051; 1049.01; 455.69]	0.07	0.08	0.13	0.13
81..Weld 81 [-1307.56; 975.21; 1879]	0.13	0.08	0.12	0.13
106..Weld 106 [1189.8; 919.49; 1016.78]	0.13	0.06	0.12	0.13
127..Weld 127 [1231.57; 373.73; 573.92]	0.07	0.08	0.13	0.13
59..Weld 59 [-89.5; 790.34; 969.57]	0.12	0.08	0.12	0.12
61..Weld 61 [89.5; 790.34; 969.57]	0.12	0.07	0.11	0.12
65..Weld 65 [-629; 1895; 225.71]	0.12	0.07	0.11	0.12
64..Weld 64 [629; 1895; 243.35]	0.11	0.07	0.11	0.11
309..Weld 309 [126; 1387.4; 7985.61]	0.10	0.05	0.11	0.11
1..Weld 1 [-89.5; -393.64; 893.64]	0.05	0.03	0.10	0.10
28..Weld 28 [-89.5; 1068.43; 455.69]	0.10	0.07	0.10	0.10
63..Weld 63 [-0.05; 1895; 968.38]	0.05	0.07	0.10	0.10
2..Weld 2 [89.5; -393.63; 893.65]	0.05	0.02	0.09	0.09
16..Weld 16 [629; 0; 160.9]	0.07	0.04	0.09	0.09
18..Weld 18 [-629; 0; 160.9]	0.09	0.06	0.09	0.09
21..Weld 21 [-629; 316.34; 199.56]	0.09	0.05	0.09	0.09
60..Weld 60 [-89.5; -326.39; 694.85]	0.05	0.06	0.09	0.09
92..Weld 92 [-851.09; 1133.7; 5161.39]	0.09	0.04	0.08	0.09
118..Weld 118 [851.09; 1133.7; 5161.39]	0.09	0.04	0.08	0.09
27..Weld 27 [629; 316.34; 199.56]	0.06	0.01	0.08	0.08
102..Weld 102 [1374.87; 506.11; 1038.72]	0.08	0.04	0.07	0.08

144..Weld 144 [-126; 1219.05; 8321.95]	0.08	0.05	0.08	0.08
24..Weld 24 [-629; -316.35; 199.55]	0.06	0.03	0.07	0.07
76..Weld 76 [-779.68; 715.2; 8312.99]	0.04	0.03	0.07	0.07
77..Weld 77 [-1374.87; 506.11; 1038.72]	0.07	0.04	0.06	0.07
89..Weld 89 [-1096.16; 1316.16; 2176.28]	0.07	0.03	0.06	0.07
109..Weld 109 [1096.16; 1316.16; 2176.28]	0.07	0.03	0.06	0.07
23..Weld 23 [629; -316.36; 199.54]	0.05	0.01	0.06	0.06
83..Weld 83 [-909.3; 964.67; 2147.16]	0.06	0.03	0.06	0.06
85..Weld 85 [-1001.2; 507.49; 1007.19]	0.06	0.03	0.05	0.06
103..Weld 103 [1001.2; 507.49; 1007.19]	0.06	0.03	0.06	0.06
108..Weld 108 [1283.05; 963.52; 2177.77]	0.06	0.04	0.06	0.06
110..Weld 110 [909.3; 964.67; 2147.16]	0.06	0.03	0.06	0.06
96..Weld 96 [-1204.6; 686.56; 827.51]	0.05	0.02	0.05	0.05
104..Weld 104 [1204.6; 686.56; 827.51]	0.05	0.02	0.05	0.05
135..Weld 135 [0; 1056.41; 8319.06]	0.04	0.04	0.05	0.05
80..Weld 80 [-1160.49; 904.71; 3671.59]	0.04	0.03	0.04	0.04
87..Weld 87 [-786.74; 905.86; 3640.98]	0.04	0.03	0.03	0.04
114..Weld 114 [1160.49; 904.71; 3671.59]	0.04	0.03	0.03	0.04
116..Weld 116 [786.74; 905.86; 3640.98]	0.04	0.03	0.03	0.04

117..Weld 117 [664.19; 846.9; 5134.8]	0.04	0.03	0.04	0.04
317..Weld 317 [0.02; 1397.47; 7419.48]	0.02	0.02	0.04	0.04
79..Weld 79 [-1037.93; 845.67; 5165.41]	0.03	0.02	0.02	0.03
91..Weld 91 [-973.65; 1224.93; 3668.84]	0.03	0.01	0.02	0.03
115..Weld 115 [973.65; 1224.93; 3668.84]	0.03	0.01	0.02	0.03
119..Weld 119 [1037.93; 845.67; 5165.41]	0.03	0.02	0.02	0.03
30..Weld 30 [629; 1054.8; 455.69]	0.02	0.01	0.02	0.02
AbsMax over welds	0.83	0.36	0.78	0.83

4..Eurocode3 Bolts (EN 1993-1-8, 2005)

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	**Check**	[S4] 4..Category B and E. Shear resistance at serviceability
Load Group	LG2..LC1	**Selection**	2 Properties

ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension	Category B Utilization factor 1 Tension and compression	Utilization factor total
105323	230231.91	0.26	217034.08	0.36	0.36
105324	230231.91	0.10	230231.91	0.10	0.10
105325	230231.91	0.15	223725.56	0.17	0.17
105326	230231.91	0.09	230231.91	0.09	0.09
105327	230231.91	0.10	230171.27	0.10	0.10
105328	230231.91	0.10	230231.91	0.10	0.10
105329	230231.91	0.26	226074.89	0.29	0.29
105330	230231.91	0.27	220640.06	0.33	0.33
105331	230231.91	0.26	220988.00	0.32	0.32
105332	230231.91	0.24	217411.11	0.32	0.32
105333	230231.91	0.09	230231.91	0.09	0.09
105334	230231.91	0.15	223934.05	0.17	0.17
105335	230231.91	0.10	225669.64	0.11	0.11
105336	230231.91	0.09	230231.91	0.09	0.09
105337	230231.91	0.09	226766.78	0.09	0.09
105338	230231.91	0.25	226170.33	0.27	0.27
105339	230231.91	0.10	230231.91	0.10	0.10
105340	230231.91	0.09	225552.00	0.10	0.10
105341	230231.91	0.22	211241.02	0.34	0.34
105342	230231.91	0.25	213919.72	0.36	0.36
105343	230231.91	0.19	208209.47	0.32	0.32
105344	230231.91	0.08	227549.83	0.09	0.09
105345	230231.91	0.08	226727.44	0.08	0.08
105346	230231.91	0.07	227546.23	0.08	0.08
105347	230231.91	0.09	228325.48	0.09	0.09
105348	230231.91	0.09	230231.91	0.09	0.09
105349	230231.91	0.12	230231.91	0.12	0.12
105350	230231.91	0.24	204452.63	0.43	0.43
105351	230231.91	0.05	230231.91	0.05	0.05
105352	230231.91	0.09	230170.33	0.09	0.09
105353	230231.91	0.25	200375.31	0.52	0.52
105354	230231.91	0.08	230171.47	0.08	0.08
105355	230231.91	0.08	228359.56	0.08	0.08
105356	158123.88	0.13	158123.88	0.13	0.13
105357	158123.88	0.16	158123.88	0.16	0.16
105358	158123.88	0.16	158123.88	0.16	0.16
105359	158123.88	0.15	158123.88	0.15	0.15
105360	158123.88	0.15	158123.88	0.15	0.15
105361	158123.88	0.14	158123.88	0.14	0.14

105362	158123.88	0.17	158123.88	0.17	0.17
105363	158123.88	0.17	158123.88	0.17	0.17
105364	158123.88	0.09	158123.88	0.09	0.09
105365	158123.88	0.18	158123.88	0.18	0.18
105366	158123.88	0.17	158123.88	0.17	0.17
105367	158123.88	0.17	158123.88	0.17	0.17
105368	230231.91	0.03	230231.91	0.03	0.03
105369	230231.91	0.34	196321.53	0.80	0.80
105370	230231.91	0.10	230231.91	0.10	0.10
105371	230231.91	0.15	230231.91	0.15	0.15
105372	230231.91	0.12	230231.91	0.12	0.12
105373	230231.91	0.02	230231.91	0.02	0.02
105374	230231.91	0.29	197425.27	0.65	0.65
105375	230231.91	0.13	230231.91	0.13	0.13
105376	230231.91	0.16	229594.97	0.16	0.16
105377	230231.91	0.12	230231.91	0.13	0.13
105378	230231.91	0.03	230231.91	0.03	0.03
105379	230231.91	0.02	230231.91	0.02	0.02
105380	230231.91	0.16	229242.23	0.16	0.16
105381	230231.91	0.23	200870.91	0.46	0.46
105382	230231.91	0.12	230185.61	0.12	0.12
105383	230231.91	0.05	230231.91	0.05	0.05
105384	230231.91	0.10	230117.53	0.10	0.10
105385	230231.91	0.20	207110.73	0.34	0.34
105386	230231.91	0.21	204488.36	0.39	0.39
105387	230231.91	0.08	230231.91	0.08	0.08
105388	230231.91	0.09	230231.91	0.09	0.09
105389	230231.91	0.09	230231.91	0.09	0.09
105390	230231.91	0.21	211029.44	0.32	0.32
105391	230231.91	0.10	230231.91	0.10	0.10
105392	230231.91	0.12	230231.91	0.12	0.12
105393	230231.91	0.09	230231.91	0.09	0.09
105394	230231.91	0.08	230231.91	0.08	0.08
105395	230231.91	0.08	230231.91	0.08	0.08
105396	230231.91	0.21	214823.73	0.30	0.30

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	Check	[S4] 5..Category B and E. Slip-resistance at serviceability (Preloaded)
Load Group	LG2..LC1	Selection	2 Properties

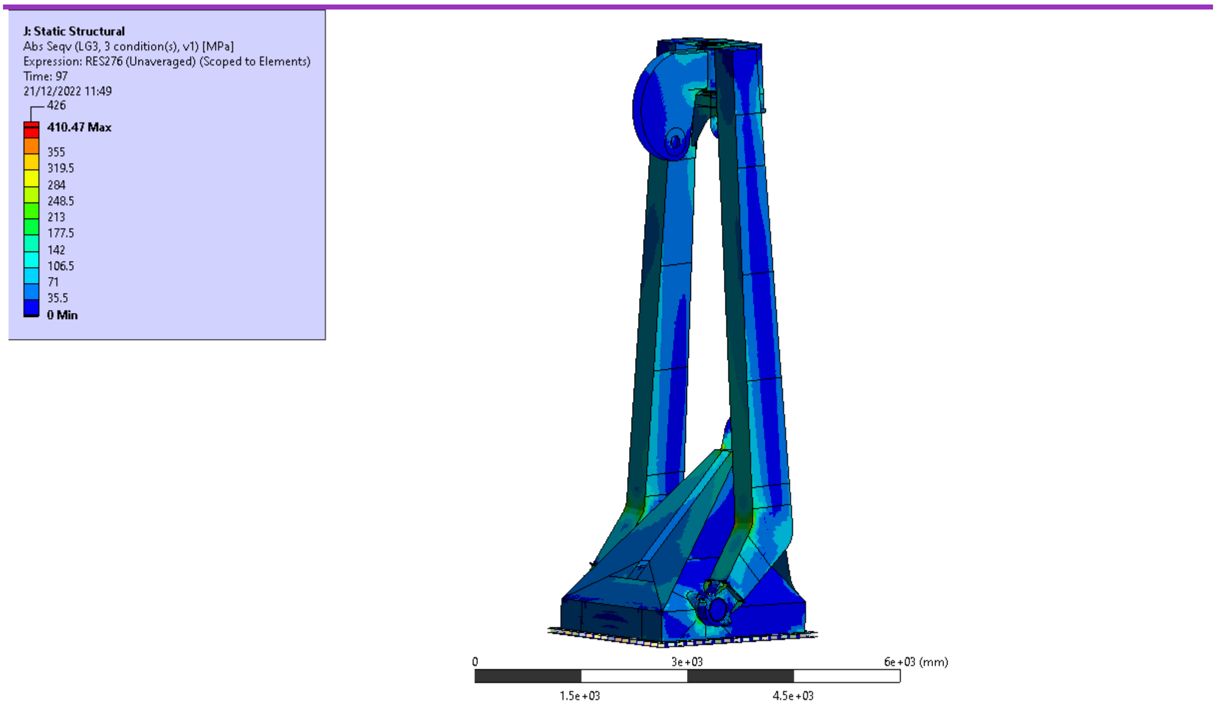
ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt [KN]	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension [KN]	Category B Utilization factor 1 Tension and compression	Shear resistance per shear plane [KN]	Category B Utilization factor 2	Bearing resistance [KN]	Category B Utilization factor 3	Tension resistance [KN]
105369	230.2	0.34	196.3	0.80	554.2	0.14	0.0	0.00	868.3
105374	230.2	0.29	197.4	0.65	554.2	0.12	0.0	0.00	868.3
105353	230.2	0.25	200.4	0.52	554.2	0.10	0.0	0.00	868.3
105381	230.2	0.23	200.9	0.46	554.2	0.09	0.0	0.00	868.3
105350	230.2	0.24	204.5	0.43	554.2	0.10	0.0	0.00	868.3
105386	230.2	0.21	204.5	0.39	554.2	0.09	0.0	0.00	868.3
105385	230.2	0.20	207.1	0.34	554.2	0.08	0.0	0.00	868.3
105343	230.2	0.19	208.2	0.32	554.2	0.08	0.0	0.00	868.3
105390	230.2	0.21	211.0	0.32	554.2	0.09	0.0	0.00	868.3
105341	230.2	0.22	211.2	0.34	554.2	0.09	0.0	0.00	868.3
105342	230.2	0.25	213.9	0.36	554.2	0.10	0.0	0.00	868.3
105396	230.2	0.21	214.8	0.30	554.2	0.09	0.0	0.00	868.3
105323	230.2	0.26	217.0	0.36	554.2	0.11	0.0	0.00	868.3
105332	230.2	0.24	217.4	0.32	554.2	0.10	0.0	0.00	868.3
105330	230.2	0.27	220.6	0.33	554.2	0.11	0.0	0.00	868.3
105331	230.2	0.26	221.0	0.32	554.2	0.11	0.0	0.00	868.3
105329	230.2	0.26	226.1	0.29	554.2	0.11	0.0	0.00	868.3
105338	230.2	0.25	226.2	0.27	554.2	0.10	0.0	0.00	868.3
105365	158.1	0.18	158.1	0.18	282.7	0.10	0.0	0.00	447.3
105367	158.1	0.17	158.1	0.17	282.7	0.10	0.0	0.00	447.3
105366	158.1	0.17	158.1	0.17	282.7	0.10	0.0	0.00	447.3
105325	230.2	0.15	223.7	0.17	554.2	0.06	0.0	0.00	868.3
105363	158.1	0.17	158.1	0.17	282.7	0.09	0.0	0.00	447.3
105362	158.1	0.17	158.1	0.17	282.7	0.09	0.0	0.00	447.3
105334	230.2	0.15	223.9	0.17	554.2	0.06	0.0	0.00	868.3
105358	158.1	0.16	158.1	0.16	282.7	0.09	0.0	0.00	447.3
105357	158.1	0.16	158.1	0.16	282.7	0.09	0.0	0.00	447.3
105376	230.2	0.16	229.6	0.16	554.2	0.07	0.0	0.00	868.3
105380	230.2	0.16	229.2	0.16	554.2	0.06	0.0	0.00	868.3
105371	230.2	0.15	230.2	0.15	554.2	0.06	0.0	0.00	868.3
105360	158.1	0.15	158.1	0.15	282.7	0.08	0.0	0.00	447.3
105359	158.1	0.15	158.1	0.15	282.7	0.08	0.0	0.00	447.3
105361	158.1	0.14	158.1	0.14	282.7	0.08	0.0	0.00	447.3
105356	158.1	0.13	158.1	0.13	282.7	0.07	0.0	0.00	447.3
105375	230.2	0.13	230.2	0.13	554.2	0.05	0.0	0.00	868.3
105377	230.2	0.12	230.2	0.13	554.2	0.05	0.0	0.00	868.3

105349	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105372	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105382	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105392	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105335	230.2	0.10	225.7	0.11	554.2	0.04	0.0	0.00	868.3
105340	230.2	0.09	225.6	0.10	554.2	0.04	0.0	0.00	868.3
105328	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105384	230.2	0.10	230.1	0.10	554.2	0.04	0.0	0.00	868.3
105370	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105339	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105391	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105324	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105327	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105364	158.1	0.09	158.1	0.09	282.7	0.05	0.0	0.00	447.3
105326	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105333	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105393	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105352	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105389	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105348	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105336	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105347	230.2	0.09	228.3	0.09	554.2	0.04	0.0	0.00	868.3
105337	230.2	0.09	226.8	0.09	554.2	0.04	0.0	0.00	868.3
105388	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105344	230.2	0.08	227.5	0.09	554.2	0.04	0.0	0.00	868.3
105354	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105395	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105387	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105394	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105355	230.2	0.08	228.4	0.08	554.2	0.03	0.0	0.00	868.3
105345	230.2	0.08	226.7	0.08	554.2	0.03	0.0	0.00	868.3
105346	230.2	0.07	227.5	0.08	554.2	0.03	0.0	0.00	868.3
105351	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105383	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105368	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105378	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105373	230.2	0.02	230.2	0.02	554.2	0.01	0.0	0.00	868.3
105379	230.2	0.02	230.2	0.02	554.2	0.01	0.0	0.00	868.3

ID / Point	Category E Utilization factor 1	Punching shear resistance [KN]	Category E Utilization factor 2	Combined utilization factor	Design tensile load [KN]	Design shear load [KN]	Utilization factor overall	pretension load [KN]
105369	0.70	6080.1	0.10	0.64	604.7	78.4	0.70	844.2
105374	0.68	6080.1	0.10	0.60	586.4	66.9	0.68	844.2
105353	0.63	6080.1	0.09	0.55	544.5	57.7	0.63	844.2
105381	0.62	6080.1	0.09	0.53	535.7	52.3	0.62	844.2
105350	0.55	6080.1	0.08	0.49	481.8	54.1	0.55	844.2
105386	0.55	6080.1	0.08	0.48	480.0	49.4	0.55	844.2
105385	0.51	6080.1	0.07	0.44	443.9	45.5	0.51	844.2
105343	0.49	6080.1	0.07	0.43	424.1	44.4	0.49	844.2
105390	0.44	6080.1	0.06	0.40	381.4	47.9	0.44	844.2
105341	0.43	6080.1	0.06	0.40	377.6	50.1	0.43	844.2
105342	0.38	6080.1	0.05	0.38	334.3	57.4	0.38	844.2
105396	0.36	6080.1	0.05	0.35	315.0	49.4	0.36	844.2
105323	0.33	6080.1	0.05	0.34	282.6	60.3	0.34	844.2
105332	0.32	6080.1	0.05	0.32	274.3	54.4	0.32	844.2
105330	0.24	6080.1	0.03	0.28	207.1	61.8	0.28	844.2
105331	0.23	6080.1	0.03	0.27	198.6	60.3	0.27	844.2
105329	0.10	6080.1	0.01	0.18	91.0	60.5	0.26	844.2
105338	0.10	6080.1	0.01	0.18	88.7	56.9	0.25	844.2
105365	0.00	7962.1	0.00	0.10	0.3	29.0	0.18	434.8
105367	0.00	7962.1	0.00	0.10	0.0	27.4	0.17	434.8
105366	0.00	7962.1	0.00	0.10	0.0	27.3	0.17	434.8
105325	0.15	6080.1	0.02	0.17	133.8	34.0	0.17	844.2
105363	0.00	7962.1	0.00	0.09	0.1	26.4	0.17	434.8
105362	0.00	7962.1	0.00	0.09	0.1	26.4	0.17	434.8
105334	0.15	6080.1	0.02	0.16	126.0	34.0	0.16	844.2
105358	0.00	7962.1	0.00	0.09	0.1	25.6	0.16	434.8
105357	0.00	7962.1	0.00	0.09	0.1	25.6	0.16	434.8
105376	0.03	6080.1	0.00	0.08	22.2	36.5	0.16	844.2
105380	0.03	6080.1	0.00	0.08	23.9	35.9	0.16	844.2
105371	0.02	6080.1	0.00	0.08	19.6	34.5	0.15	844.2
105360	0.00	7962.1	0.00	0.08	0.0	23.1	0.15	434.8
105359	0.00	7962.1	0.00	0.08	0.0	23.1	0.15	434.8
105361	0.00	7962.1	0.00	0.08	0.3	21.8	0.14	434.8
105356	0.00	7962.1	0.00	0.07	0.1	20.3	0.13	434.8
105375	0.02	6080.1	0.00	0.07	18.7	28.9	0.13	844.2
105377	0.02	6080.1	0.00	0.07	19.5	28.7	0.12	844.2
105349	0.01	6080.1	0.00	0.05	7.6	28.7	0.12	844.2
105372	0.02	6080.1	0.00	0.06	15.7	28.0	0.12	844.2
105382	0.03	6080.1	0.00	0.07	22.5	27.9	0.12	844.2
105392	0.01	6080.1	0.00	0.05	6.5	26.8	0.12	844.2
105335	0.10	6080.1	0.01	0.11	84.4	22.6	0.11	844.2
105340	0.10	6080.1	0.01	0.11	90.8	20.5	0.11	844.2
105328	0.01	6080.1	0.00	0.04	5.5	23.9	0.10	844.2
105384	0.02	6080.1	0.00	0.05	16.0	23.8	0.10	844.2
105370	0.02	6080.1	0.00	0.05	16.9	23.5	0.10	844.2

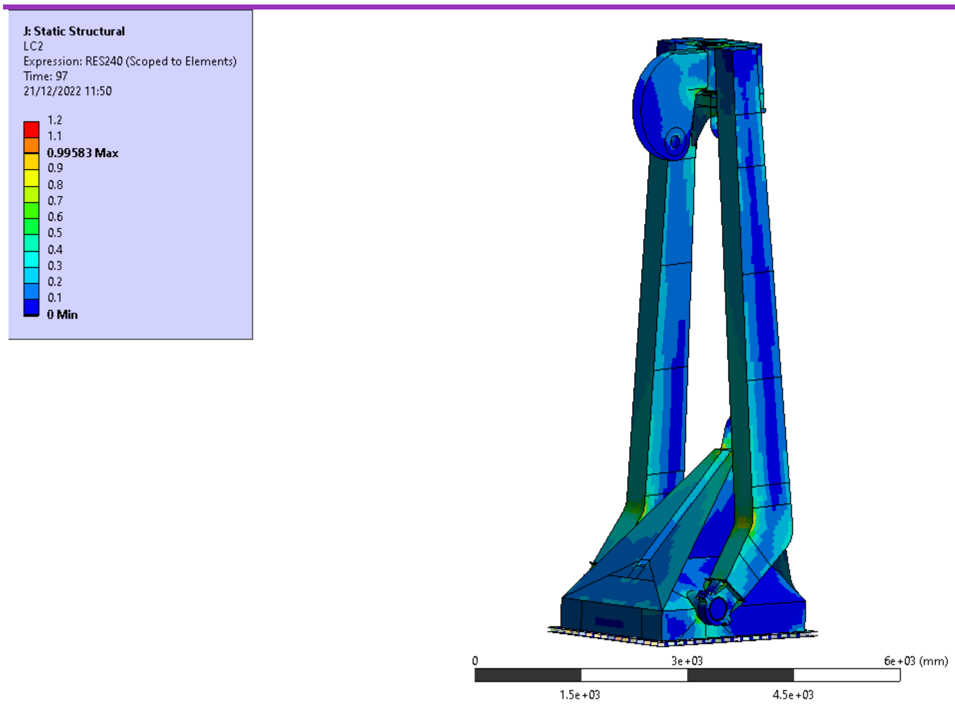
105339	0.01	6080.1	0.00	0.04	12.2	23.5	0.10	844.2
105391	0.01	6080.1	0.00	0.04	8.3	22.6	0.10	844.2
105324	0.01	6080.1	0.00	0.04	11.0	22.6	0.10	844.2
105327	0.01	6080.1	0.00	0.04	6.9	21.9	0.10	844.2
105364	0.00	7962.1	0.00	0.05	0.2	14.9	0.09	434.8
105326	0.02	6080.1	0.00	0.04	17.8	21.5	0.09	844.2
105333	0.02	6080.1	0.00	0.04	16.0	21.3	0.09	844.2
105393	0.01	6080.1	0.00	0.04	7.6	21.3	0.09	844.2
105352	0.01	6080.1	0.00	0.05	11.6	20.9	0.09	844.2
105389	0.01	6080.1	0.00	0.04	11.5	20.7	0.09	844.2
105348	0.01	6080.1	0.00	0.04	4.7	20.5	0.09	844.2
105336	0.01	6080.1	0.00	0.04	7.7	20.3	0.09	844.2
105347	0.03	6080.1	0.00	0.06	24.4	19.9	0.09	844.2
105337	0.07	6080.1	0.01	0.08	57.8	19.8	0.09	844.2
105388	0.00	6080.1	0.00	0.04	4.3	19.7	0.09	844.2
105344	0.05	6080.1	0.01	0.07	39.3	19.5	0.08	844.2
105354	0.02	6080.1	0.00	0.04	15.1	19.3	0.08	844.2
105395	0.02	6080.1	0.00	0.03	13.2	18.7	0.08	844.2
105387	0.02	6080.1	0.00	0.05	14.6	18.5	0.08	844.2
105394	0.01	6080.1	0.00	0.04	12.1	18.4	0.08	844.2
105355	0.03	6080.1	0.00	0.05	29.9	18.0	0.08	844.2
105345	0.07	6080.1	0.01	0.08	62.8	17.6	0.08	844.2
105346	0.05	6080.1	0.01	0.06	44.9	17.3	0.07	844.2
105351	0.00	6080.1	0.00	0.02	3.7	12.3	0.05	844.2
105383	0.00	6080.1	0.00	0.02	3.3	11.2	0.05	844.2
105368	0.00	6080.1	0.00	0.01	2.9	7.5	0.03	844.2
105378	0.00	6080.1	0.00	0.01	2.5	6.8	0.03	844.2
105373	0.00	6080.1	0.00	0.01	2.3	3.8	0.02	844.2
105379	0.00	6080.1	0.00	0.01	2.2	3.5	0.02	844.2

LG3..LC2

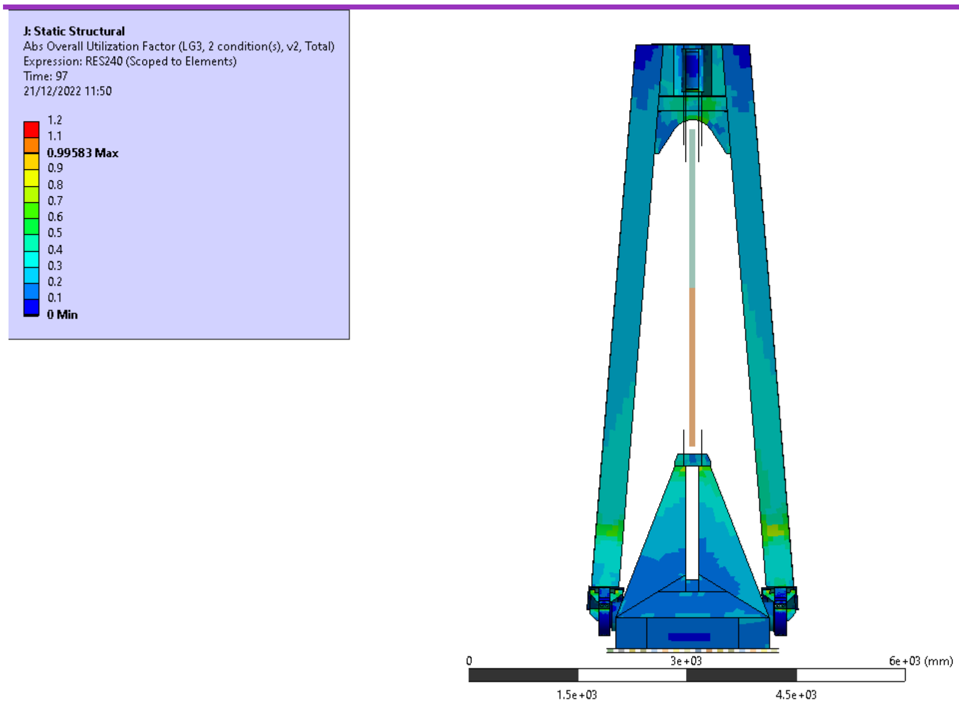


Load Group	LG3..LC2	**Parameter**	AbsoluteStress Equivalent
Selection	90397 element(s)	**View**	1..Default View
Data Conversion	No Averaging		

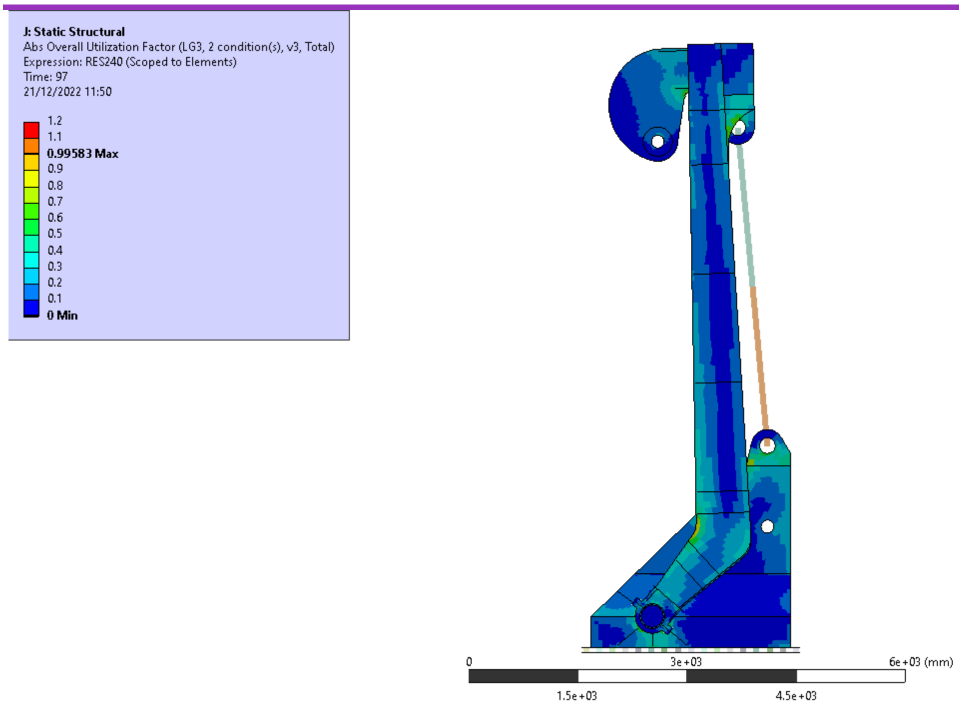
1..DNVGL-ST-0378 – Static Stress Check



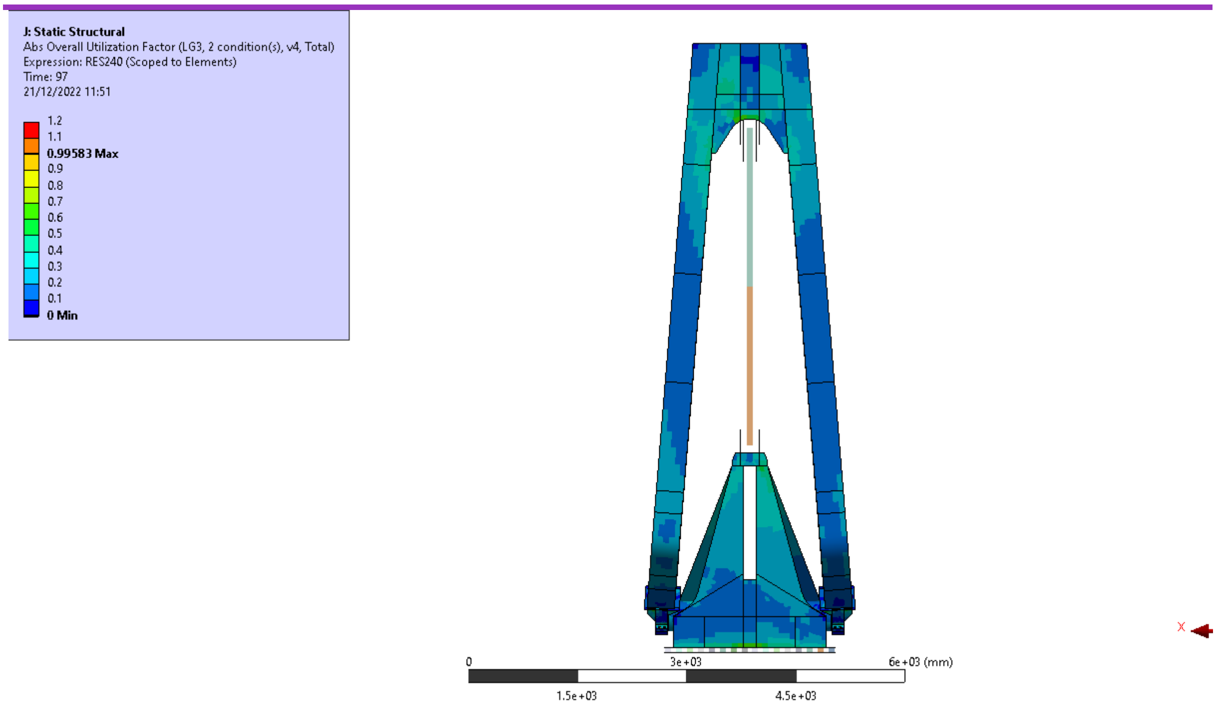
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	1..Default View



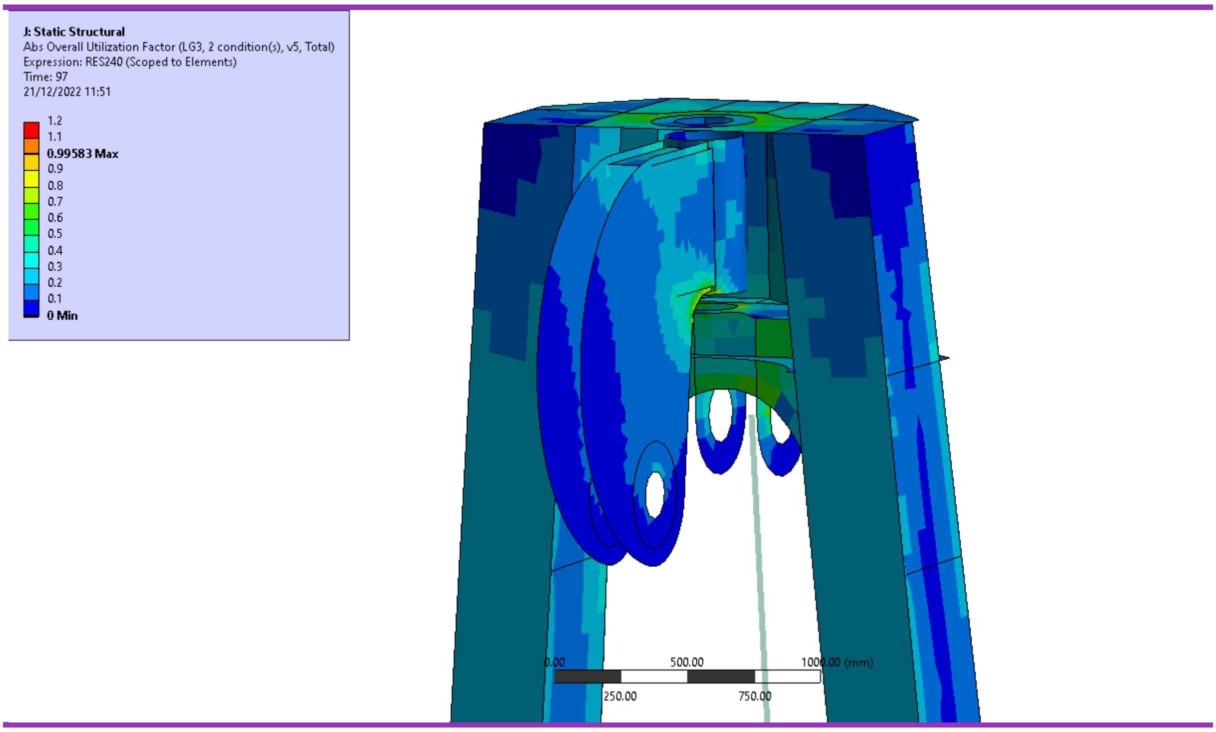
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	2..Front View



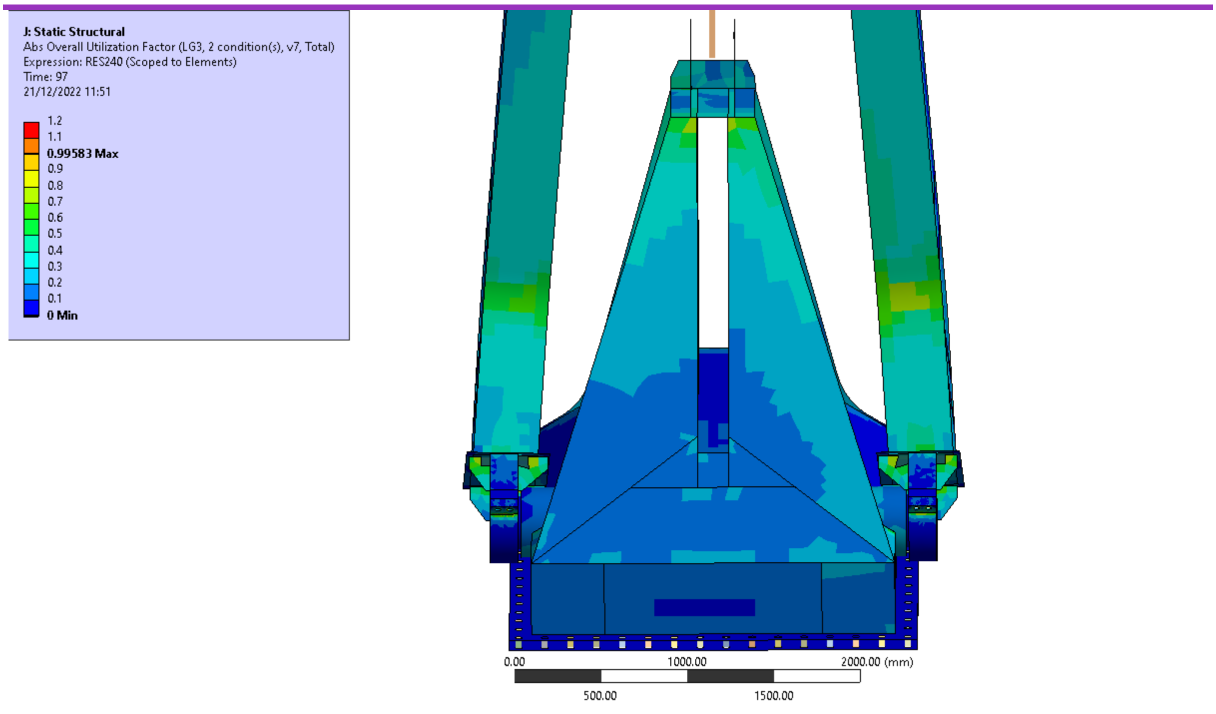
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	3..Side View



Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	4..Back View

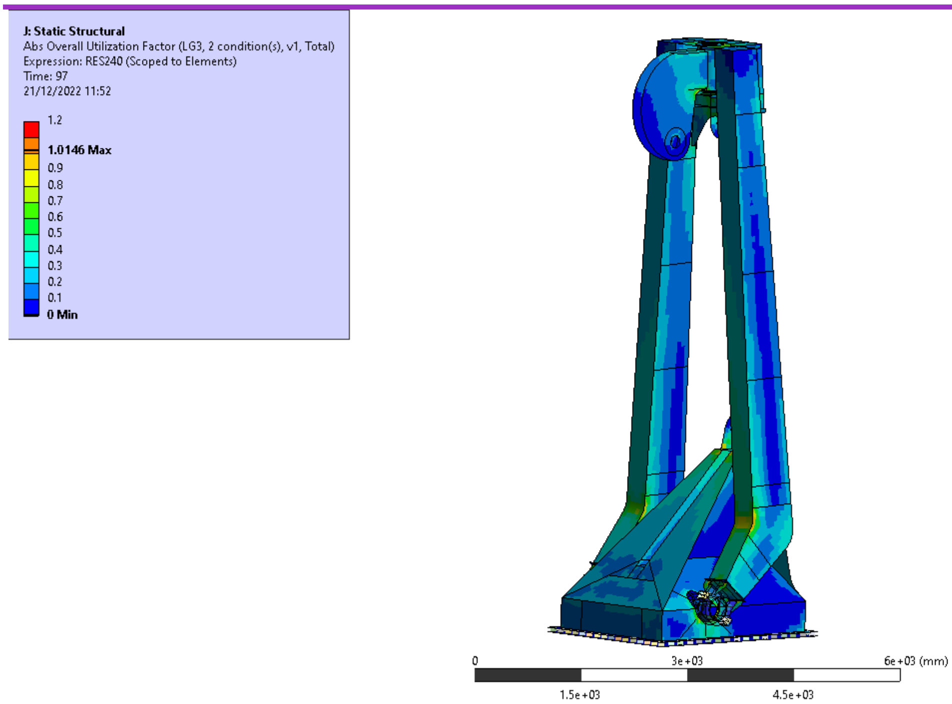


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	5..A-Frame Head and Tumbler Side

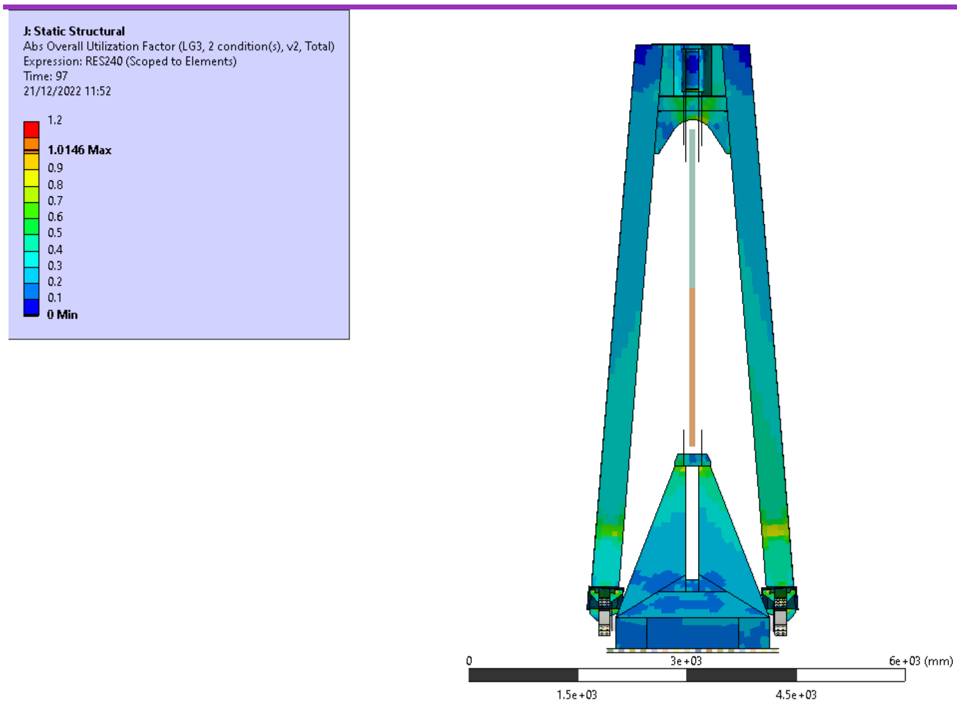


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	7..Fixed Part Front

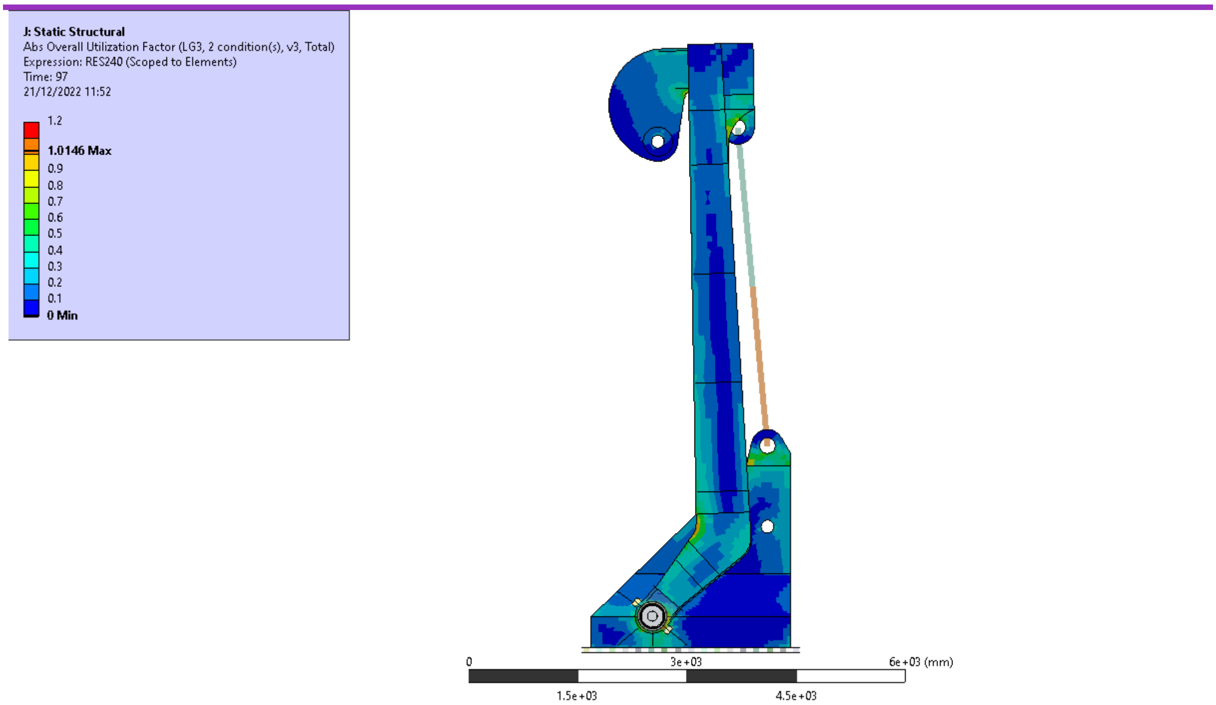
2..DNVGL-ST-0378 – Buckling check



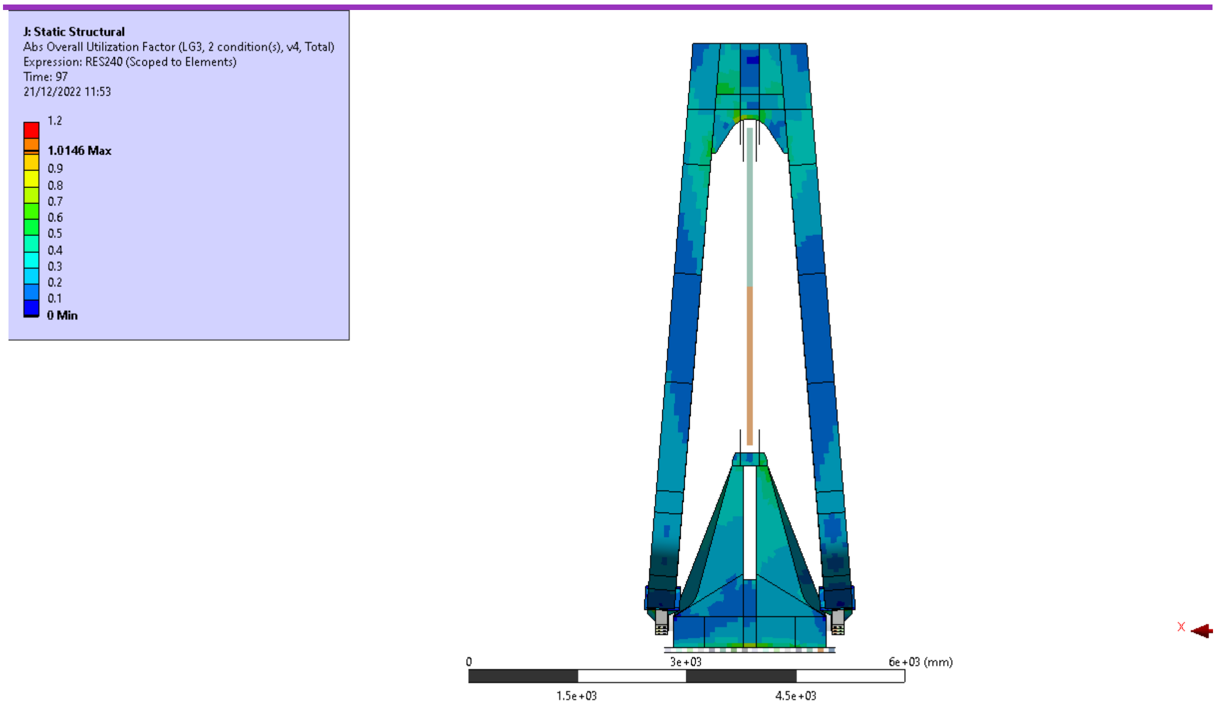
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	1..Default View



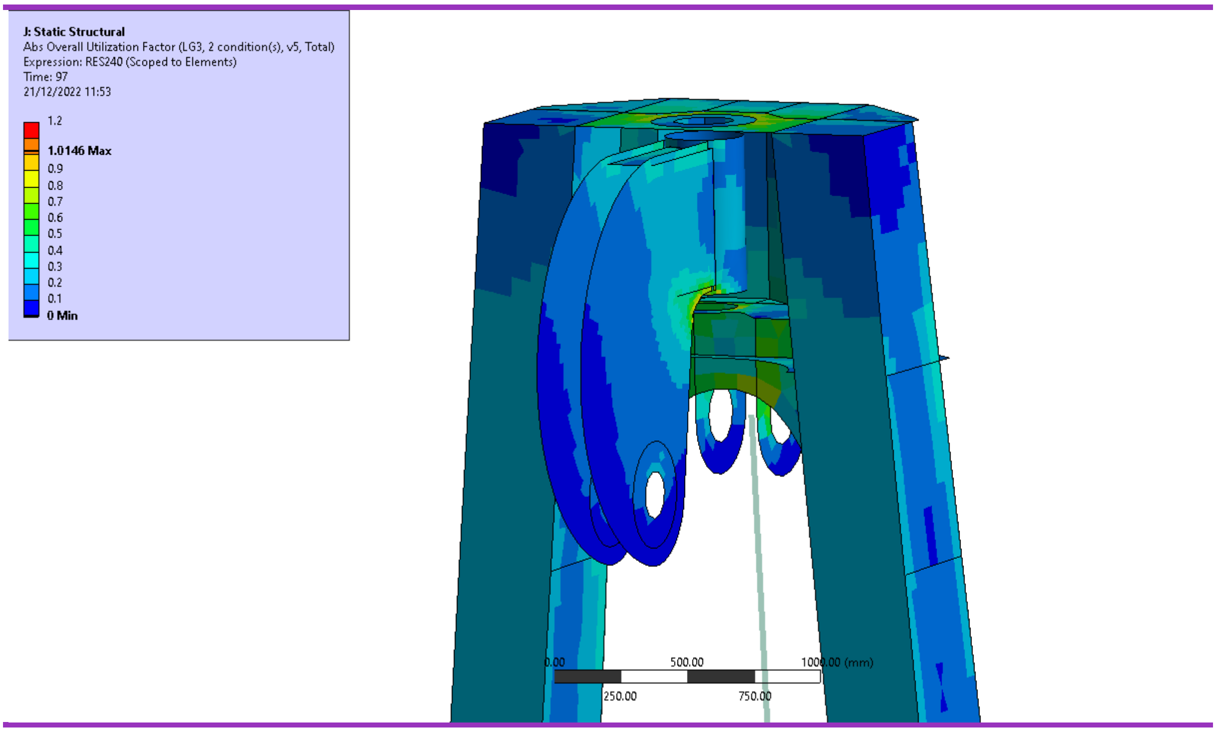
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	2..Front View



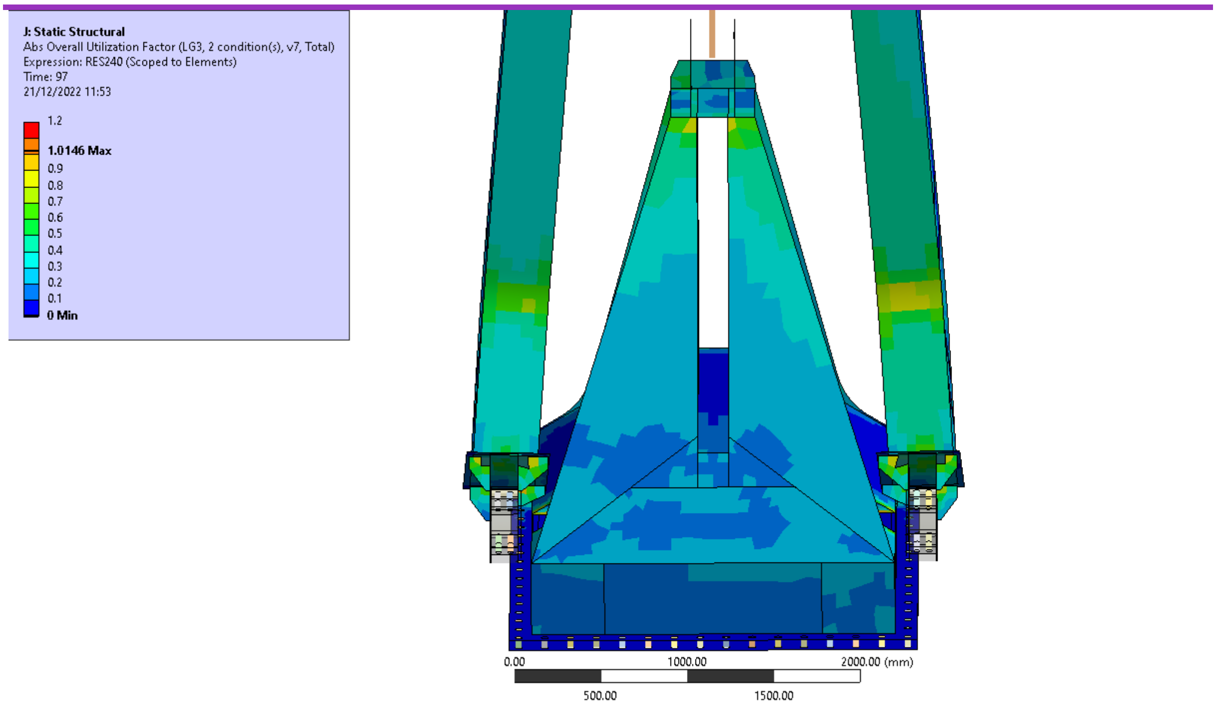
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	3..Side View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	4..Back View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	5..A-Frame Head and Tumbler Side



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG3..LC2	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	7..Fixed Part Front

3..Eurocode3 Weld (EN1993-1-8, 2005)

Standard	2..Eurocode3 Weld (EN1993-1-8, 2005)	**Check**	[S2] 15..Weld Check Total
Load Group	LG3..LC2	**Selection**	216 Welds

Title	Uf VM total	Uf N total	Uf material total	Uf Overall
133..Weld 133 [0.02; 1068.92; 7616.17]	0.93	0.36	0.87	0.93
101..Weld 101 [-1350.01; 377.18; 570.92]	0.39	0.44	0.74	0.74
140..Weld 140 [193.98; 1000.95; 7614.96]	0.67	0.35	0.70	0.70
66..Weld 66 [89; 486.24; 7704.11]	0.36	0.24	0.68	0.68
68..Weld 68 [-89; 486.23; 7704.11]	0.36	0.26	0.68	0.68
137..Weld 137 [-193.99; 1000.94; 7614.96]	0.65	0.35	0.68	0.68
54..Weld 54 [-126; 1895; 2613.59]	0.35	0.33	0.66	0.66
56..Weld 56 [126; 1601.57; 2530]	0.35	0.35	0.66	0.66
55..Weld 55 [-126; 1602.19; 2530]	0.34	0.33	0.64	0.64
100..Weld 100 [-1199.61; 51.75; 854.1]	0.34	0.33	0.63	0.63
53..Weld 53 [126; 1895; 2624.55]	0.26	0.19	0.50	0.50
319..Weld 319 [-324.59; 937.54; 7411.3]	0.26	0.30	0.49	0.49
321..Weld 321 [307.4; 937.54; 7411.3]	0.26	0.30	0.49	0.49
120..Weld 120 [541.22; 787.81; 6633.6]	0.45	0.19	0.42	0.45
86..Weld 86 [-541.22; 787.81; 6633.6]	0.43	0.18	0.40	0.43
33..Weld 33 [1051; -523.44; 455.69]	0.22	0.21	0.41	0.41
122..Weld 122 [914.97; 786.85; 6664.22]	0.41	0.19	0.38	0.41
78..Weld 78 [-914.97; 786.85; 6664.22]	0.39	0.18	0.36	0.39
35..Weld 35 [-1051; -523.44; 455.69]	0.19	0.18	0.37	0.37

52..Weld 52 [-0.07; -314.33; 970.77]	0.20	0.24	0.37	0.37
57..Weld 57 [89.5; 1601.11; 2530]	0.19	0.18	0.36	0.36
58..Weld 58 [-89.5; 1629.09; 2530]	0.19	0.17	0.36	0.36
139..Weld 139 [332.39; 921.43; 8316.66]	0.27	0.09	0.36	0.36
136..Weld 136 [-332.39; 921.43; 8316.66]	0.26	0.09	0.35	0.35
67..Weld 67 [89; 366.33; 8220.3]	0.18	0.09	0.34	0.34
17..Weld 17 [1051; 0; 160.77]	0.31	0.16	0.32	0.32
95..Weld 95 [-666.06; 996.1; 7412.34]	0.30	0.10	0.31	0.31
142..Weld 142 [126; 1165.49; 7415.36]	0.31	0.17	0.30	0.31
74..Weld 74 [-853.79; 757.41; 7408.1]	0.30	0.12	0.28	0.30
41..Weld 41 [1051; 525.5; 30]	0.15	0.19	0.29	0.29
123..Weld 123 [853.94; 757.46; 7408.1]	0.29	0.11	0.27	0.29
143..Weld 143 [-126; 1165.54; 7415.36]	0.28	0.17	0.28	0.28
19..Weld 19 [-1051; 0; 160.77]	0.27	0.16	0.26	0.27
318..Weld 318 [308.72; 1397.47; 7419.48]	0.14	0.06	0.26	0.26
25..Weld 25 [-1051; -316.45; 199.47]	0.21	0.16	0.25	0.25
50..Weld 50 [-629; -844; 243.64]	0.25	0.15	0.24	0.25
22..Weld 22 [1051; -316.45; 199.47]	0.21	0.16	0.23	0.23
26..Weld 26 [1051; 316.45; 199.46]	0.19	0.13	0.23	0.23
308..Weld 308 [126; 1395.68; 7520.24]	0.12	0.14	0.22	0.22
134..Weld 134 [126; 1062.49; 7977.56]	0.19	0.13	0.21	0.21
93..Weld 93 [-728.08; 1042.16; 6658.92]	0.20	0.10	0.20	0.20
94..Weld 94 [-591.78; 940.81; 8317]	0.10	0.03	0.20	0.20

121..Weld 121 [728.08; 1042.16; 6658.92]	0.20	0.11	0.20	0.20
45..Weld 45 [662.65; -324.61; 693.54]	0.10	0.10	0.19	0.19
105..Weld 105 [983.82; 711.97; 1227.38]	0.19	0.09	0.17	0.19
132..Weld 132 [-126; 1062.49; 7977.53]	0.17	0.13	0.19	0.19
20..Weld 20 [-1051; 316.45; 199.47]	0.18	0.12	0.18	0.18
49..Weld 49 [-662.62; -324.62; 693.55]	0.09	0.09	0.18	0.18
72..Weld 72 [-1088.51; 513.51; 4534.76]	0.09	0.11	0.18	0.18
97..Weld 97 [-1231.55; 373.73; 573.92]	0.09	0.10	0.18	0.18
107..Weld 107 [1357.59; 711.67; 1257.76]	0.18	0.10	0.17	0.18
320..Weld 320 [0; 937.54; 7411.3]	0.09	0.12	0.18	0.18
32..Weld 32 [629; -518.73; 455.69]	0.13	0.04	0.17	0.17
82..Weld 82 [-983.82; 711.97; 1227.38]	0.17	0.08	0.16	0.17
112..Weld 112 [933.81; 976.58; 1848.4]	0.17	0.09	0.16	0.17
138..Weld 138 [-193.47; 988.95; 8317.86]	0.16	0.10	0.17	0.17
141..Weld 141 [193.47; 988.95; 8317.86]	0.16	0.09	0.17	0.17
75..Weld 75 [-1357.59; 711.65; 1257.77]	0.16	0.09	0.15	0.16
127..Weld 127 [1231.57; 373.73; 573.92]	0.08	0.10	0.16	0.16
37..Weld 37 [-1051; 1049.01; 455.69]	0.08	0.10	0.15	0.15
46..Weld 46 [89.5; 828.32; 1044.57]	0.08	0.09	0.15	0.15
84..Weld 84 [-933.81; 976.58; 1848.4]	0.15	0.07	0.14	0.15

90..Weld 90 [-1120.63; 1334.41; 1877.77]	0.15	0.07	0.14	0.15
111..Weld 111 [1120.63; 1334.41; 1877.77]	0.15	0.07	0.14	0.15
113..Weld 113 [1307.56; 975.21; 1879]	0.15	0.09	0.14	0.15
59..Weld 59 [-89.5; 790.34; 969.57]	0.13	0.08	0.13	0.13
64..Weld 64 [629; 1895; 243.35]	0.13	0.08	0.12	0.13
65..Weld 65 [-629; 1895; 225.71]	0.13	0.08	0.13	0.13
81..Weld 81 [-1307.56; 975.21; 1879]	0.13	0.08	0.12	0.13
106..Weld 106 [1189.8; 919.49; 1016.78]	0.13	0.06	0.12	0.13
28..Weld 28 [-89.5; 1068.43; 455.69]	0.12	0.08	0.12	0.12
61..Weld 61 [89.5; 790.34; 969.57]	0.12	0.08	0.11	0.12
63..Weld 63 [-0.05; 1895; 968.38]	0.06	0.07	0.12	0.12
309..Weld 309 [126; 1387.4; 7985.61]	0.11	0.06	0.12	0.12
1..Weld 1 [-89.5; -393.64; 893.64]	0.06	0.03	0.11	0.11
60..Weld 60 [-89.5; -326.39; 694.85]	0.06	0.07	0.11	0.11
16..Weld 16 [629; 0; 160.9]	0.08	0.04	0.10	0.10
18..Weld 18 [-629; 0; 160.9]	0.10	0.07	0.10	0.10
21..Weld 21 [-629; 316.34; 199.56]	0.10	0.06	0.10	0.10
118..Weld 118 [851.09; 1133.7; 5161.39]	0.10	0.04	0.09	0.10
2..Weld 2 [89.5; -393.63; 893.65]	0.05	0.02	0.09	0.09
92..Weld 92 [-851.09; 1133.7; 5161.39]	0.09	0.04	0.08	0.09
102..Weld 102 [1374.87; 506.11; 1038.72]	0.09	0.04	0.08	0.09
24..Weld 24 [-629; -316.35; 199.55]	0.06	0.03	0.08	0.08
27..Weld 27 [629; 316.34; 199.56]	0.06	0.01	0.08	0.08

76..Weld 76 [-779.68; 715.2; 8312.99]	0.04	0.03	0.08	0.08
77..Weld 77 [-1374.87; 506.11; 1038.72]	0.08	0.04	0.07	0.08
144..Weld 144 [-126; 1219.05; 8321.95]	0.08	0.05	0.08	0.08
23..Weld 23 [629; -316.36; 199.54]	0.06	0.01	0.07	0.07
89..Weld 89 [-1096.16; 1316.16; 2176.28]	0.07	0.03	0.06	0.07
103..Weld 103 [1001.2; 507.49; 1007.19]	0.07	0.04	0.06	0.07
108..Weld 108 [1283.05; 963.52; 2177.77]	0.07	0.04	0.06	0.07
109..Weld 109 [1096.16; 1316.16; 2176.28]	0.07	0.03	0.07	0.07
110..Weld 110 [909.3; 964.67; 2147.16]	0.07	0.04	0.07	0.07
317..Weld 317 [0.02; 1397.47; 7419.48]	0.04	0.04	0.07	0.07
83..Weld 83 [-909.3; 964.67; 2147.16]	0.06	0.03	0.06	0.06
85..Weld 85 [-1001.2; 507.49; 1007.19]	0.06	0.03	0.06	0.06
135..Weld 135 [0; 1056.41; 8319.06]	0.05	0.04	0.06	0.06
96..Weld 96 [-1204.6; 686.56; 827.51]	0.05	0.02	0.05	0.05
104..Weld 104 [1204.6; 686.56; 827.51]	0.05	0.03	0.05	0.05
114..Weld 114 [1160.49; 904.71; 3671.59]	0.05	0.03	0.04	0.05
80..Weld 80 [-1160.49; 904.71; 3671.59]	0.04	0.02	0.04	0.04
87..Weld 87 [-786.74; 905.86; 3640.98]	0.04	0.03	0.04	0.04
116..Weld 116 [786.74; 905.86; 3640.98]	0.04	0.03	0.04	0.04

117..Weld 117 [664.19; 846.9; 5134.8]	0.04	0.03	0.04	0.04
79..Weld 79 [-1037.93; 845.67; 5165.41]	0.03	0.02	0.03	0.03
91..Weld 91 [-973.65; 1224.93; 3668.84]	0.03	0.01	0.02	0.03
115..Weld 115 [973.65; 1224.93; 3668.84]	0.03	0.02	0.03	0.03
119..Weld 119 [1037.93; 845.67; 5165.41]	0.03	0.02	0.03	0.03
30..Weld 30 [629; 1054.8; 455.69]	0.02	0.01	0.02	0.02
AbsMax over welds	0.93	0.44	0.87	0.93

4..Eurocode3 Bolts (EN 1993-1-8, 2005)

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	**Check**	[S4] 4..Category B and E. Shear resistance at serviceability
Load Group	LG3..LC2	**Selection**	2 Properties

ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension	Category B Utilization factor 1 Tension and compression	Utilization factor total
105323	230231.91	0.30	218497.64	0.42	0.42
105324	230231.91	0.13	230231.91	0.13	0.13
105325	230231.91	0.17	224414.88	0.19	0.19
105326	230231.91	0.10	230231.91	0.10	0.10
105327	230231.91	0.11	230216.94	0.11	0.11
105328	230231.91	0.11	228157.11	0.11	0.11
105329	230231.91	0.30	226515.61	0.33	0.33
105330	230231.91	0.30	221707.36	0.39	0.39
105331	230231.91	0.26	222054.91	0.32	0.32
105332	230231.91	0.23	218844.59	0.31	0.31
105333	230231.91	0.12	230231.91	0.12	0.12
105334	230231.91	0.15	224627.78	0.17	0.17
105335	230231.91	0.11	226108.88	0.12	0.12
105336	230231.91	0.09	229970.58	0.09	0.09
105337	230231.91	0.09	226936.53	0.10	0.10
105338	230231.91	0.24	226603.94	0.27	0.27
105339	230231.91	0.10	230231.91	0.10	0.10
105340	230231.91	0.10	226002.13	0.11	0.11
105341	230231.91	0.25	213215.70	0.40	0.40
105342	230231.91	0.28	215654.61	0.43	0.43
105343	230231.91	0.22	210448.50	0.38	0.38
105344	230231.91	0.09	227399.58	0.10	0.10
105345	230231.91	0.09	226884.55	0.10	0.10
105346	230231.91	0.09	227296.34	0.09	0.09
105347	230231.91	0.09	228155.81	0.10	0.10
105348	230231.91	0.08	230231.91	0.08	0.08
105349	230231.91	0.12	230231.91	0.12	0.12
105350	230231.91	0.26	207050.64	0.50	0.50
105351	230231.91	0.06	230231.91	0.06	0.06
105352	230231.91	0.10	230231.91	0.10	0.10
105353	230231.91	0.28	203379.27	0.59	0.59
105354	230231.91	0.10	228698.28	0.10	0.10
105355	230231.91	0.09	227507.17	0.09	0.09
105356	158123.88	0.15	158123.88	0.15	0.15
105357	158123.88	0.18	158123.88	0.18	0.18
105358	158123.88	0.18	158123.88	0.18	0.18
105359	158123.88	0.17	158123.88	0.17	0.17

105360	158123.88	0.17	158123.88	0.17	0.17
105361	158123.88	0.16	158123.88	0.16	0.16
105362	158123.88	0.19	158123.88	0.19	0.19
105363	158123.88	0.19	158123.88	0.19	0.19
105364	158123.88	0.11	158123.88	0.11	0.11
105365	158123.88	0.21	158123.88	0.21	0.21
105366	158123.88	0.20	158123.88	0.20	0.20
105367	158123.88	0.20	158123.88	0.20	0.20
105368	230231.91	0.04	230231.91	0.04	0.04
105369	230231.91	0.36	199769.34	0.87	0.87
105370	230231.91	0.11	227407.17	0.12	0.12
105371	230231.91	0.16	230231.91	0.17	0.17
105372	230231.91	0.13	230231.91	0.14	0.14
105373	230231.91	0.03	230231.91	0.03	0.03
105374	230231.91	0.28	200702.19	0.64	0.64
105375	230231.91	0.14	225705.44	0.15	0.15
105376	230231.91	0.17	229810.84	0.18	0.18
105377	230231.91	0.14	223545.53	0.16	0.16
105378	230231.91	0.06	230231.91	0.06	0.06
105379	230231.91	0.04	230231.91	0.04	0.04
105380	230231.91	0.17	229423.69	0.18	0.18
105381	230231.91	0.21	203779.28	0.43	0.43
105382	230231.91	0.15	221688.75	0.16	0.16
105383	230231.91	0.07	230231.91	0.07	0.07
105384	230231.91	0.12	230099.95	0.13	0.13
105385	230231.91	0.19	209448.67	0.33	0.33
105386	230231.91	0.20	207123.19	0.37	0.37
105387	230231.91	0.11	222667.33	0.12	0.12
105388	230231.91	0.11	230231.91	0.11	0.11
105389	230231.91	0.11	230231.91	0.12	0.12
105390	230231.91	0.20	213013.92	0.32	0.32
105391	230231.91	0.11	225713.34	0.12	0.12
105392	230231.91	0.15	230231.91	0.15	0.15
105393	230231.91	0.11	230231.91	0.11	0.11
105394	230231.91	0.10	230231.91	0.10	0.10
105395	230231.91	0.09	229973.20	0.09	0.09
105396	230231.91	0.21	216447.59	0.30	0.30

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	**Check**	[S4] 5..Category B and E. Slip-resistance at serviceability (Preloaded)
Load Group	LG3..LC2	**Selection**	2 Properties

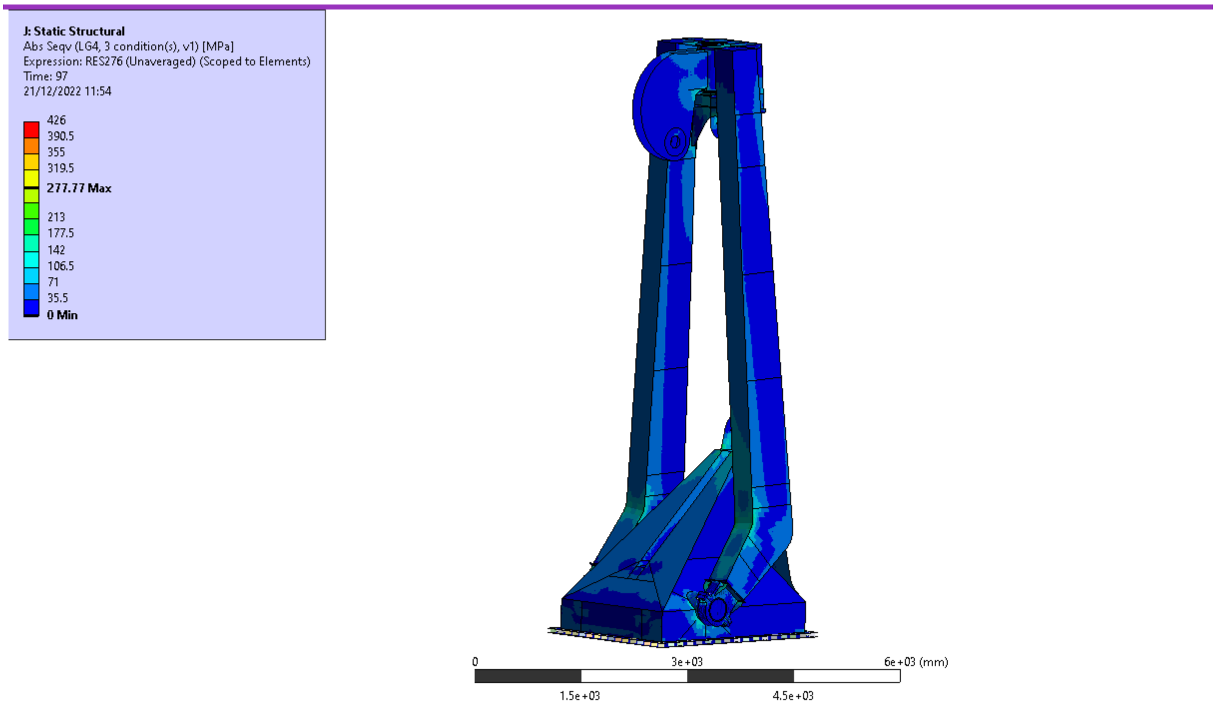
ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt [KN]	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension [KN]	Category B Utilization factor 1 Tension and compression	Shear resistance per shear plane [KN]	Category B Utilization factor 2	Bearing resistance [KN]	Category B Utilization factor 3	Tension resistance [KN]
105369	230.2	0.36	199.8	0.87	554.2	0.15	0.0	0.00	868.3
105374	230.2	0.28	200.7	0.64	554.2	0.12	0.0	0.00	868.3
105353	230.2	0.28	203.4	0.59	554.2	0.11	0.0	0.00	868.3
105381	230.2	0.21	203.8	0.43	554.2	0.09	0.0	0.00	868.3
105350	230.2	0.26	207.1	0.50	554.2	0.11	0.0	0.00	868.3
105386	230.2	0.20	207.1	0.37	554.2	0.08	0.0	0.00	868.3
105343	230.2	0.22	210.4	0.38	554.2	0.09	0.0	0.00	868.3
105385	230.2	0.19	209.4	0.33	554.2	0.08	0.0	0.00	868.3
105341	230.2	0.25	213.2	0.40	554.2	0.10	0.0	0.00	868.3
105390	230.2	0.20	213.0	0.32	554.2	0.08	0.0	0.00	868.3
105342	230.2	0.28	215.7	0.43	554.2	0.12	0.0	0.00	868.3
105323	230.2	0.30	218.5	0.42	554.2	0.12	0.0	0.00	868.3
105396	230.2	0.21	216.4	0.30	554.2	0.09	0.0	0.00	868.3
105332	230.2	0.23	218.8	0.31	554.2	0.10	0.0	0.00	868.3
105330	230.2	0.30	221.7	0.39	554.2	0.13	0.0	0.00	868.3
105329	230.2	0.30	226.5	0.33	554.2	0.12	0.0	0.00	868.3
105331	230.2	0.26	222.1	0.32	554.2	0.11	0.0	0.00	868.3
105338	230.2	0.24	226.6	0.27	554.2	0.10	0.0	0.00	868.3
105365	158.1	0.21	158.1	0.21	282.7	0.12	0.0	0.00	447.3
105367	158.1	0.20	158.1	0.20	282.7	0.11	0.0	0.00	447.3
105366	158.1	0.20	158.1	0.20	282.7	0.11	0.0	0.00	447.3
105363	158.1	0.19	158.1	0.19	282.7	0.11	0.0	0.00	447.3
105362	158.1	0.19	158.1	0.19	282.7	0.11	0.0	0.00	447.3
105325	230.2	0.17	224.4	0.19	554.2	0.07	0.0	0.00	868.3
105358	158.1	0.18	158.1	0.18	282.7	0.10	0.0	0.00	447.3
105357	158.1	0.18	158.1	0.18	282.7	0.10	0.0	0.00	447.3
105376	230.2	0.17	229.8	0.18	554.2	0.07	0.0	0.00	868.3
105380	230.2	0.17	229.4	0.18	554.2	0.07	0.0	0.00	868.3
105334	230.2	0.15	224.6	0.17	554.2	0.06	0.0	0.00	868.3
105360	158.1	0.17	158.1	0.17	282.7	0.09	0.0	0.00	447.3
105359	158.1	0.17	158.1	0.17	282.7	0.09	0.0	0.00	447.3
105371	230.2	0.16	230.2	0.17	554.2	0.07	0.0	0.00	868.3
105361	158.1	0.16	158.1	0.16	282.7	0.09	0.0	0.00	447.3
105382	230.2	0.15	221.7	0.16	554.2	0.06	0.0	0.00	868.3
105392	230.2	0.15	230.2	0.15	554.2	0.06	0.0	0.00	868.3
105356	158.1	0.15	158.1	0.15	282.7	0.08	0.0	0.00	447.3

105377	230.2	0.14	223.5	0.16	554.2	0.06	0.0	0.00	868.3
105375	230.2	0.14	225.7	0.15	554.2	0.06	0.0	0.00	868.3
105372	230.2	0.13	230.2	0.14	554.2	0.06	0.0	0.00	868.3
105324	230.2	0.13	230.2	0.13	554.2	0.05	0.0	0.00	868.3
105384	230.2	0.12	230.1	0.13	554.2	0.05	0.0	0.00	868.3
105387	230.2	0.11	222.7	0.12	554.2	0.04	0.0	0.00	868.3
105340	230.2	0.10	226.0	0.11	554.2	0.04	0.0	0.00	868.3
105349	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105333	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105389	230.2	0.11	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105335	230.2	0.11	226.1	0.12	554.2	0.04	0.0	0.00	868.3
105391	230.2	0.11	225.7	0.12	554.2	0.05	0.0	0.00	868.3
105393	230.2	0.11	230.2	0.11	554.2	0.05	0.0	0.00	868.3
105370	230.2	0.11	227.4	0.12	554.2	0.05	0.0	0.00	868.3
105327	230.2	0.11	230.2	0.11	554.2	0.05	0.0	0.00	868.3
105388	230.2	0.11	230.2	0.11	554.2	0.05	0.0	0.00	868.3
105328	230.2	0.11	228.2	0.11	554.2	0.05	0.0	0.00	868.3
105364	158.1	0.11	158.1	0.11	282.7	0.06	0.0	0.00	447.3
105339	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105394	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105352	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105326	230.2	0.10	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105354	230.2	0.10	228.7	0.10	554.2	0.04	0.0	0.00	868.3
105347	230.2	0.09	228.2	0.10	554.2	0.04	0.0	0.00	868.3
105337	230.2	0.09	226.9	0.10	554.2	0.04	0.0	0.00	868.3
105336	230.2	0.09	230.0	0.09	554.2	0.04	0.0	0.00	868.3
105344	230.2	0.09	227.4	0.10	554.2	0.04	0.0	0.00	868.3
105355	230.2	0.09	227.5	0.09	554.2	0.04	0.0	0.00	868.3
105345	230.2	0.09	226.9	0.10	554.2	0.04	0.0	0.00	868.3
105346	230.2	0.09	227.3	0.09	554.2	0.04	0.0	0.00	868.3
105395	230.2	0.09	230.0	0.09	554.2	0.04	0.0	0.00	868.3
105348	230.2	0.08	230.2	0.08	554.2	0.04	0.0	0.00	868.3
105383	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105378	230.2	0.06	230.2	0.06	554.2	0.02	0.0	0.00	868.3
105351	230.2	0.06	230.2	0.06	554.2	0.02	0.0	0.00	868.3
105379	230.2	0.04	230.2	0.04	554.2	0.02	0.0	0.00	868.3
105368	230.2	0.04	230.2	0.04	554.2	0.02	0.0	0.00	868.3
105373	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3

ID / Point	Category E Utilization factor 1	Punching shear resistance [KN]	Category E Utilization factor 2	Combined utilization factor	Design tensile load [KN]	Design shear load [KN]	Utilization factor overall	pretension load [KN]
105369	0.71	6080.1	0.10	0.66	620.7	82.2	0.71	844.2
105374	0.68	6080.1	0.10	0.60	591.0	65.2	0.68	844.2
105353	0.65	6080.1	0.09	0.58	565.3	63.3	0.65	844.2
105381	0.62	6080.1	0.09	0.53	536.6	48.6	0.62	844.2
105350	0.58	6080.1	0.08	0.53	507.3	60.4	0.58	844.2
105386	0.56	6080.1	0.08	0.48	482.9	46.9	0.56	844.2
105343	0.52	6080.1	0.07	0.46	452.9	50.7	0.52	844.2
105385	0.52	6080.1	0.07	0.45	447.8	43.9	0.52	844.2
105341	0.47	6080.1	0.07	0.44	408.0	57.3	0.47	844.2
105390	0.44	6080.1	0.06	0.40	384.9	46.5	0.44	844.2
105342	0.42	6080.1	0.06	0.42	365.9	65.4	0.42	844.2
105323	0.36	6080.1	0.05	0.38	314.5	68.8	0.38	844.2
105396	0.37	6080.1	0.05	0.35	318.3	48.2	0.37	844.2
105332	0.32	6080.1	0.05	0.32	277.0	53.1	0.32	844.2
105330	0.27	6080.1	0.04	0.32	233.1	69.8	0.32	844.2
105329	0.12	6080.1	0.02	0.21	102.7	68.7	0.30	844.2
105331	0.23	6080.1	0.03	0.27	200.2	60.3	0.27	844.2
105338	0.10	6080.1	0.01	0.18	90.0	56.2	0.24	844.2
105365	0.00	7962.1	0.00	0.12	0.6	33.0	0.21	434.8
105367	0.00	7962.1	0.00	0.11	0.2	31.0	0.20	434.8
105366	0.00	7962.1	0.00	0.11	0.2	31.0	0.20	434.8
105363	0.00	7962.1	0.00	0.11	0.7	29.9	0.19	434.8
105362	0.00	7962.1	0.00	0.11	0.7	29.9	0.19	434.8
105325	0.17	6080.1	0.02	0.19	150.6	38.1	0.19	844.2
105358	0.00	7962.1	0.00	0.10	0.7	29.2	0.18	434.8
105357	0.00	7962.1	0.00	0.10	0.7	29.2	0.18	434.8
105376	0.06	6080.1	0.01	0.12	56.1	39.8	0.17	844.2
105380	0.07	6080.1	0.01	0.12	64.8	39.6	0.17	844.2
105334	0.15	6080.1	0.02	0.17	126.8	34.9	0.17	844.2
105360	0.00	7962.1	0.00	0.09	0.3	26.2	0.17	434.8
105359	0.00	7962.1	0.00	0.09	0.3	26.2	0.17	434.8
105371	0.05	6080.1	0.01	0.10	44.3	37.8	0.16	844.2
105361	0.00	7962.1	0.00	0.09	0.7	24.7	0.16	434.8
105382	0.13	6080.1	0.02	0.15	109.3	33.6	0.15	844.2
105392	0.02	6080.1	0.00	0.06	14.3	33.9	0.15	844.2
105356	0.00	7962.1	0.00	0.08	1.9	23.1	0.15	434.8
105377	0.11	6080.1	0.02	0.13	92.4	32.6	0.14	844.2
105375	0.08	6080.1	0.01	0.12	73.4	31.6	0.14	844.2
105372	0.04	6080.1	0.01	0.08	33.2	30.9	0.13	844.2
105324	0.02	6080.1	0.00	0.05	19.3	29.5	0.13	844.2
105384	0.06	6080.1	0.01	0.09	53.5	28.6	0.12	844.2
105387	0.11	6080.1	0.02	0.12	91.2	24.8	0.12	844.2
105340	0.12	6080.1	0.02	0.12	102.7	23.6	0.12	844.2
105349	0.04	6080.1	0.01	0.05	34.8	27.1	0.12	844.2
105333	0.03	6080.1	0.00	0.06	26.5	26.9	0.12	844.2

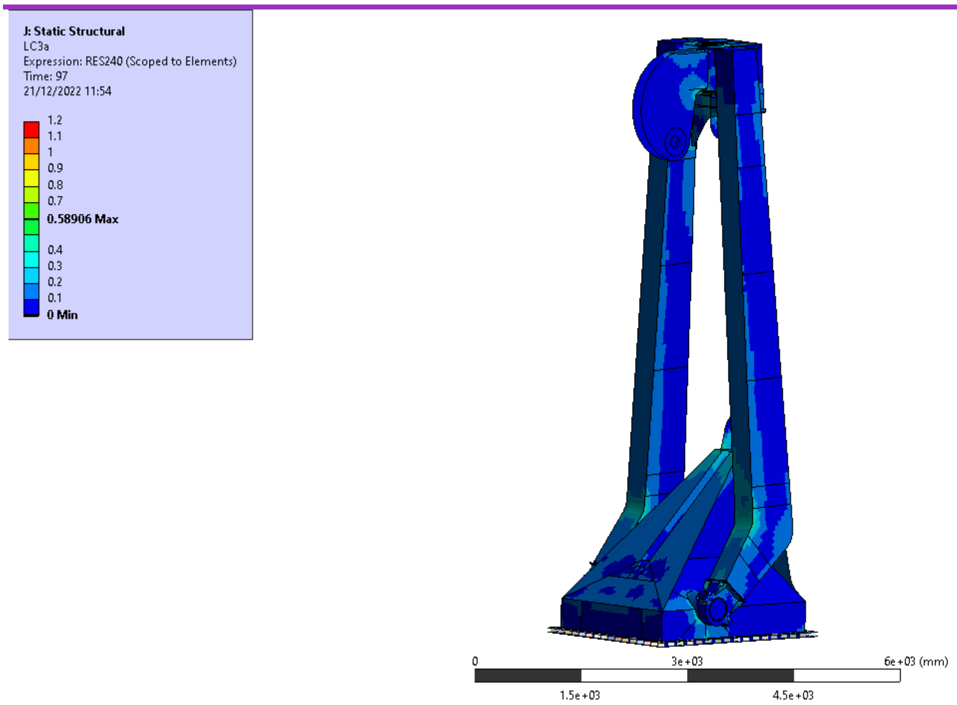
105389	0.05	6080.1	0.01	0.07	42.1	26.3	0.11	844.2
105335	0.10	6080.1	0.01	0.11	85.8	24.5	0.11	844.2
105391	0.08	6080.1	0.01	0.09	70.7	26.0	0.11	844.2
105393	0.03	6080.1	0.00	0.06	29.6	26.0	0.11	844.2
105370	0.06	6080.1	0.01	0.09	54.6	26.0	0.11	844.2
105327	0.01	6080.1	0.00	0.05	11.1	25.9	0.11	844.2
105388	0.01	6080.1	0.00	0.05	10.0	25.6	0.11	844.2
105328	0.06	6080.1	0.01	0.08	56.1	25.5	0.11	844.2
105364	0.00	7962.1	0.00	0.06	0.6	16.9	0.11	434.8
105339	0.05	6080.1	0.01	0.06	42.9	23.3	0.10	844.2
105394	0.03	6080.1	0.00	0.05	26.5	23.0	0.10	844.2
105352	0.03	6080.1	0.00	0.06	22.0	22.6	0.10	844.2
105326	0.07	6080.1	0.01	0.08	56.8	22.5	0.10	844.2
105354	0.04	6080.1	0.01	0.05	38.8	22.3	0.10	844.2
105347	0.04	6080.1	0.01	0.06	31.0	21.9	0.09	844.2
105337	0.07	6080.1	0.01	0.09	60.4	21.8	0.09	844.2
105336	0.03	6080.1	0.00	0.05	23.3	21.7	0.09	844.2
105344	0.05	6080.1	0.01	0.07	43.2	21.3	0.09	844.2
105355	0.05	6080.1	0.01	0.06	45.5	21.2	0.09	844.2
105345	0.08	6080.1	0.01	0.09	72.7	21.0	0.09	844.2
105346	0.06	6080.1	0.01	0.07	56.3	20.6	0.09	844.2
105395	0.06	6080.1	0.01	0.07	56.0	19.9	0.09	844.2
105348	0.03	6080.1	0.00	0.04	24.7	19.4	0.08	844.2
105383	0.01	6080.1	0.00	0.03	6.5	17.3	0.07	844.2
105378	0.01	6080.1	0.00	0.02	5.0	13.0	0.06	844.2
105351	0.02	6080.1	0.00	0.02	17.0	12.7	0.06	844.2
105379	0.01	6080.1	0.00	0.02	5.8	9.6	0.04	844.2
105368	0.01	6080.1	0.00	0.02	12.3	8.4	0.04	844.2
105373	0.01	6080.1	0.00	0.02	8.4	6.0	0.03	844.2

LG4..LC3a

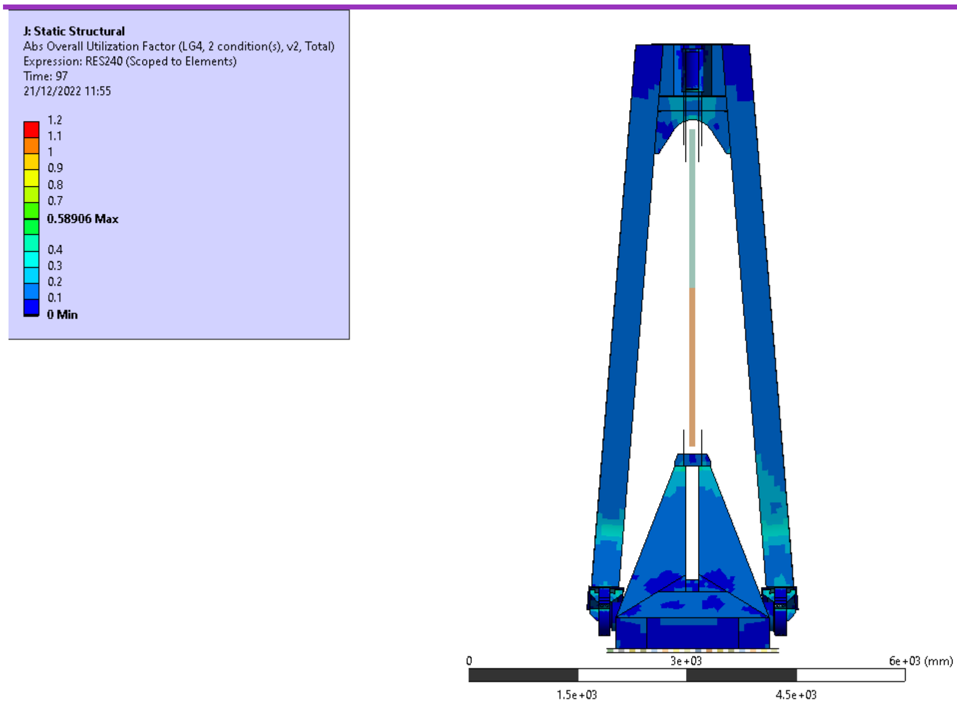


Load Group	LG4..LC3a	**Parameter**	AbsoluteStress Equivalent
Selection	90397 element(s)	**View**	1..Default View
Data Conversion	No Averaging		

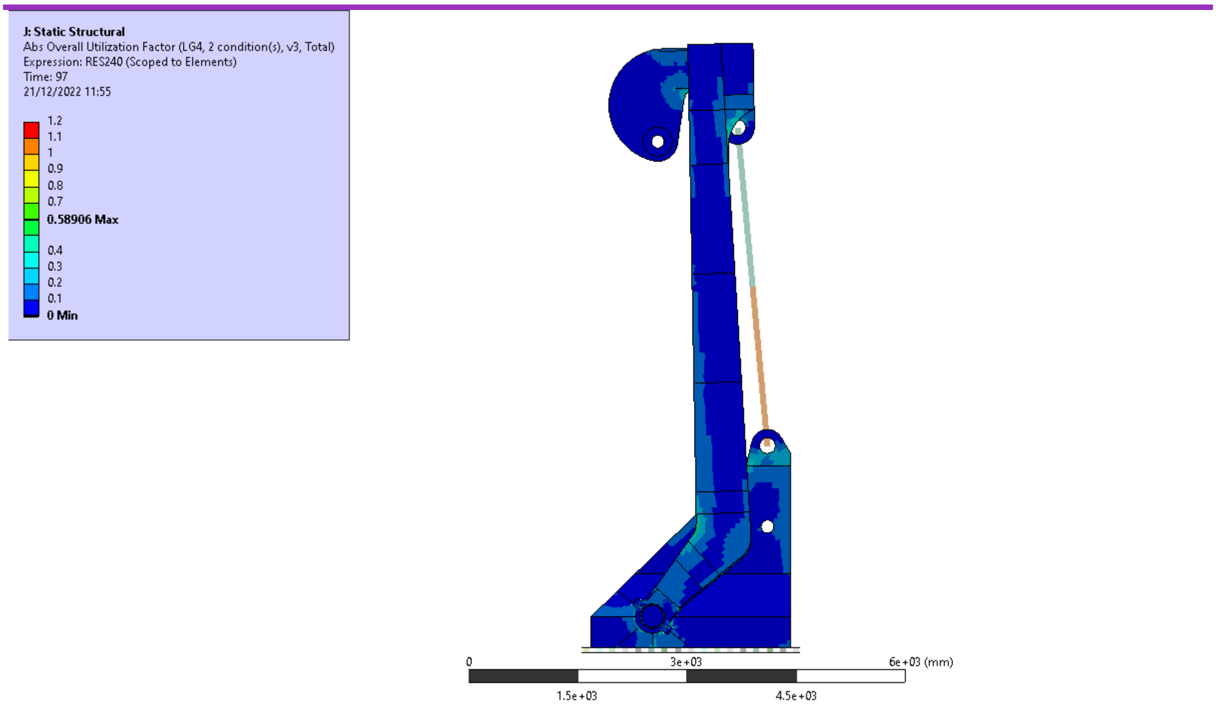
1..DNVGL-ST-0378 – Static Stress Check



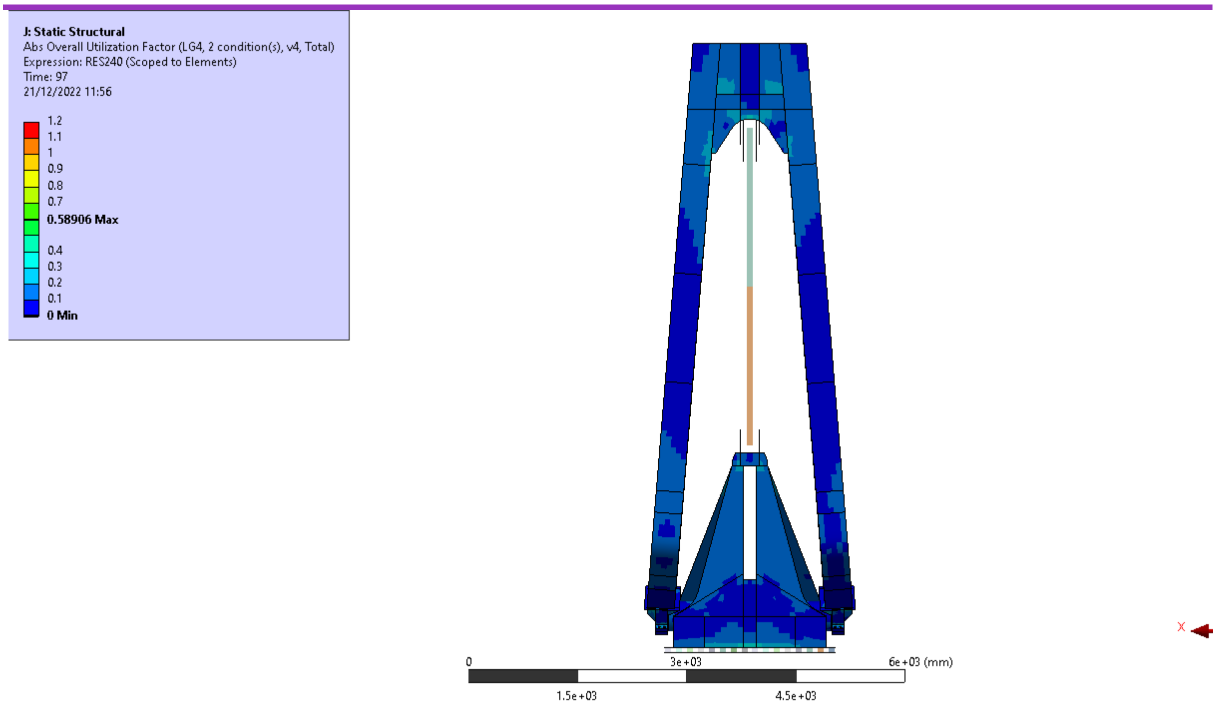
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	1..Default View



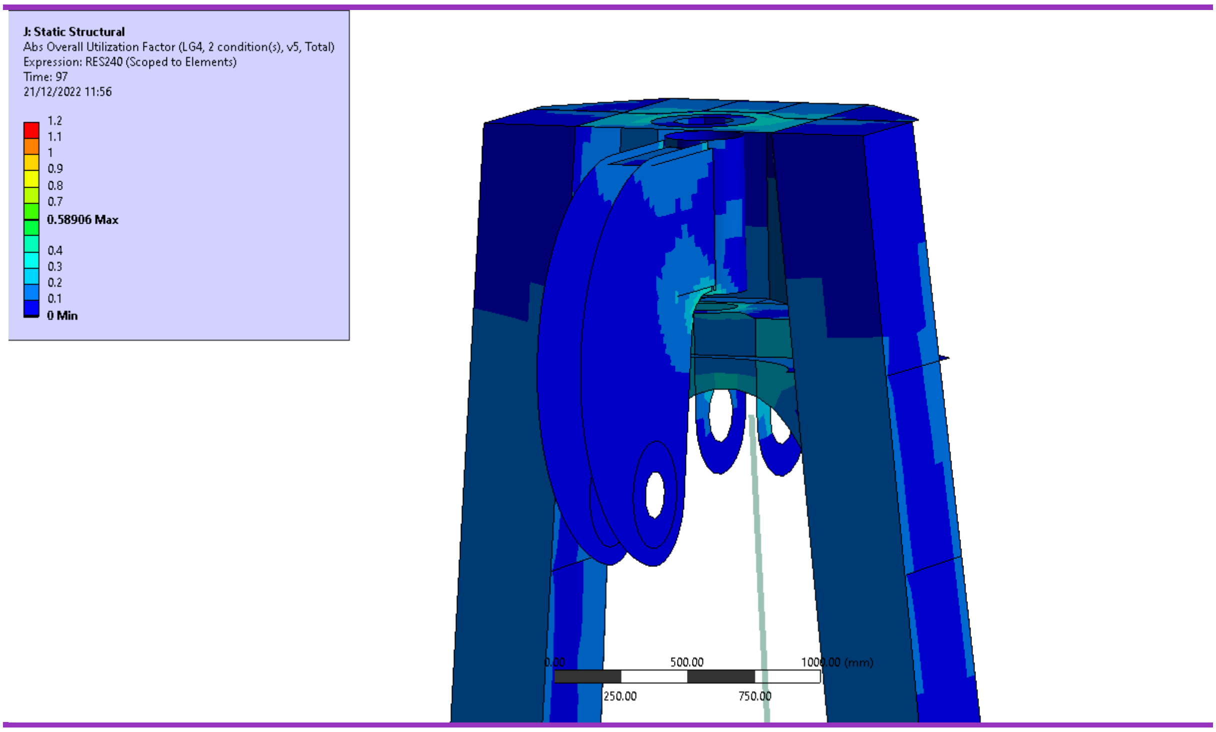
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	2..Front View



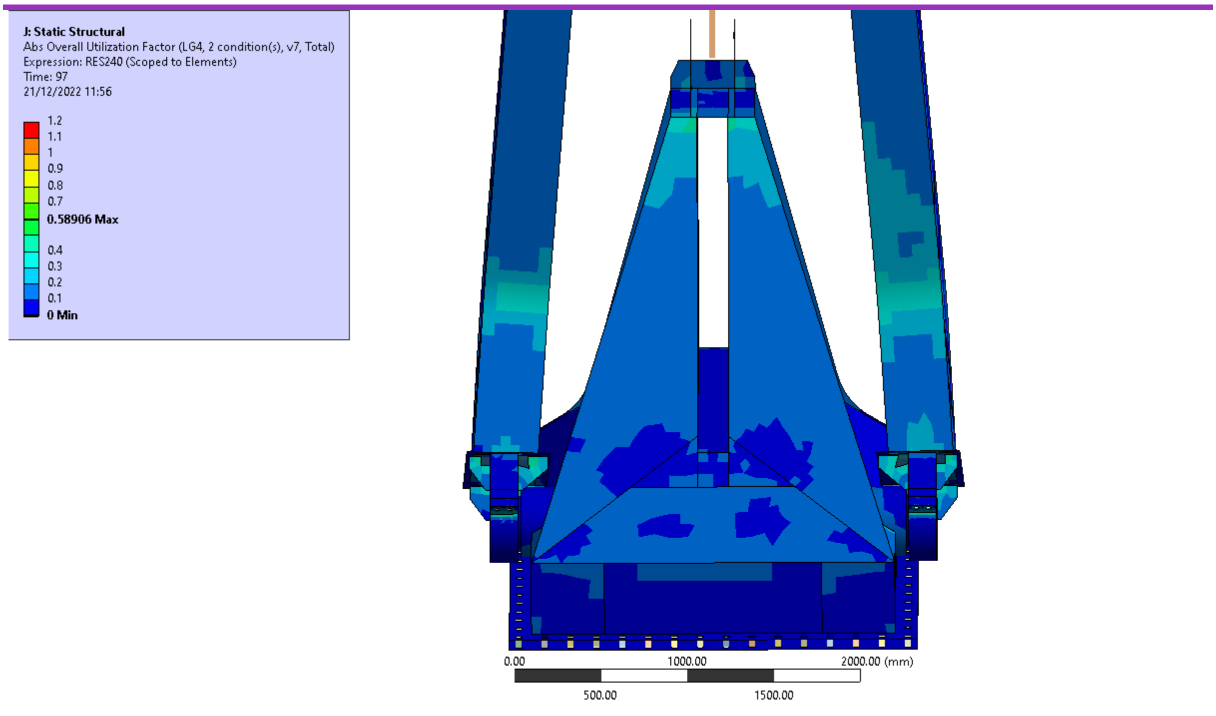
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	3..Side View



Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	4..Back View

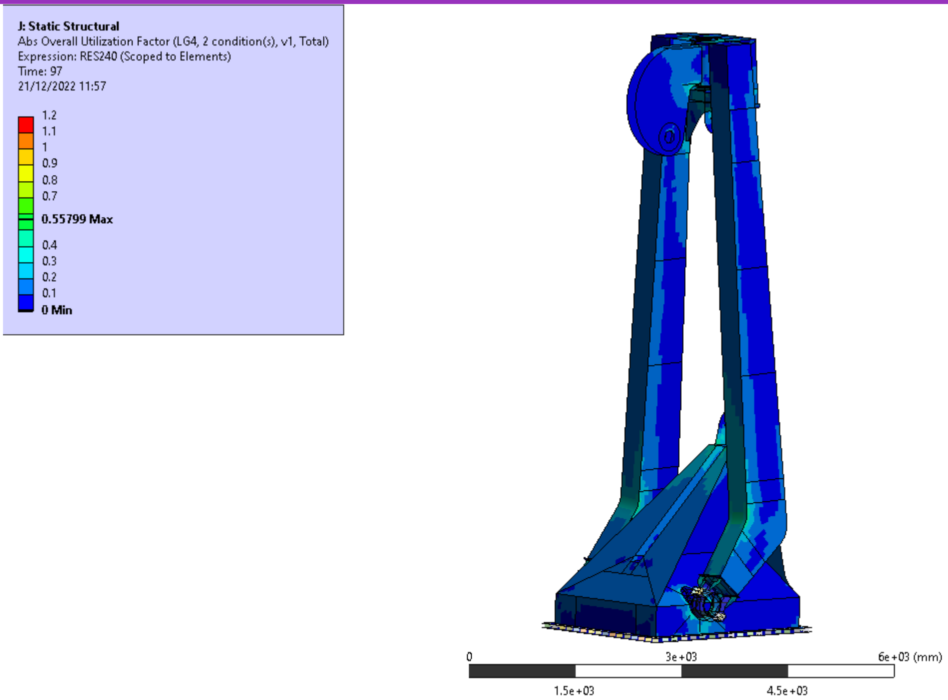


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	5..A-Frame Head and Tumbler Side

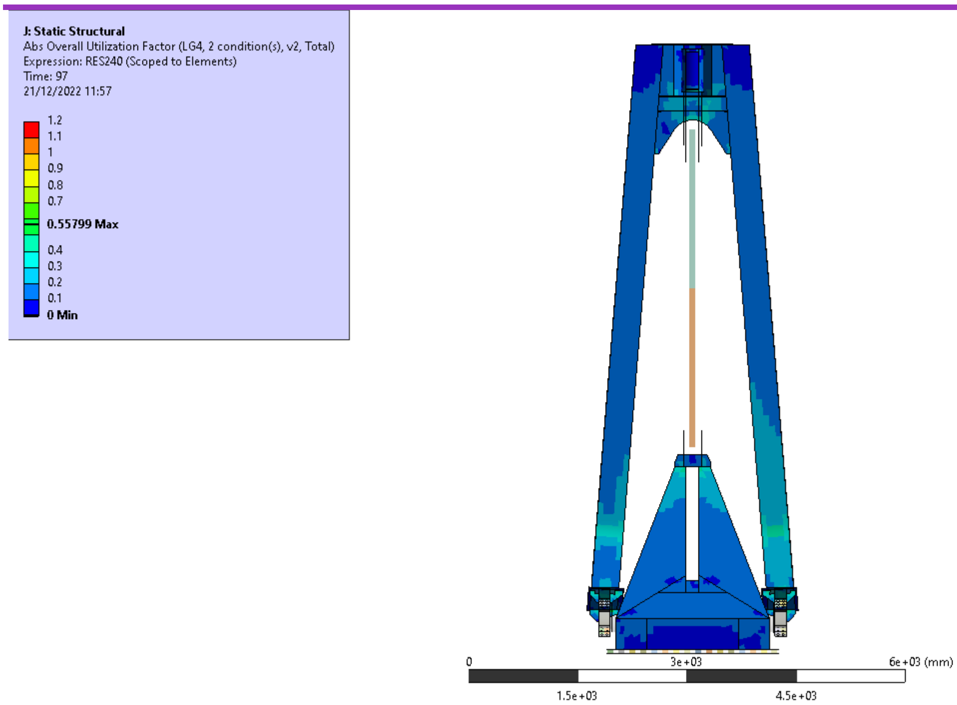


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	7..Fixed Part Front

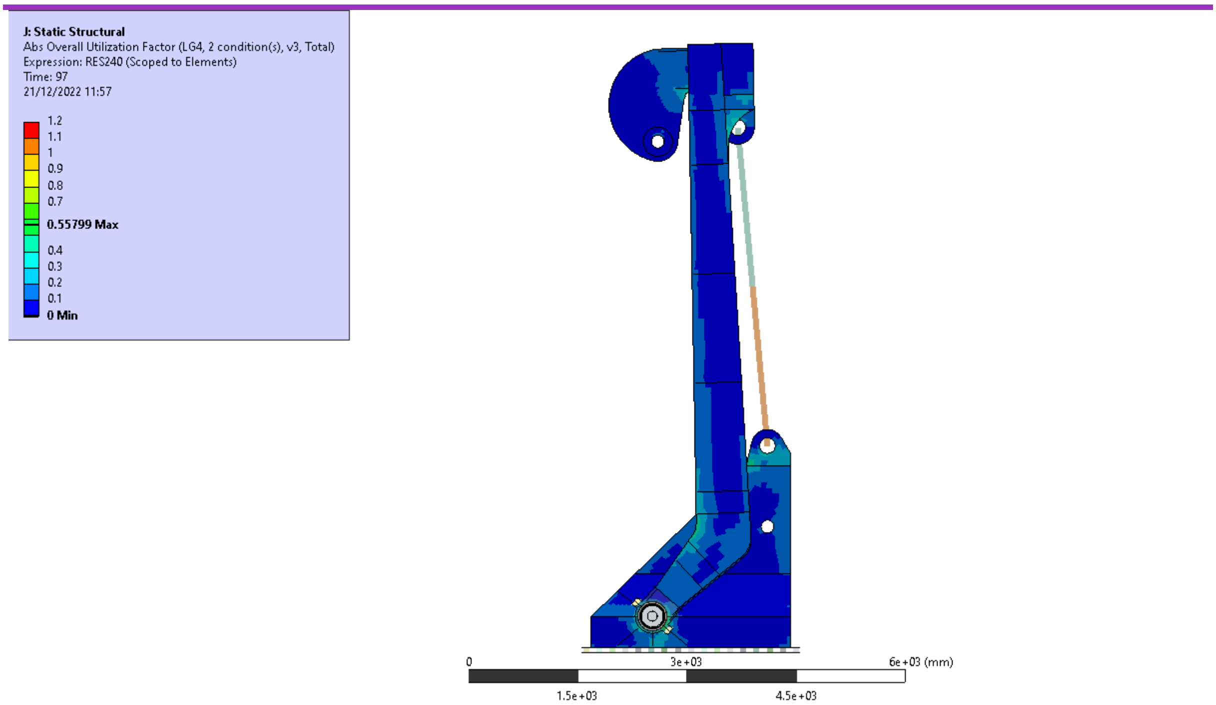
2..DNVGL-ST-0378 – Buckling Check



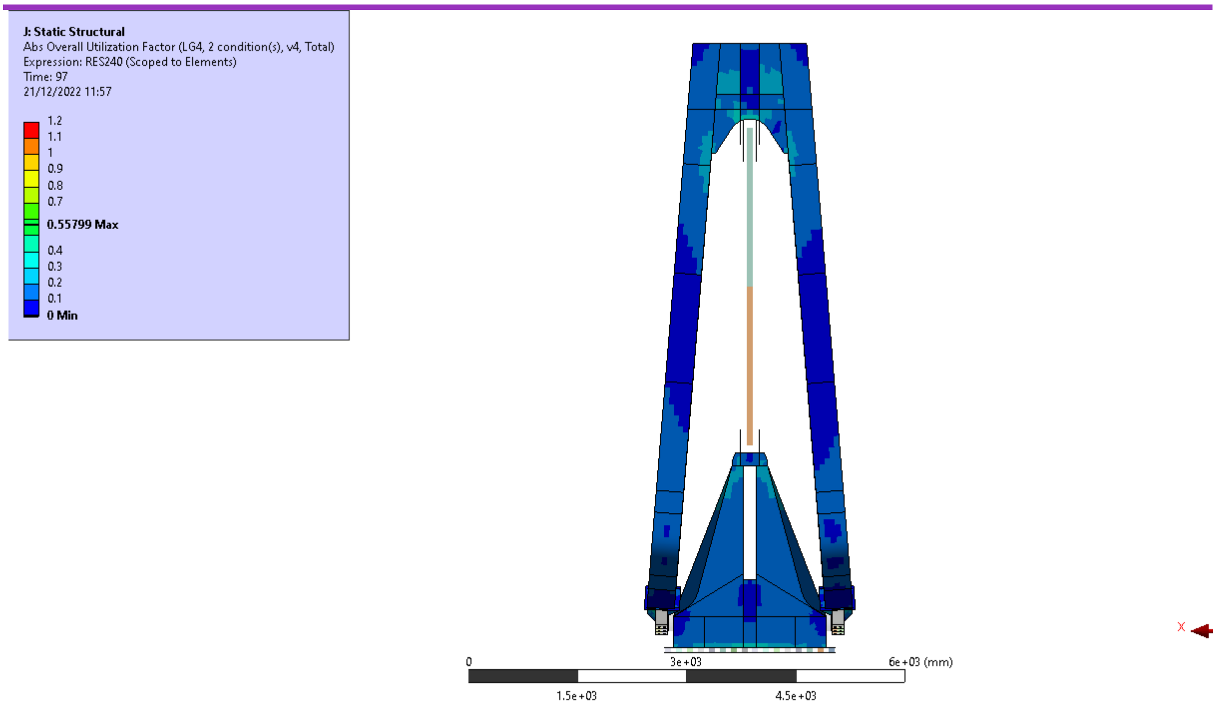
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	1..Default View



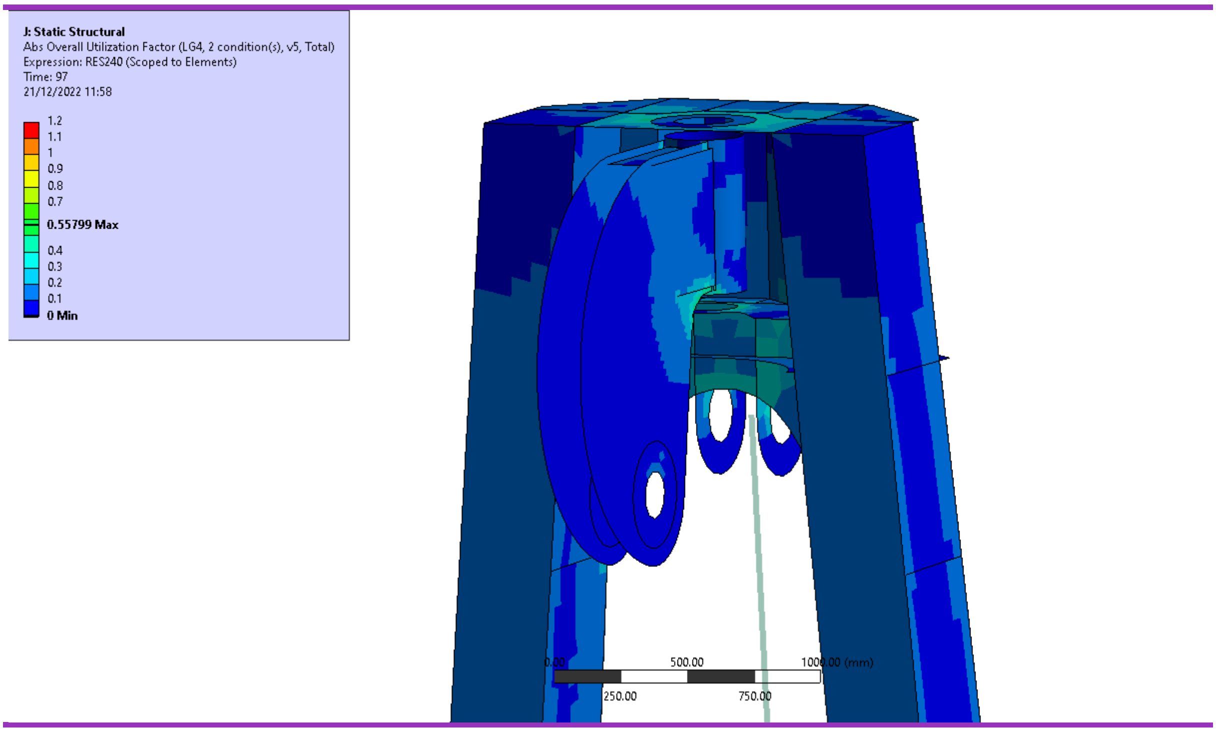
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	2..Front View



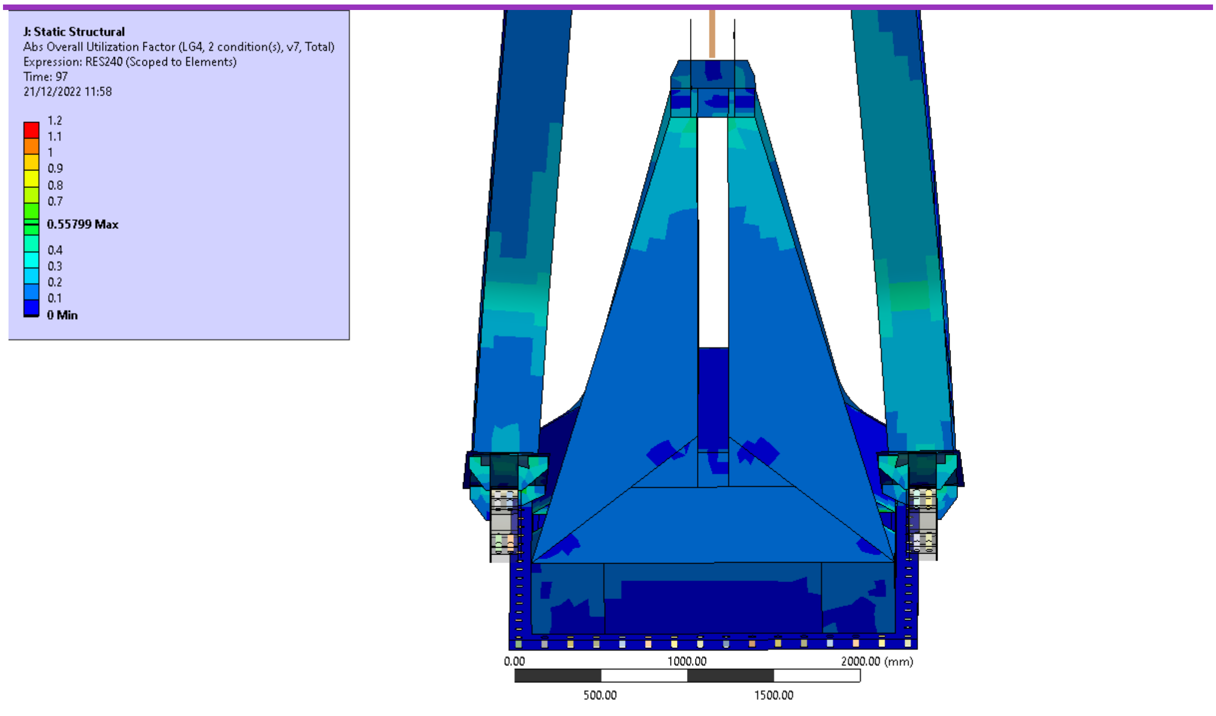
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	3..Side View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	4..Back View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	5..A-Frame Head and Tumbler Side



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG4..LC3a	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	7..Fixed Part Front

3..Eurocode3 Weld (EN1993-1-8, 2005)

Standard	2..Eurocode3 Weld (EN1993-1-8, 2005)	**Check**	[S2] 15..Weld Check Total
Load Group	LG4..LC3a	**Selection**	216 Welds

Title	Uf VM total	Uf N total	Uf material total	Uf Overall
133..Weld 133 [0.02; 1068.92; 7616.17]	0.57	0.21	0.53	0.57
101..Weld 101 [-1350.01; 377.18; 570.92]	0.25	0.26	0.47	0.47
137..Weld 137 [-193.99; 1000.94; 7614.96]	0.45	0.23	0.47	0.47
140..Weld 140 [193.98; 1000.95; 7614.96]	0.45	0.23	0.47	0.47
100..Weld 100 [-1199.61; 51.75; 854.1]	0.23	0.22	0.44	0.44
55..Weld 55 [-126; 1602.19; 2530]	0.23	0.21	0.42	0.42
56..Weld 56 [126; 1601.57; 2530]	0.22	0.21	0.42	0.42
66..Weld 66 [89; 486.24; 7704.11]	0.22	0.15	0.42	0.42
68..Weld 68 [-89; 486.23; 7704.11]	0.22	0.15	0.41	0.41
54..Weld 54 [-126; 1895; 2613.59]	0.19	0.17	0.36	0.36
53..Weld 53 [126; 1895; 2624.55]	0.19	0.14	0.35	0.35
319..Weld 319 [-324.59; 937.54; 7411.3]	0.18	0.21	0.34	0.34
321..Weld 321 [307.4; 937.54; 7411.3]	0.18	0.21	0.33	0.33
120..Weld 120 [541.22; 787.81; 6633.6]	0.32	0.13	0.30	0.32
86..Weld 86 [-541.22; 787.81; 6633.6]	0.28	0.11	0.26	0.28
122..Weld 122 [914.97; 786.85; 6664.22]	0.28	0.13	0.26	0.28
35..Weld 35 [-1051; -523.44; 455.69]	0.14	0.12	0.26	0.26
52..Weld 52 [-0.07; -314.33; 970.77]	0.14	0.17	0.26	0.26
33..Weld 33 [1051; -523.44; 455.69]	0.13	0.12	0.25	0.25

136..Weld 136 [-332.39; 921.43; 8316.66]	0.18	0.06	0.25	0.25
78..Weld 78 [-914.97; 786.85; 6664.22]	0.24	0.11	0.23	0.24
139..Weld 139 [332.39; 921.43; 8316.66]	0.17	0.06	0.24	0.24
17..Weld 17 [1051; 0; 160.77]	0.22	0.12	0.21	0.22
57..Weld 57 [89.5; 1601.11; 2530]	0.12	0.11	0.22	0.22
58..Weld 58 [-89.5; 1629.09; 2530]	0.11	0.09	0.21	0.21
67..Weld 67 [89; 366.33; 8220.3]	0.11	0.05	0.20	0.20
142..Weld 142 [126; 1165.49; 7415.36]	0.20	0.11	0.19	0.20
50..Weld 50 [-629; -844; 243.64]	0.19	0.11	0.18	0.19
19..Weld 19 [-1051; 0; 160.77]	0.18	0.11	0.18	0.18
41..Weld 41 [1051; 525.5; 30]	0.09	0.11	0.18	0.18
74..Weld 74 [-853.79; 757.41; 7408.1]	0.18	0.07	0.17	0.18
95..Weld 95 [-666.06; 996.1; 7412.34]	0.18	0.07	0.18	0.18
123..Weld 123 [853.94; 757.46; 7408.1]	0.18	0.07	0.17	0.18
308..Weld 308 [126; 1395.68; 7520.24]	0.09	0.11	0.18	0.18
143..Weld 143 [-126; 1165.54; 7415.36]	0.17	0.10	0.17	0.17
318..Weld 318 [308.72; 1397.47; 7419.48]	0.09	0.04	0.17	0.17
25..Weld 25 [-1051; -316.45; 199.47]	0.14	0.09	0.16	0.16
22..Weld 22 [1051; -316.45; 199.47]	0.14	0.10	0.15	0.15
121..Weld 121 [728.08; 1042.16; 6658.92]	0.14	0.07	0.14	0.14
134..Weld 134 [126; 1062.49; 7977.56]	0.12	0.09	0.14	0.14
26..Weld 26 [1051; 316.45; 199.46]	0.13	0.08	0.13	0.13

45..Weld 45 [662.65; -324.61; 693.54]	0.07	0.07	0.13	0.13
93..Weld 93 [-728.08; 1042.16; 6658.92]	0.13	0.06	0.13	0.13
94..Weld 94 [-591.78; 940.81; 8317]	0.07	0.02	0.13	0.13
132..Weld 132 [-126; 1062.49; 7977.53]	0.12	0.09	0.13	0.13
20..Weld 20 [-1051; 316.45; 199.47]	0.11	0.08	0.12	0.12
72..Weld 72 [-1088.51; 513.51; 4534.76]	0.06	0.08	0.12	0.12
82..Weld 82 [-983.82; 711.97; 1227.38]	0.12	0.05	0.11	0.12
105..Weld 105 [983.82; 711.97; 1227.38]	0.12	0.05	0.11	0.12
107..Weld 107 [1357.59; 711.67; 1257.76]	0.12	0.07	0.11	0.12
320..Weld 320 [0; 937.54; 7411.3]	0.06	0.08	0.12	0.12
32..Weld 32 [629; -518.73; 455.69]	0.08	0.02	0.11	0.11
49..Weld 49 [-662.62; -324.62; 693.55]	0.06	0.06	0.11	0.11
75..Weld 75 [-1357.59; 711.65; 1257.77]	0.11	0.06	0.10	0.11
97..Weld 97 [-1231.55; 373.73; 573.92]	0.06	0.06	0.11	0.11
112..Weld 112 [933.81; 976.58; 1848.4]	0.11	0.05	0.10	0.11
138..Weld 138 [-193.47; 988.95; 8317.86]	0.10	0.07	0.11	0.11
141..Weld 141 [193.47; 988.95; 8317.86]	0.10	0.07	0.11	0.11
46..Weld 46 [89.5; 828.32; 1044.57]	0.05	0.06	0.10	0.10
84..Weld 84 [-933.81; 976.58; 1848.4]	0.10	0.05	0.10	0.10
90..Weld 90 [-1120.63; 1334.41; 1877.77]	0.10	0.05	0.10	0.10

111..Weld 111 [1120.63; 1334.41; 1877.77]	0.10	0.05	0.10	0.10
113..Weld 113 [1307.56; 975.21; 1879]	0.10	0.05	0.09	0.10
59..Weld 59 [-89.5; 790.34; 969.57]	0.09	0.05	0.08	0.09
81..Weld 81 [-1307.56; 975.21; 1879]	0.09	0.05	0.08	0.09
106..Weld 106 [1189.8; 919.49; 1016.78]	0.09	0.04	0.08	0.09
127..Weld 127 [1231.57; 373.73; 573.92]	0.05	0.06	0.09	0.09
28..Weld 28 [-89.5; 1068.43; 455.69]	0.08	0.05	0.08	0.08
37..Weld 37 [-1051; 1049.01; 455.69]	0.04	0.05	0.08	0.08
61..Weld 61 [89.5; 790.34; 969.57]	0.08	0.05	0.08	0.08
65..Weld 65 [-629; 1895; 225.71]	0.08	0.05	0.07	0.08
1..Weld 1 [-89.5; -393.64; 893.64]	0.04	0.02	0.07	0.07
60..Weld 60 [-89.5; -326.39; 694.85]	0.04	0.05	0.07	0.07
63..Weld 63 [-0.05; 1895; 968.38]	0.04	0.04	0.07	0.07
64..Weld 64 [629; 1895; 243.35]	0.07	0.04	0.07	0.07
309..Weld 309 [126; 1387.4; 7985.61]	0.06	0.04	0.07	0.07
317..Weld 317 [0.02; 1397.47; 7419.48]	0.04	0.02	0.07	0.07
2..Weld 2 [89.5; -393.63; 893.65]	0.03	0.02	0.06	0.06
16..Weld 16 [629; 0; 160.9]	0.05	0.03	0.06	0.06
18..Weld 18 [-629; 0; 160.9]	0.06	0.05	0.06	0.06
21..Weld 21 [-629; 316.34; 199.56]	0.06	0.04	0.06	0.06
102..Weld 102 [1374.87; 506.11; 1038.72]	0.06	0.03	0.05	0.06
118..Weld 118 [851.09; 1133.7; 5161.39]	0.06	0.03	0.06	0.06
144..Weld 144 [-126; 1219.05; 8321.95]	0.05	0.03	0.06	0.06

23..Weld 23 [629; -316.36; 199.54]	0.04	0.01	0.05	0.05
27..Weld 27 [629; 316.34; 199.56]	0.04	0.01	0.05	0.05
76..Weld 76 [-779.68; 715.2; 8312.99]	0.02	0.02	0.05	0.05
77..Weld 77 [-1374.87; 506.11; 1038.72]	0.05	0.03	0.05	0.05
89..Weld 89 [-1096.16; 1316.16; 2176.28]	0.05	0.02	0.04	0.05
92..Weld 92 [-851.09; 1133.7; 5161.39]	0.05	0.02	0.05	0.05
109..Weld 109 [1096.16; 1316.16; 2176.28]	0.05	0.02	0.04	0.05
110..Weld 110 [909.3; 964.67; 2147.16]	0.05	0.02	0.04	0.05
24..Weld 24 [-629; -316.35; 199.55]	0.04	0.02	0.04	0.04
83..Weld 83 [-909.3; 964.67; 2147.16]	0.04	0.02	0.04	0.04
85..Weld 85 [-1001.2; 507.49; 1007.19]	0.04	0.02	0.04	0.04
96..Weld 96 [-1204.6; 686.56; 827.51]	0.04	0.02	0.03	0.04
103..Weld 103 [1001.2; 507.49; 1007.19]	0.04	0.02	0.04	0.04
104..Weld 104 [1204.6; 686.56; 827.51]	0.04	0.02	0.03	0.04
108..Weld 108 [1283.05; 963.52; 2177.77]	0.04	0.03	0.04	0.04
80..Weld 80 [-1160.49; 904.71; 3671.59]	0.03	0.02	0.03	0.03
114..Weld 114 [1160.49; 904.71; 3671.59]	0.03	0.02	0.03	0.03
116..Weld 116 [786.74; 905.86; 3640.98]	0.02	0.02	0.03	0.03
117..Weld 117 [664.19; 846.9; 5134.8]	0.03	0.02	0.03	0.03
135..Weld 135 [0; 1056.41; 8319.06]	0.03	0.02	0.03	0.03

79..Weld 79 [-1037.93; 845.67; 5165.41]	0.02	0.01	0.02	0.02
87..Weld 87 [-786.74; 905.86; 3640.98]	0.02	0.02	0.02	0.02
91..Weld 91 [-973.65; 1224.93; 3668.84]	0.02	0.01	0.02	0.02
115..Weld 115 [973.65; 1224.93; 3668.84]	0.02	0.01	0.02	0.02
119..Weld 119 [1037.93; 845.67; 5165.41]	0.02	0.01	0.02	0.02
30..Weld 30 [629; 1054.8; 455.69]	0.01	0.01	0.01	0.01
AbsMax over welds	0.57	0.26	0.53	0.57

4..Eurocode3 Bolts (EN 1993-1-8, 2005)

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	**Check**	[S4] 4..Category B and E. Shear resistance at serviceability
Load Group	LG4..LC3a	**Selection**	2 Properties

ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension	Category B Utilization factor 1 Tension and compression	Utilization factor total
105323	230231.91	0.17	230231.91	0.20	0.20
105324	230231.91	0.07	230231.91	0.07	0.07
105325	230231.91	0.09	230231.91	0.10	0.10
105326	230231.91	0.07	230231.91	0.07	0.07
105327	230231.91	0.09	230231.91	0.09	0.09
105328	230231.91	0.08	230231.91	0.08	0.08
105329	230231.91	0.16	230231.91	0.17	0.17
105330	230231.91	0.17	230231.91	0.19	0.19
105331	230231.91	0.17	230231.91	0.19	0.19
105332	230231.91	0.15	230231.91	0.18	0.18
105333	230231.91	0.08	230231.91	0.08	0.08
105334	230231.91	0.10	230231.91	0.11	0.11
105335	230231.91	0.08	230231.91	0.08	0.08
105336	230231.91	0.06	230231.91	0.06	0.06
105337	230231.91	0.07	230231.91	0.07	0.07
105338	230231.91	0.16	230231.91	0.17	0.17
105339	230231.91	0.07	230231.91	0.07	0.07
105340	230231.91	0.06	230231.91	0.06	0.06
105341	230231.91	0.14	230231.91	0.17	0.17
105342	230231.91	0.16	230231.91	0.19	0.19
105343	230231.91	0.12	230231.91	0.16	0.16
105344	230231.91	0.07	230231.91	0.07	0.07
105345	230231.91	0.05	230231.91	0.05	0.05
105346	230231.91	0.05	230231.91	0.05	0.05
105347	230231.91	0.07	230231.91	0.08	0.08
105348	230231.91	0.07	230231.91	0.07	0.07
105349	230231.91	0.09	230231.91	0.09	0.09
105350	230231.91	0.14	230231.91	0.20	0.20
105351	230231.91	0.04	230231.91	0.04	0.04
105352	230231.91	0.08	230231.91	0.08	0.08
105353	230231.91	0.15	230231.91	0.22	0.22
105354	230231.91	0.05	230231.91	0.05	0.05
105355	230231.91	0.05	230231.91	0.05	0.05
105356	158123.88	0.10	158123.88	0.10	0.10
105357	158123.88	0.13	158123.88	0.13	0.13
105358	158123.88	0.13	158123.88	0.13	0.13
105359	158123.88	0.12	158123.88	0.12	0.12
105360	158123.88	0.12	158123.88	0.12	0.12
105361	158123.88	0.11	158123.88	0.11	0.11

105362	158123.88	0.14	158123.88	0.14	0.14
105363	158123.88	0.14	158123.88	0.14	0.14
105364	158123.88	0.08	158123.88	0.08	0.08
105365	158123.88	0.15	158123.88	0.15	0.15
105366	158123.88	0.14	158123.88	0.14	0.14
105367	158123.88	0.14	158123.88	0.14	0.14
105368	230231.91	0.03	230231.91	0.03	0.03
105369	230231.91	0.20	230231.91	0.31	0.31
105370	230231.91	0.07	230231.91	0.07	0.07
105371	230231.91	0.13	230231.91	0.13	0.13
105372	230231.91	0.11	230231.91	0.11	0.11
105373	230231.91	0.02	230231.91	0.02	0.02
105374	230231.91	0.17	230231.91	0.26	0.26
105375	230231.91	0.09	230231.91	0.09	0.09
105376	230231.91	0.13	230231.91	0.13	0.13
105377	230231.91	0.08	230231.91	0.08	0.08
105378	230231.91	0.04	230231.91	0.04	0.04
105379	230231.91	0.03	230231.91	0.03	0.03
105380	230231.91	0.12	230231.91	0.13	0.13
105381	230231.91	0.13	230231.91	0.19	0.19
105382	230231.91	0.08	230231.91	0.08	0.08
105383	230231.91	0.05	230231.91	0.05	0.05
105384	230231.91	0.09	230231.91	0.09	0.09
105385	230231.91	0.12	230231.91	0.16	0.16
105386	230231.91	0.13	230231.91	0.18	0.18
105387	230231.91	0.05	230231.91	0.05	0.05
105388	230231.91	0.06	230231.91	0.06	0.06
105389	230231.91	0.09	230231.91	0.09	0.09
105390	230231.91	0.13	230231.91	0.17	0.17
105391	230231.91	0.07	230231.91	0.07	0.07
105392	230231.91	0.08	230231.91	0.08	0.08
105393	230231.91	0.08	230231.91	0.08	0.08
105394	230231.91	0.08	230231.91	0.08	0.08
105395	230231.91	0.06	230231.91	0.06	0.06
105396	230231.91	0.14	230231.91	0.17	0.17

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	Check	[S4] 5..Category B and E. Slip-resistance at serviceability (Preloaded)
Load Group	LG4..LC3a	Selection	2 Properties

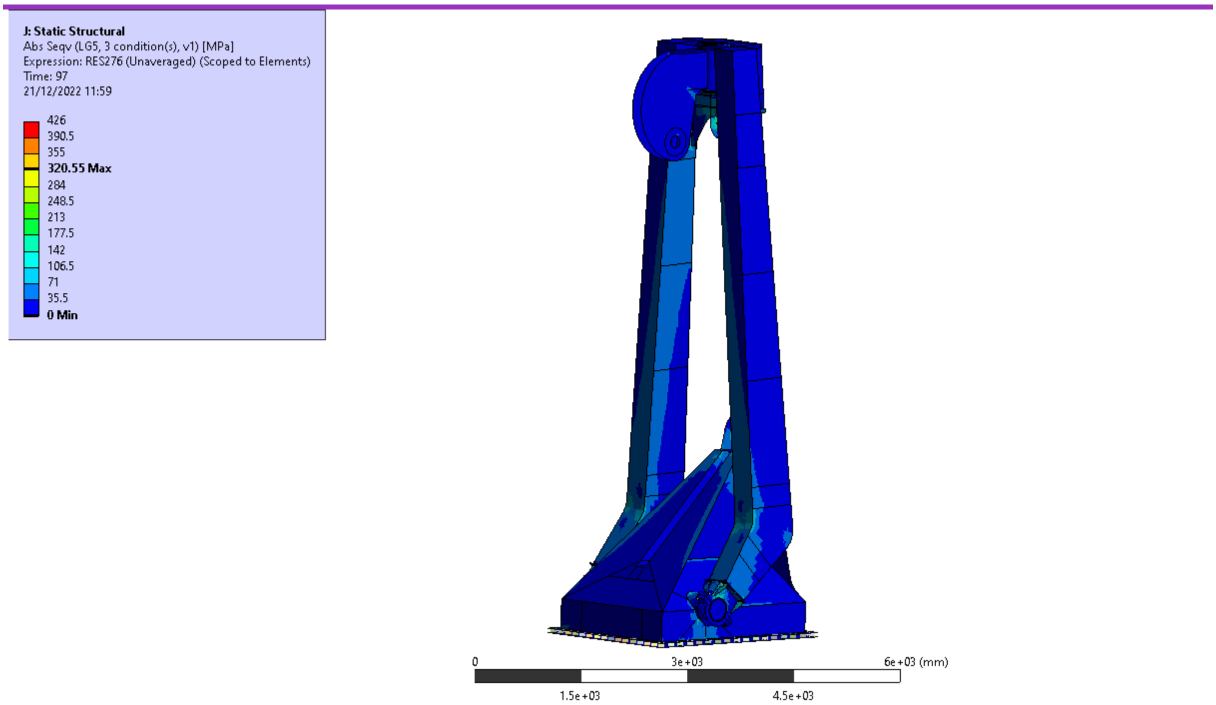
ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt [KN]	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension [KN]	Category B Utilization factor 1 Tension and compression	Shear resistance per shear plane [KN]	Category B Utilization factor 2	Bearing resistance [KN]	Category B Utilization factor 3	Tension resistance [KN]
105369	230.2	0.20	230.2	0.31	554.2	0.08	0.0	0.00	868.3
105374	230.2	0.17	230.2	0.26	554.2	0.07	0.0	0.00	868.3
105353	230.2	0.15	230.2	0.22	554.2	0.06	0.0	0.00	868.3
105381	230.2	0.13	230.2	0.19	554.2	0.06	0.0	0.00	868.3
105350	230.2	0.14	230.2	0.20	554.2	0.06	0.0	0.00	868.3
105386	230.2	0.13	230.2	0.18	554.2	0.05	0.0	0.00	868.3
105385	230.2	0.12	230.2	0.16	554.2	0.05	0.0	0.00	868.3
105343	230.2	0.12	230.2	0.16	554.2	0.05	0.0	0.00	868.3
105390	230.2	0.13	230.2	0.17	554.2	0.05	0.0	0.00	868.3
105341	230.2	0.14	230.2	0.17	554.2	0.06	0.0	0.00	868.3
105342	230.2	0.16	230.2	0.19	554.2	0.06	0.0	0.00	868.3
105396	230.2	0.14	230.2	0.17	554.2	0.06	0.0	0.00	868.3
105323	230.2	0.17	230.2	0.20	554.2	0.07	0.0	0.00	868.3
105332	230.2	0.15	230.2	0.18	554.2	0.06	0.0	0.00	868.3
105330	230.2	0.17	230.2	0.19	554.2	0.07	0.0	0.00	868.3
105331	230.2	0.17	230.2	0.19	554.2	0.07	0.0	0.00	868.3
105329	230.2	0.16	230.2	0.17	554.2	0.07	0.0	0.00	868.3
105338	230.2	0.16	230.2	0.17	554.2	0.06	0.0	0.00	868.3
105365	158.1	0.15	158.1	0.15	282.7	0.08	0.0	0.00	447.3
105367	158.1	0.14	158.1	0.14	282.7	0.08	0.0	0.00	447.3
105366	158.1	0.14	158.1	0.14	282.7	0.08	0.0	0.00	447.3
105363	158.1	0.14	158.1	0.14	282.7	0.08	0.0	0.00	447.3
105362	158.1	0.14	158.1	0.14	282.7	0.08	0.0	0.00	447.3
105358	158.1	0.13	158.1	0.13	282.7	0.07	0.0	0.00	447.3
105357	158.1	0.13	158.1	0.13	282.7	0.07	0.0	0.00	447.3
105371	230.2	0.13	230.2	0.13	554.2	0.05	0.0	0.00	868.3
105376	230.2	0.13	230.2	0.13	554.2	0.05	0.0	0.00	868.3
105380	230.2	0.12	230.2	0.13	554.2	0.05	0.0	0.00	868.3
105360	158.1	0.12	158.1	0.12	282.7	0.07	0.0	0.00	447.3
105359	158.1	0.12	158.1	0.12	282.7	0.07	0.0	0.00	447.3
105361	158.1	0.11	158.1	0.11	282.7	0.06	0.0	0.00	447.3
105372	230.2	0.11	230.2	0.11	554.2	0.04	0.0	0.00	868.3
105325	230.2	0.09	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105356	158.1	0.10	158.1	0.10	282.7	0.06	0.0	0.00	447.3
105334	230.2	0.10	230.2	0.11	554.2	0.04	0.0	0.00	868.3
105349	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3

105389	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105375	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105384	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105327	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105392	230.2	0.08	230.2	0.08	554.2	0.04	0.0	0.00	868.3
105377	230.2	0.08	230.2	0.08	554.2	0.04	0.0	0.00	868.3
105393	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105382	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105352	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105333	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105394	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105364	158.1	0.08	158.1	0.08	282.7	0.04	0.0	0.00	447.3
105335	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105328	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105347	230.2	0.07	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105324	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105339	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105370	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105344	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105337	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105391	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105348	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105340	230.2	0.06	230.2	0.06	554.2	0.02	0.0	0.00	868.3
105326	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105388	230.2	0.06	230.2	0.06	554.2	0.03	0.0	0.00	868.3
105336	230.2	0.06	230.2	0.06	554.2	0.03	0.0	0.00	868.3
105395	230.2	0.06	230.2	0.06	554.2	0.02	0.0	0.00	868.3
105354	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105387	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105355	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105345	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105383	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105346	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105378	230.2	0.04	230.2	0.04	554.2	0.02	0.0	0.00	868.3
105351	230.2	0.04	230.2	0.04	554.2	0.02	0.0	0.00	868.3
105379	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105368	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105373	230.2	0.02	230.2	0.02	554.2	0.01	0.0	0.00	868.3

ID / Point	Category E Utilization factor 1	Punching shear resistance [KN]	Category E Utilization factor 2	Combined utilization factor	Design tensile load [KN]	Design shear load [KN]	Utilization factor overall	pretension load [KN]
105369	0.43	6080.1	0.06	0.38	371.1	46.5	0.43	844.2
105374	0.42	6080.1	0.06	0.36	360.6	40.2	0.42	844.2
105353	0.39	6080.1	0.06	0.33	337.2	34.5	0.39	844.2
105381	0.38	6080.1	0.05	0.32	331.9	30.5	0.38	844.2
105350	0.35	6080.1	0.05	0.30	300.6	33.1	0.35	844.2
105386	0.34	6080.1	0.05	0.30	299.3	29.1	0.34	844.2
105385	0.32	6080.1	0.05	0.28	277.0	28.0	0.32	844.2
105343	0.31	6080.1	0.04	0.27	265.6	27.5	0.31	844.2
105390	0.27	6080.1	0.04	0.25	237.8	30.0	0.27	844.2
105341	0.27	6080.1	0.04	0.25	236.7	31.3	0.27	844.2
105342	0.24	6080.1	0.03	0.24	209.8	36.0	0.24	844.2
105396	0.23	6080.1	0.03	0.22	196.3	31.1	0.23	844.2
105323	0.20	6080.1	0.03	0.21	177.9	38.2	0.21	844.2
105332	0.20	6080.1	0.03	0.20	170.6	34.4	0.20	844.2
105330	0.15	6080.1	0.02	0.18	130.4	39.1	0.18	844.2
105331	0.14	6080.1	0.02	0.17	123.3	38.0	0.17	844.2
105329	0.07	6080.1	0.01	0.11	57.2	37.6	0.16	844.2
105338	0.06	6080.1	0.01	0.11	55.0	36.0	0.16	844.2
105365	0.07	7962.1	0.00	0.08	29.4	23.5	0.15	434.8
105367	0.07	7962.1	0.00	0.08	33.5	22.2	0.14	434.8
105366	0.07	7962.1	0.00	0.08	33.5	22.2	0.14	434.8
105363	0.07	7962.1	0.00	0.08	32.6	21.4	0.14	434.8
105362	0.07	7962.1	0.00	0.08	32.6	21.4	0.14	434.8
105358	0.08	7962.1	0.00	0.08	36.2	20.8	0.13	434.8
105357	0.08	7962.1	0.00	0.08	36.2	20.8	0.13	434.8
105371	0.02	6080.1	0.00	0.07	14.6	29.6	0.13	844.2
105376	0.02	6080.1	0.00	0.07	21.4	29.0	0.13	844.2
105380	0.03	6080.1	0.00	0.07	27.3	28.6	0.12	844.2
105360	0.07	7962.1	0.00	0.07	31.0	18.7	0.12	434.8
105359	0.07	7962.1	0.00	0.07	31.0	18.7	0.12	434.8
105361	0.08	7962.1	0.00	0.07	33.8	17.6	0.11	434.8
105372	0.01	6080.1	0.00	0.05	12.6	24.6	0.11	844.2
105325	0.10	6080.1	0.01	0.11	82.5	21.2	0.11	844.2
105356	0.07	7962.1	0.00	0.07	33.0	16.5	0.10	434.8
105334	0.09	6080.1	0.01	0.10	78.2	23.1	0.10	844.2
105349	0.02	6080.1	0.00	0.04	14.3	21.4	0.09	844.2
105389	0.02	6080.1	0.00	0.04	21.5	20.6	0.09	844.2
105375	0.02	6080.1	0.00	0.04	17.3	20.5	0.09	844.2
105384	0.03	6080.1	0.00	0.04	25.4	19.8	0.09	844.2
105327	0.01	6080.1	0.00	0.04	5.9	19.6	0.09	844.2
105392	0.01	6080.1	0.00	0.04	8.3	19.5	0.08	844.2
105377	0.03	6080.1	0.00	0.04	26.1	19.5	0.08	844.2
105393	0.02	6080.1	0.00	0.04	14.9	19.4	0.08	844.2
105382	0.04	6080.1	0.01	0.05	31.1	18.8	0.08	844.2
105352	0.01	6080.1	0.00	0.04	11.0	18.4	0.08	844.2

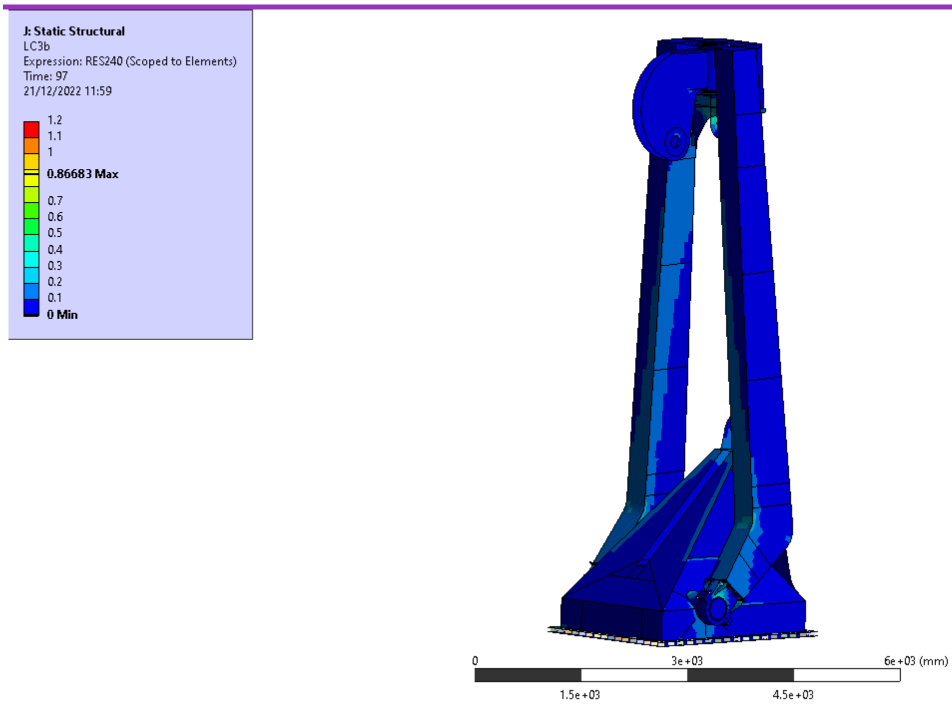
105333	0.01	6080.1	0.00	0.04	12.5	18.3	0.08	844.2
105394	0.02	6080.1	0.00	0.03	13.0	17.9	0.08	844.2
105364	0.07	7962.1	0.00	0.06	29.8	12.1	0.08	434.8
105335	0.06	6080.1	0.01	0.07	49.8	17.5	0.08	844.2
105328	0.01	6080.1	0.00	0.03	12.1	17.5	0.08	844.2
105347	0.02	6080.1	0.00	0.04	18.2	17.2	0.07	844.2
105324	0.01	6080.1	0.00	0.03	9.6	17.2	0.07	844.2
105339	0.02	6080.1	0.00	0.03	18.0	17.1	0.07	844.2
105370	0.02	6080.1	0.00	0.03	13.6	16.7	0.07	844.2
105344	0.03	6080.1	0.00	0.05	25.2	16.7	0.07	844.2
105337	0.04	6080.1	0.01	0.06	34.9	16.4	0.07	844.2
105391	0.02	6080.1	0.00	0.03	19.3	16.3	0.07	844.2
105348	0.01	6080.1	0.00	0.03	9.8	15.4	0.07	844.2
105340	0.07	6080.1	0.01	0.06	56.9	12.7	0.07	844.2
105326	0.03	6080.1	0.00	0.03	23.3	15.0	0.07	844.2
105388	0.01	6080.1	0.00	0.03	6.8	14.4	0.06	844.2
105336	0.01	6080.1	0.00	0.03	9.6	14.2	0.06	844.2
105395	0.02	6080.1	0.00	0.02	19.3	13.7	0.06	844.2
105354	0.02	6080.1	0.00	0.02	13.9	12.6	0.05	844.2
105387	0.03	6080.1	0.00	0.04	26.2	12.3	0.05	844.2
105355	0.03	6080.1	0.00	0.03	22.1	11.6	0.05	844.2
105345	0.05	6080.1	0.01	0.04	40.3	11.2	0.05	844.2
105383	0.01	6080.1	0.00	0.02	5.6	11.2	0.05	844.2
105346	0.03	6080.1	0.00	0.03	30.3	11.1	0.05	844.2
105378	0.01	6080.1	0.00	0.02	5.0	8.8	0.04	844.2
105351	0.01	6080.1	0.00	0.02	7.3	8.5	0.04	844.2
105379	0.01	6080.1	0.00	0.01	5.0	6.8	0.03	844.2
105368	0.01	6080.1	0.00	0.01	6.2	6.7	0.03	844.2
105373	0.01	6080.1	0.00	0.01	5.3	4.9	0.02	844.2

LG5..LC3b

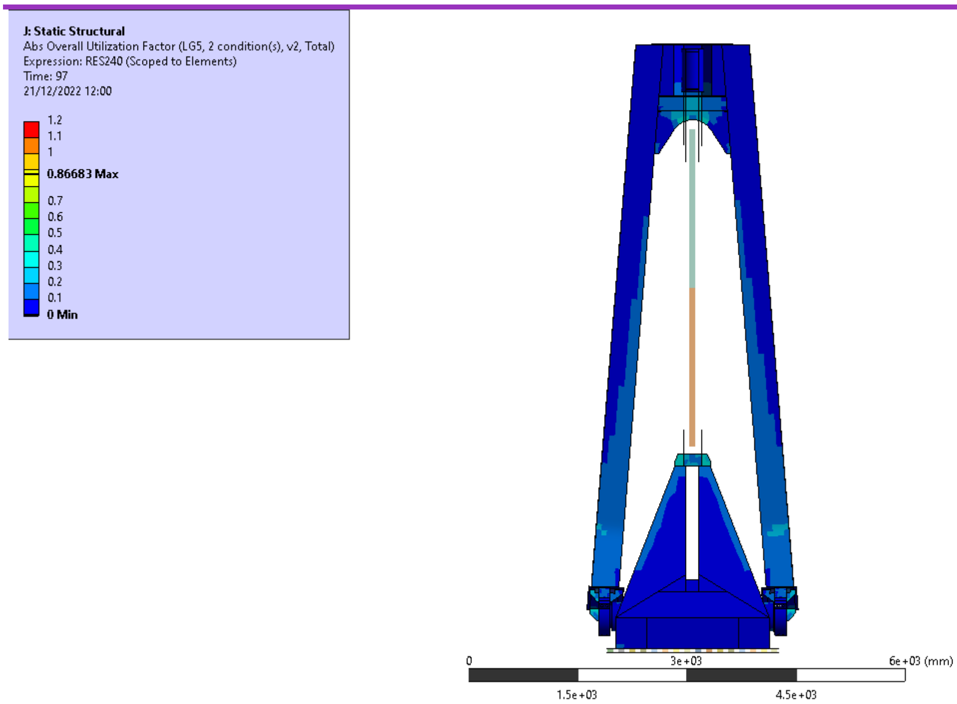


Load Group	LG5..LC3b	**Parameter**	AbsoluteStress Equivalent
Selection	90397 element(s)	**View**	1..Default View
Data Conversion	No Averaging		

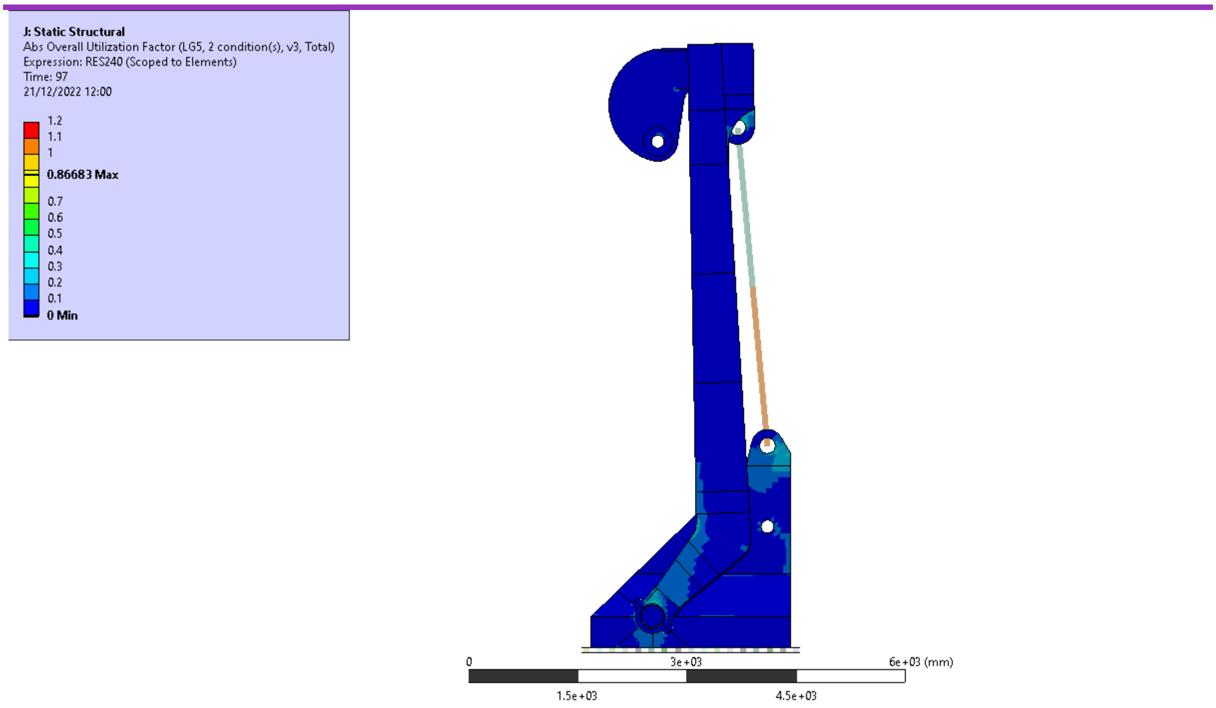
1..DNVGL-ST-0378 – Static Stress Check



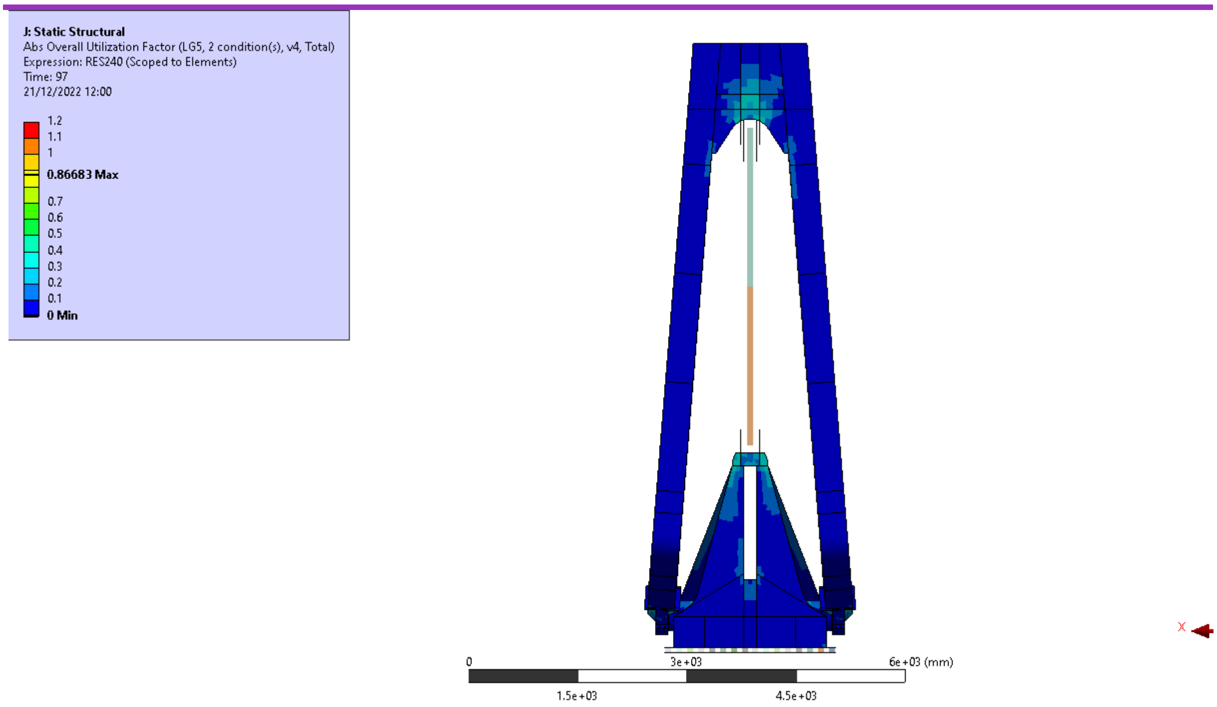
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	1..Default View



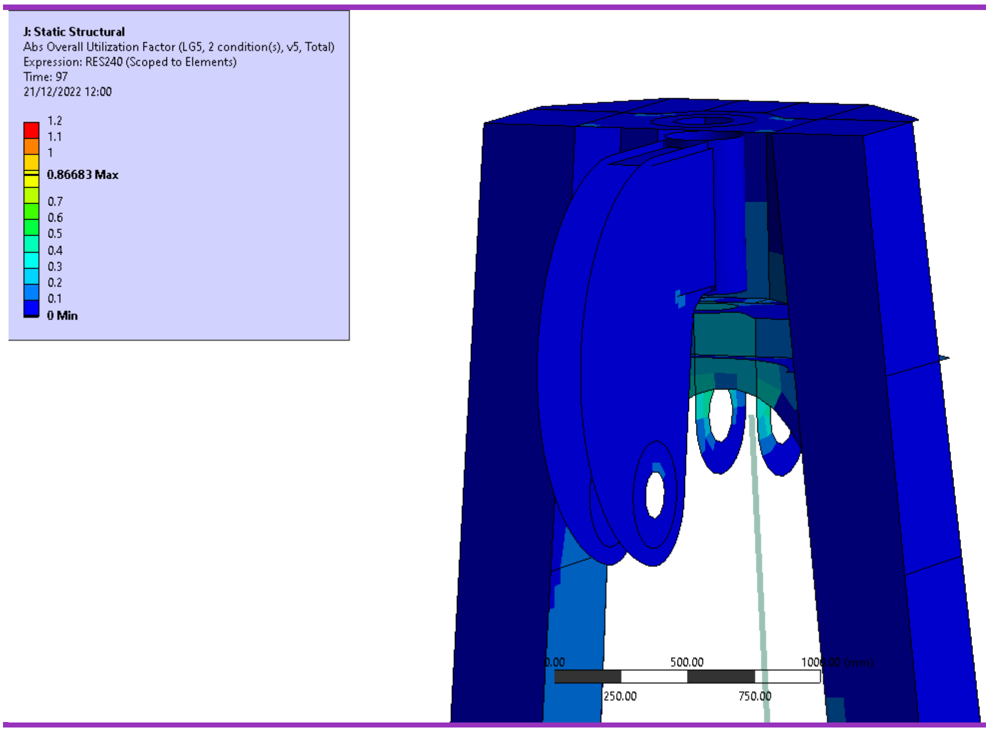
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	2..Front View



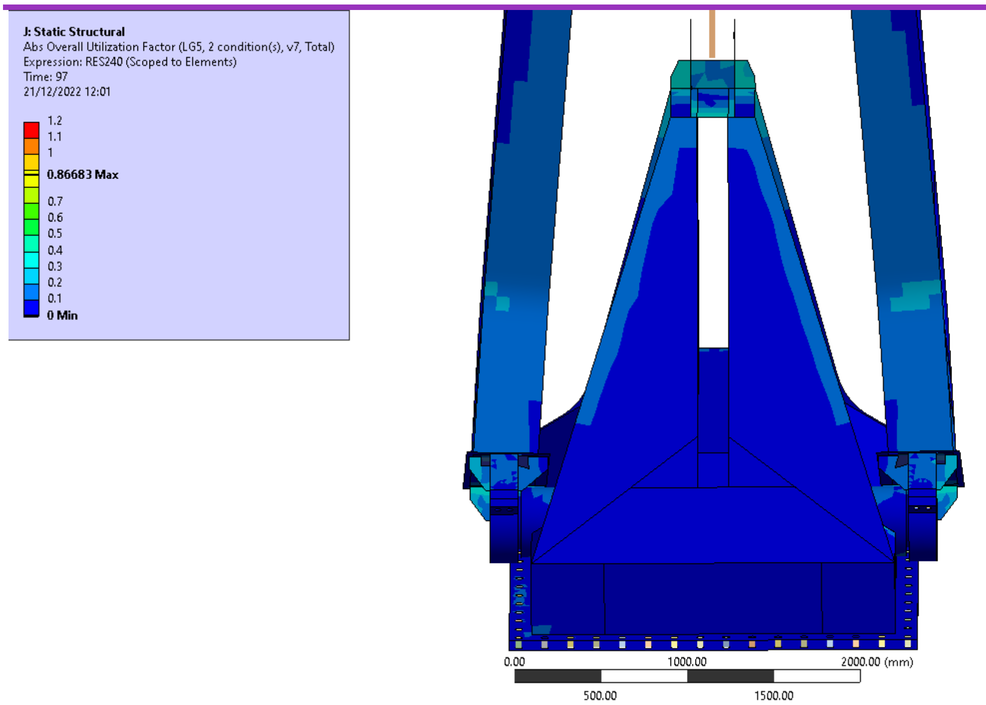
Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	3..Side View



Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	4..Back View

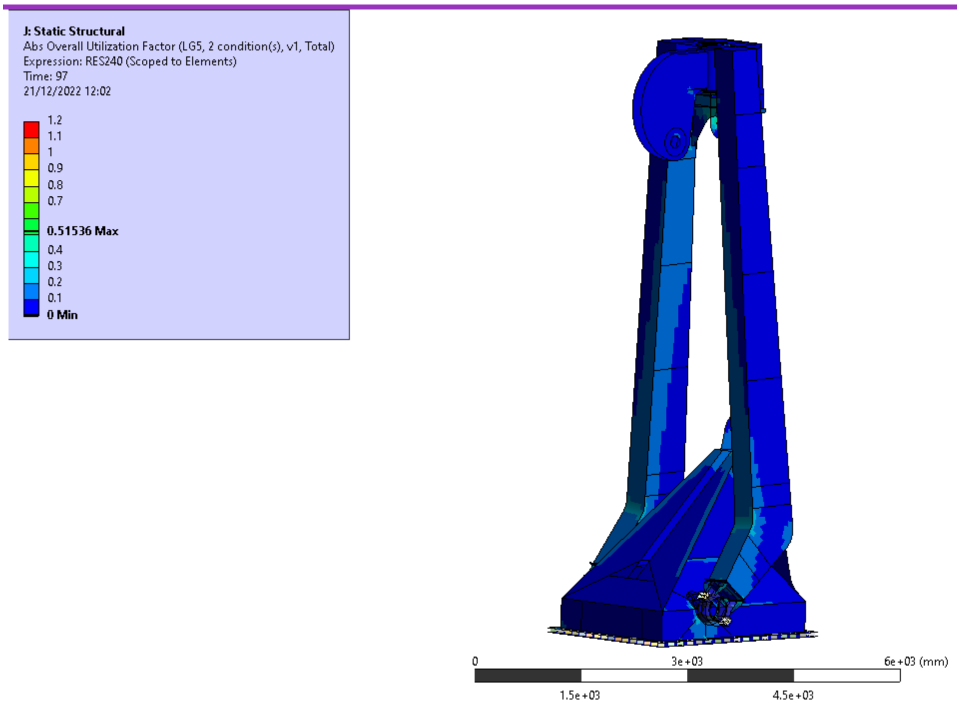


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	5..A-Frame Head and Tumbler Side

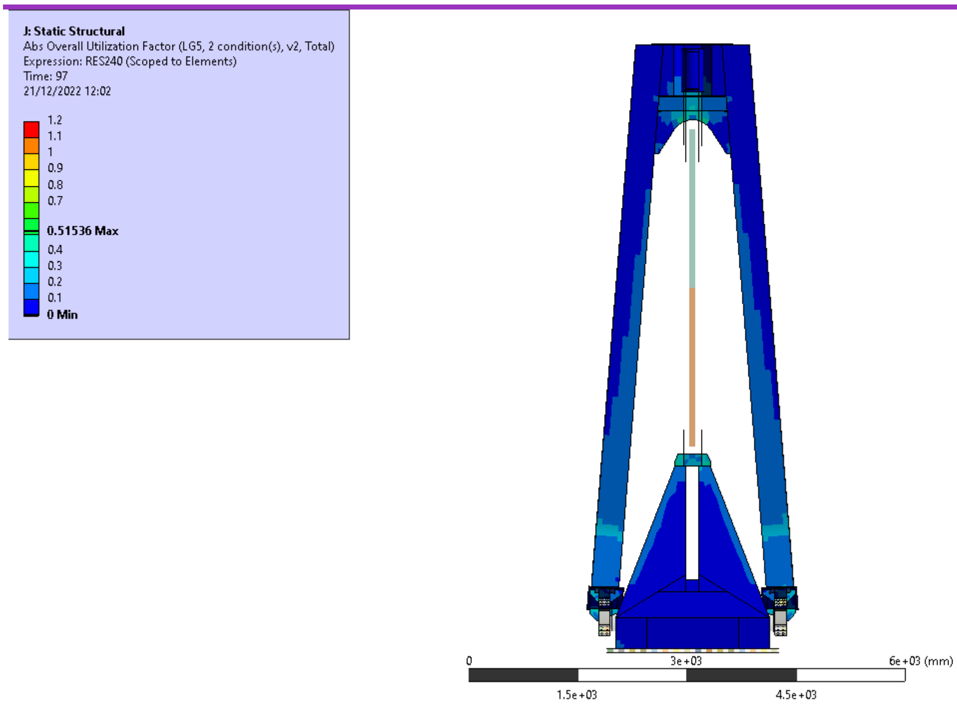


Check	[S3] 1..Static Stress Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	90397 element(s)	**View**	7..Fixed Part Front

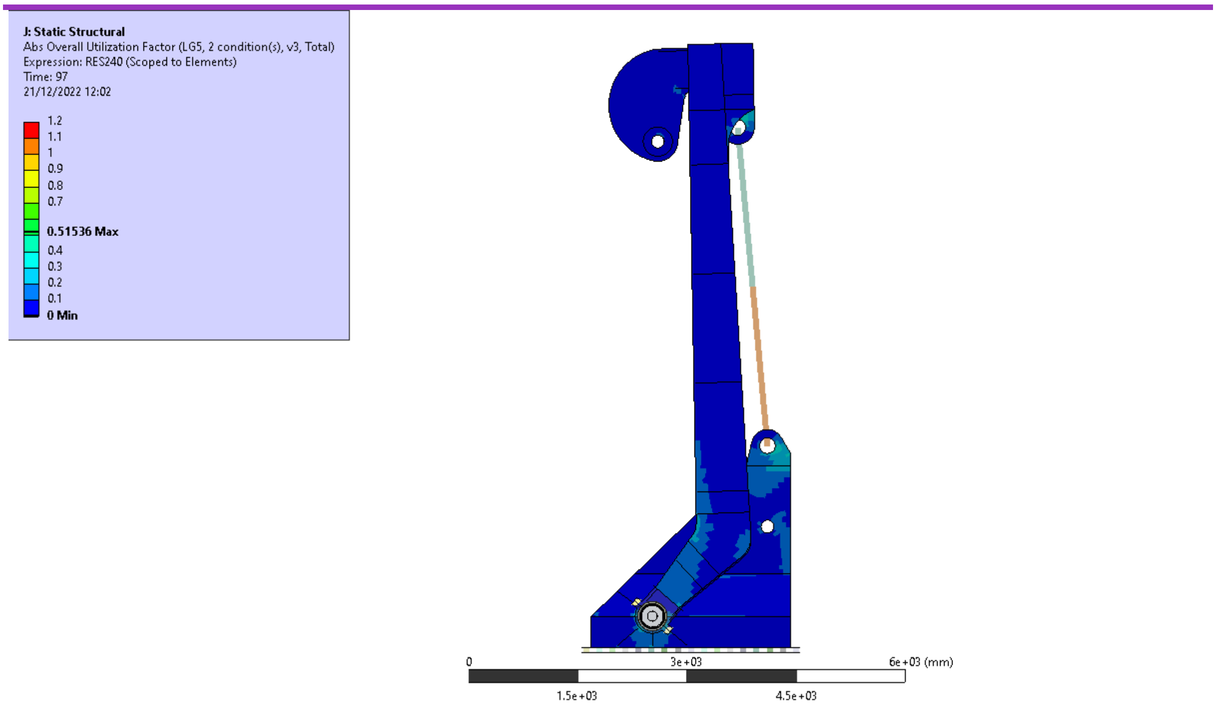
2..DNVGL-ST-0378 – Buckling Check



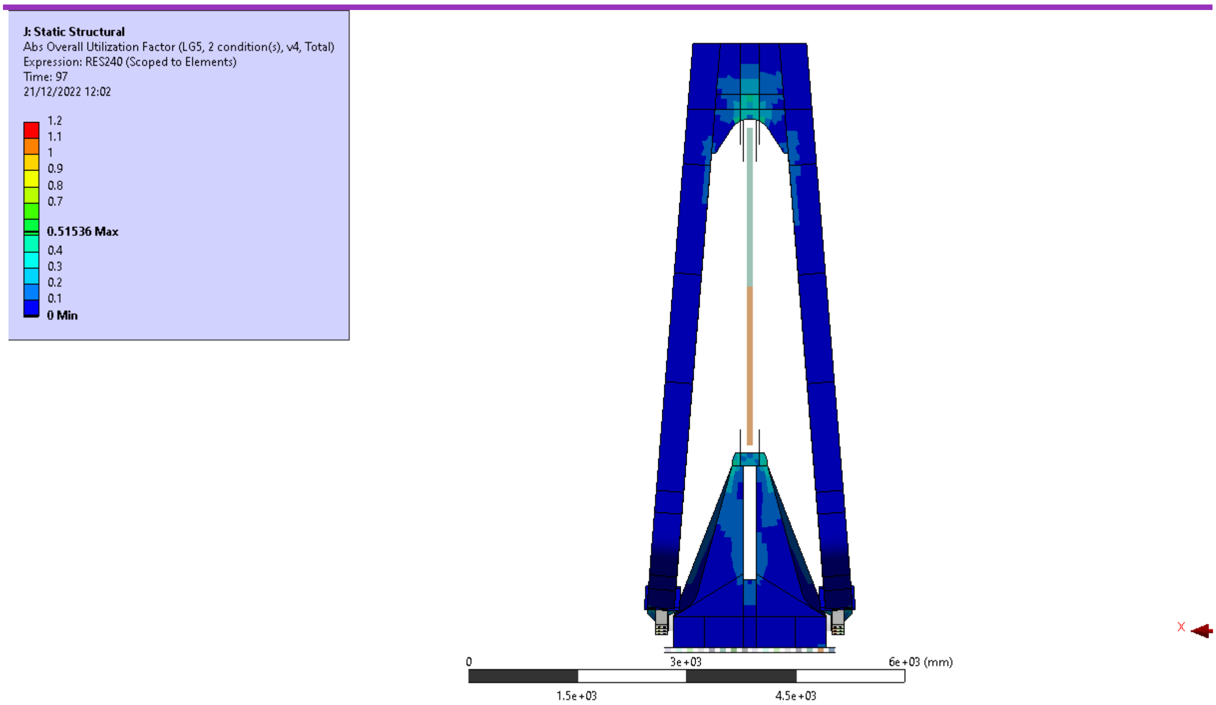
Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	1..Default View



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	2..Front View

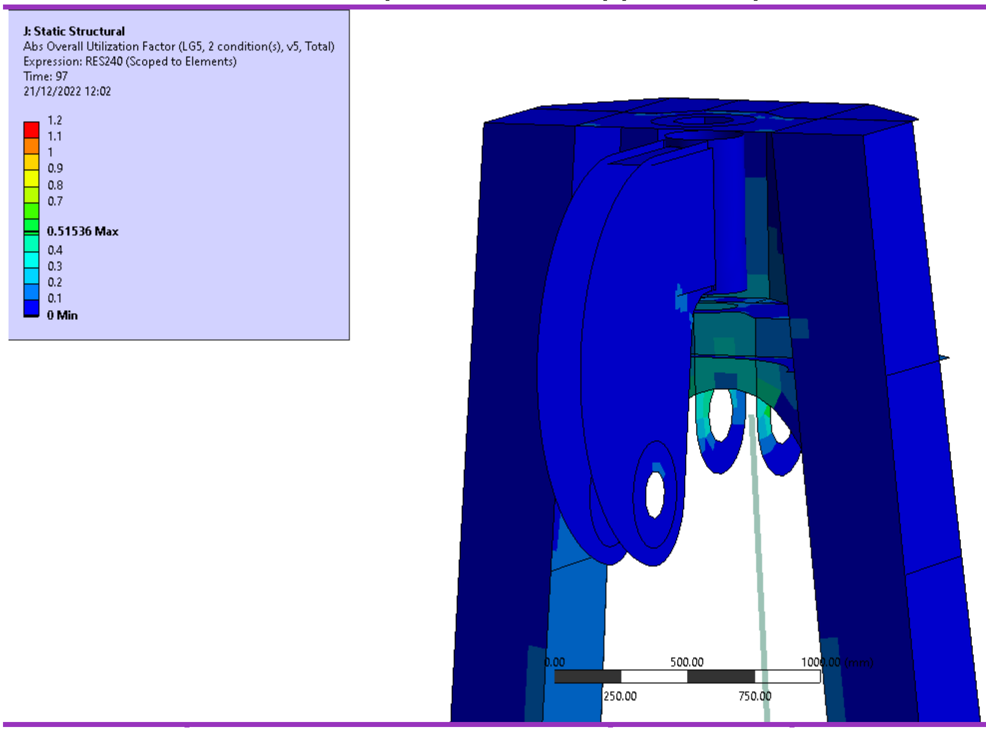


Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	3..Side View

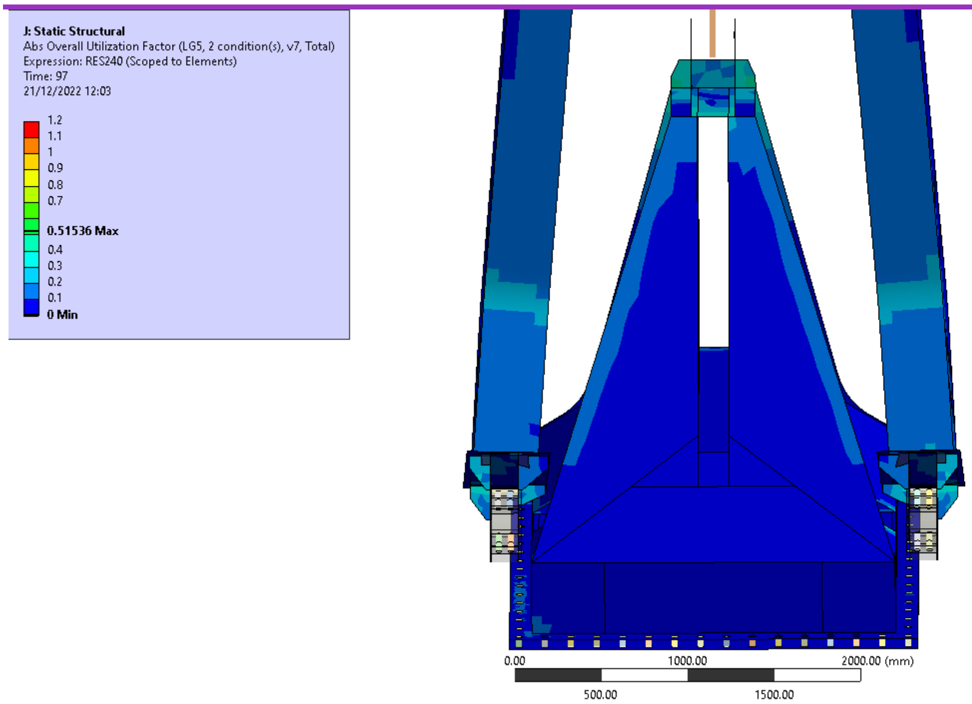


Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	4..Back View

Abs Overall Utilization Factor (LG5, 3 condition(s), v5, Total)



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	5..A-Frame Head and Tumbler Side



Check	[S3] 2..Buckling Check	**Point**	Total
Load Group	LG5..LC3b	**Parameter**	AbsoluteOverall Utilization Factor
Selection	26726 element(s)	**View**	7..Fixed Part Front

2..Eurocode3 Weld (EN1993-1-8, 2005)

Standard	2..Eurocode3 Weld (EN1993-1-8, 2005)	**Check**	[S2] 15..Weld Check Total
Load Group	LG5..LC3b	**Selection**	216 Welds

Title	Uf VM total	Uf N total	Uf material total	Uf Overall
101..Weld 101 [-1350.01; 377.18; 570.92]	0.48	0.57	0.91	0.91
57..Weld 57 [89.5; 1601.11; 2530]	0.22	0.28	0.42	0.42
58..Weld 58 [-89.5; 1629.09; 2530]	0.22	0.28	0.42	0.42
53..Weld 53 [126; 1895; 2624.55]	0.22	0.19	0.40	0.40
54..Weld 54 [-126; 1895; 2613.59]	0.21	0.22	0.40	0.40
100..Weld 100 [-1199.61; 51.75; 854.1]	0.17	0.19	0.31	0.31
133..Weld 133 [0.02; 1068.92; 7616.17]	0.29	0.16	0.30	0.30
137..Weld 137 [-193.99; 1000.94; 7614.96]	0.25	0.15	0.24	0.25
140..Weld 140 [193.98; 1000.95; 7614.96]	0.24	0.15	0.23	0.24
55..Weld 55 [-126; 1602.19; 2530]	0.12	0.14	0.22	0.22
56..Weld 56 [126; 1601.57; 2530]	0.12	0.14	0.22	0.22
17..Weld 17 [1051; 0; 160.77]	0.16	0.04	0.20	0.20
308..Weld 308 [126; 1395.68; 7520.24]	0.09	0.07	0.17	0.17
19..Weld 19 [-1051; 0; 160.77]	0.12	0.03	0.16	0.16
35..Weld 35 [-1051; -523.44; 455.69]	0.08	0.07	0.16	0.16
46..Weld 46 [89.5; 828.32; 1044.57]	0.08	0.10	0.15	0.15
142..Weld 142 [126; 1165.49; 7415.36]	0.15	0.10	0.15	0.15
143..Weld 143 [-126; 1165.54; 7415.36]	0.15	0.10	0.15	0.15
33..Weld 33 [1051; -523.44; 455.69]	0.08	0.07	0.14	0.14
41..Weld 41 [1051; 525.5; 30]	0.07	0.08	0.13	0.13

95..Weld 95 [-666.06; 996.1; 7412.34]	0.12	0.06	0.13	0.13
22..Weld 22 [1051; -316.45; 199.47]	0.10	0.05	0.12	0.12
26..Weld 26 [1051; 316.45; 199.46]	0.11	0.07	0.12	0.12
50..Weld 50 [-629; -844; 243.64]	0.12	0.07	0.12	0.12
20..Weld 20 [-1051; 316.45; 199.47]	0.10	0.05	0.11	0.11
25..Weld 25 [-1051; -316.45; 199.47]	0.08	0.04	0.11	0.11
63..Weld 63 [-0.05; 1895; 968.38]	0.06	0.02	0.11	0.11
97..Weld 97 [-1231.55; 373.73; 573.92]	0.05	0.06	0.10	0.10
127..Weld 127 [1231.57; 373.73; 573.92]	0.05	0.06	0.10	0.10
136..Weld 136 [-332.39; 921.43; 8316.66]	0.07	0.02	0.09	0.09
139..Weld 139 [332.39; 921.43; 8316.66]	0.07	0.02	0.09	0.09
317..Weld 317 [0.02; 1397.47; 7419.48]	0.05	0.04	0.09	0.09
52..Weld 52 [-0.07; -314.33; 970.77]	0.04	0.01	0.08	0.08
66..Weld 66 [89; 486.24; 7704.11]	0.04	0.04	0.08	0.08
68..Weld 68 [-89; 486.23; 7704.11]	0.05	0.04	0.08	0.08
320..Weld 320 [0; 937.54; 7411.3]	0.08	0.05	0.08	0.08
72..Weld 72 [-1088.51; 513.51; 4534.76]	0.04	0.02	0.07	0.07
123..Weld 123 [853.94; 757.46; 7408.1]	0.05	0.02	0.07	0.07
132..Weld 132 [-126; 1062.49; 7977.53]	0.05	0.03	0.07	0.07
135..Weld 135 [0; 1056.41; 8319.06]	0.05	0.02	0.07	0.07
28..Weld 28 [-89.5; 1068.43; 455.69]	0.05	0.01	0.06	0.06
74..Weld 74 [-853.79; 757.41; 7408.1]	0.05	0.02	0.06	0.06

105..Weld 105 [983.82; 711.97; 1227.38]	0.06	0.04	0.06	0.06
134..Weld 134 [126; 1062.49; 7977.56]	0.05	0.03	0.06	0.06
319..Weld 319 [-324.59; 937.54; 7411.3]	0.06	0.04	0.06	0.06
321..Weld 321 [307.4; 937.54; 7411.3]	0.05	0.04	0.06	0.06
37..Weld 37 [-1051; 1049.01; 455.69]	0.03	0.03	0.05	0.05
64..Weld 64 [629; 1895; 243.35]	0.04	0.03	0.05	0.05
65..Weld 65 [-629; 1895; 225.71]	0.05	0.04	0.05	0.05
75..Weld 75 [-1357.59; 711.65; 1257.77]	0.05	0.03	0.04	0.05
82..Weld 82 [-983.82; 711.97; 1227.38]	0.05	0.03	0.05	0.05
84..Weld 84 [-933.81; 976.58; 1848.4]	0.05	0.03	0.05	0.05
112..Weld 112 [933.81; 976.58; 1848.4]	0.05	0.03	0.05	0.05
138..Weld 138 [-193.47; 988.95; 8317.86]	0.05	0.03	0.05	0.05
141..Weld 141 [193.47; 988.95; 8317.86]	0.05	0.02	0.05	0.05
16..Weld 16 [629; 0; 160.9]	0.03	0.01	0.04	0.04
45..Weld 45 [662.65; -324.61; 693.54]	0.02	0.02	0.04	0.04
94..Weld 94 [-591.78; 940.81; 8317]	0.02	0.01	0.04	0.04
107..Weld 107 [1357.59; 711.67; 1257.76]	0.04	0.03	0.04	0.04
113..Weld 113 [1307.56; 975.21; 1879]	0.04	0.02	0.03	0.04
309..Weld 309 [126; 1387.4; 7985.61]	0.03	0.01	0.04	0.04
318..Weld 318 [308.72; 1397.47; 7419.48]	0.02	0.02	0.04	0.04
1..Weld 1 [-89.5; -393.64; 893.64]	0.01	0.01	0.03	0.03

2..Weld 2 [89.5; -393.63; 893.65]	0.01	0.01	0.03	0.03
18..Weld 18 [-629; 0; 160.9]	0.03	0.01	0.03	0.03
23..Weld 23 [629; -316.36; 199.54]	0.02	0.01	0.03	0.03
32..Weld 32 [629; -518.73; 455.69]	0.02	0.00	0.03	0.03
49..Weld 49 [-662.62; -324.62; 693.55]	0.02	0.02	0.03	0.03
60..Weld 60 [-89.5; -326.39; 694.85]	0.01	0.02	0.03	0.03
61..Weld 61 [89.5; 790.34; 969.57]	0.02	0.02	0.03	0.03
67..Weld 67 [89; 366.33; 8220.3]	0.01	0.01	0.03	0.03
76..Weld 76 [-779.68; 715.2; 8312.99]	0.02	0.00	0.03	0.03
77..Weld 77 [-1374.87; 506.11; 1038.72]	0.03	0.02	0.03	0.03
78..Weld 78 [-914.97; 786.85; 6664.22]	0.03	0.02	0.03	0.03
79..Weld 79 [-1037.93; 845.67; 5165.41]	0.02	0.01	0.03	0.03
80..Weld 80 [-1160.49; 904.71; 3671.59]	0.03	0.02	0.03	0.03
81..Weld 81 [-1307.56; 975.21; 1879]	0.03	0.02	0.03	0.03
85..Weld 85 [-1001.2; 507.49; 1007.19]	0.03	0.02	0.03	0.03
86..Weld 86 [-541.22; 787.81; 6633.6]	0.02	0.01	0.03	0.03
91..Weld 91 [-973.65; 1224.93; 3668.84]	0.02	0.01	0.03	0.03
92..Weld 92 [-851.09; 1133.7; 5161.39]	0.03	0.01	0.03	0.03
93..Weld 93 [-728.08; 1042.16; 6658.92]	0.03	0.02	0.03	0.03
103..Weld 103 [1001.2; 507.49; 1007.19]	0.03	0.02	0.03	0.03
114..Weld 114 [1160.49; 904.71; 3671.59]	0.03	0.02	0.03	0.03

115..Weld 115 [973.65; 1224.93; 3668.84]	0.02	0.01	0.03	0.03
118..Weld 118 [851.09; 1133.7; 5161.39]	0.03	0.01	0.03	0.03
119..Weld 119 [1037.93; 845.67; 5165.41]	0.03	0.01	0.03	0.03
120..Weld 120 [541.22; 787.81; 6633.6]	0.02	0.01	0.03	0.03
121..Weld 121 [728.08; 1042.16; 6658.92]	0.03	0.02	0.03	0.03
122..Weld 122 [914.97; 786.85; 6664.22]	0.03	0.02	0.03	0.03
144..Weld 144 [-126; 1219.05; 8321.95]	0.02	0.01	0.03	0.03
21..Weld 21 [-629; 316.34; 199.56]	0.02	0.01	0.02	0.02
24..Weld 24 [-629; -316.35; 199.55]	0.02	0.00	0.02	0.02
30..Weld 30 [629; 1054.8; 455.69]	0.02	0.01	0.02	0.02
59..Weld 59 [-89.5; 790.34; 969.57]	0.02	0.01	0.02	0.02
83..Weld 83 [-909.3; 964.67; 2147.16]	0.02	0.01	0.02	0.02
87..Weld 87 [-786.74; 905.86; 3640.98]	0.01	0.00	0.02	0.02
102..Weld 102 [1374.87; 506.11; 1038.72]	0.02	0.02	0.02	0.02
104..Weld 104 [1204.6; 686.56; 827.51]	0.02	0.01	0.02	0.02
106..Weld 106 [1189.8; 919.49; 1016.78]	0.02	0.01	0.02	0.02
110..Weld 110 [909.3; 964.67; 2147.16]	0.02	0.01	0.02	0.02
111..Weld 111 [1120.63; 1334.41; 1877.77]	0.02	0.01	0.01	0.02
116..Weld 116 [786.74; 905.86; 3640.98]	0.01	0.00	0.02	0.02
117..Weld 117 [664.19; 846.9; 5134.8]	0.01	0.01	0.02	0.02

27..Weld 27 [629; 316.34; 199.56]	0.01	0.01	0.01	0.01
89..Weld 89 [-1096.16; 1316.16; 2176.28]	0.01	0.01	0.01	0.01
90..Weld 90 [-1120.63; 1334.41; 1877.77]	0.01	0.01	0.01	0.01
96..Weld 96 [-1204.6; 686.56; 827.51]	0.01	0.01	0.01	0.01
108..Weld 108 [1283.05; 963.52; 2177.77]	0.01	0.01	0.01	0.01
109..Weld 109 [1096.16; 1316.16; 2176.28]	0.01	0.01	0.01	0.01
AbsMax over welds	0.48	0.57	0.91	0.91

4..Eurocode3 Bolts (EN 1993-1-8, 2005)

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	**Check**	[S4] 4..Category B and E. Shear resistance at serviceability
Load Group	LG5..LC3b	**Selection**	2 Properties

ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension	Category B Utilization factor 1 Tension and compression	Utilization factor total
105323	230231.91	0.10	230231.91	0.11	0.11
105324	230231.91	0.08	230231.91	0.08	0.08
105325	230231.91	0.05	230231.91	0.05	0.05
105326	230231.91	0.14	225194.98	0.16	0.16
105327	230231.91	0.09	230104.47	0.09	0.09
105328	230231.91	0.14	217779.20	0.16	0.16
105329	230231.91	0.11	230231.91	0.11	0.11
105330	230231.91	0.10	230231.91	0.11	0.11
105331	230231.91	0.06	230231.91	0.06	0.06
105332	230231.91	0.09	230231.91	0.09	0.09
105333	230231.91	0.09	230231.91	0.09	0.09
105334	230231.91	0.03	230231.91	0.03	0.03
105335	230231.91	0.02	230231.91	0.02	0.02
105336	230231.91	0.14	228147.30	0.14	0.14
105337	230231.91	0.02	229840.69	0.02	0.02
105338	230231.91	0.09	230231.91	0.09	0.09
105339	230231.91	0.11	226450.83	0.12	0.12
105340	230231.91	0.03	230231.91	0.03	0.03
105341	230231.91	0.09	230231.91	0.10	0.10
105342	230231.91	0.10	230231.91	0.11	0.11
105343	230231.91	0.08	230231.91	0.09	0.09
105344	230231.91	0.02	229103.66	0.02	0.02
105345	230231.91	0.03	229766.42	0.03	0.03
105346	230231.91	0.02	228677.30	0.02	0.02
105347	230231.91	0.02	229269.06	0.02	0.02
105348	230231.91	0.08	227823.27	0.08	0.08
105349	230231.91	0.11	226520.38	0.12	0.12
105350	230231.91	0.08	230231.91	0.09	0.09
105351	230231.91	0.06	229004.20	0.07	0.07
105352	230231.91	0.04	230029.59	0.04	0.04
105353	230231.91	0.08	230231.91	0.08	0.08
105354	230231.91	0.06	224260.36	0.06	0.06
105355	230231.91	0.04	226984.19	0.04	0.04
105356	158123.88	0.00	157779.88	0.00	0.00
105357	158123.88	0.00	157884.83	0.00	0.00
105358	158123.88	0.00	157885.77	0.00	0.00
105359	158123.88	0.00	157970.09	0.00	0.00
105360	158123.88	0.00	157971.00	0.00	0.00

105361	158123.88	0.00	157974.55	0.00	0.00
105362	158123.88	0.00	157633.22	0.00	0.00
105363	158123.88	0.00	157634.17	0.00	0.00
105364	158123.88	0.00	158123.88	0.00	0.00
105365	158123.88	0.00	158117.69	0.00	0.00
105366	158123.88	0.00	158108.13	0.00	0.00
105367	158123.88	0.00	158109.03	0.00	0.00
105368	230231.91	0.06	229461.75	0.07	0.07
105369	230231.91	0.13	230231.91	0.13	0.13
105370	230231.91	0.08	219707.98	0.09	0.09
105371	230231.91	0.04	230231.91	0.04	0.04
105372	230231.91	0.05	230231.91	0.05	0.05
105373	230231.91	0.07	229711.22	0.07	0.07
105374	230231.91	0.12	230231.91	0.12	0.12
105375	230231.91	0.07	213368.98	0.09	0.09
105376	230231.91	0.03	230231.91	0.03	0.03
105377	230231.91	0.06	206674.44	0.07	0.07
105378	230231.91	0.07	230066.75	0.07	0.07
105379	230231.91	0.07	229724.45	0.07	0.07
105380	230231.91	0.04	230231.91	0.05	0.05
105381	230231.91	0.09	230231.91	0.09	0.09
105382	230231.91	0.06	202423.28	0.09	0.09
105383	230231.91	0.07	230231.91	0.07	0.07
105384	230231.91	0.06	230231.91	0.07	0.07
105385	230231.91	0.09	230231.91	0.09	0.09
105386	230231.91	0.08	230231.91	0.08	0.08
105387	230231.91	0.09	205836.25	0.12	0.12
105388	230231.91	0.08	230231.91	0.08	0.08
105389	230231.91	0.08	230231.91	0.08	0.08
105390	230231.91	0.09	230231.91	0.09	0.09
105391	230231.91	0.12	211840.70	0.15	0.15
105392	230231.91	0.08	230231.91	0.08	0.08
105393	230231.91	0.09	230231.91	0.09	0.09
105394	230231.91	0.09	230231.91	0.09	0.09
105395	230231.91	0.15	222640.66	0.17	0.17
105396	230231.91	0.09	230231.91	0.09	0.09

Standard	4..Eurocode3 Bolts (EN 1993-1-8, 2005)	**Check**	[S4] 5..Category B and E. Slip-resistance at serviceability (Preloaded)
Load Group	LG5..LC3b	**Selection**	2 Properties

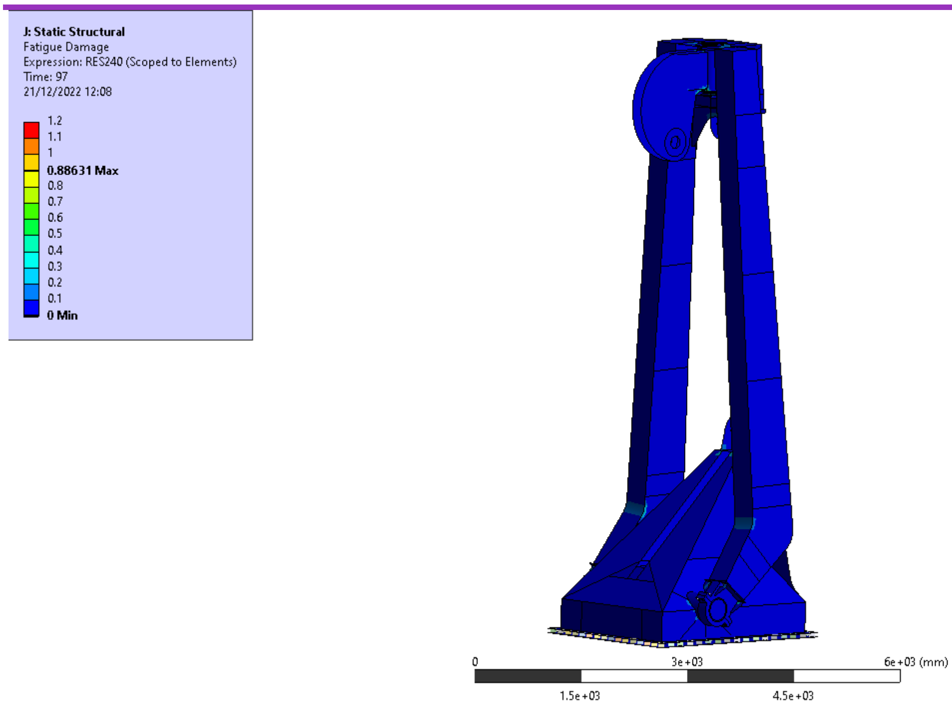
ID / Point	Design slip resistance of a preloaded class 8_8 or 10_9 bolt [KN]	Category B Utilization factor 1	Design slip resistance of a preloaded class 8_8 or 10_9 bolt with tension [KN]	Category B Utilization factor 1 Tension and compression	Shear resistance per shear plane [KN]	Category B Utilization factor 2	Bearing resistance [KN]	Category B Utilization factor 3	Tension resistance [KN]
105382	230.2	0.06	202.4	0.09	554.2	0.03	0.0	0.00	868.3
105387	230.2	0.09	205.8	0.12	554.2	0.04	0.0	0.00	868.3
105377	230.2	0.06	206.7	0.07	554.2	0.02	0.0	0.00	868.3
105391	230.2	0.12	211.8	0.15	554.2	0.05	0.0	0.00	868.3
105375	230.2	0.07	213.4	0.09	554.2	0.03	0.0	0.00	868.3
105328	230.2	0.14	217.8	0.16	554.2	0.06	0.0	0.00	868.3
105395	230.2	0.15	222.6	0.17	554.2	0.06	0.0	0.00	868.3
105380	230.2	0.04	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105326	230.2	0.14	225.2	0.16	554.2	0.06	0.0	0.00	868.3
105384	230.2	0.06	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105336	230.2	0.14	228.1	0.14	554.2	0.06	0.0	0.00	868.3
105376	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105370	230.2	0.08	219.7	0.09	554.2	0.03	0.0	0.00	868.3
105369	230.2	0.13	230.2	0.13	554.2	0.05	0.0	0.00	868.3
105323	230.2	0.10	230.2	0.11	554.2	0.04	0.0	0.00	868.3
105339	230.2	0.11	226.5	0.12	554.2	0.05	0.0	0.00	868.3
105374	230.2	0.12	230.2	0.12	554.2	0.05	0.0	0.00	868.3
105389	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105342	230.2	0.10	230.2	0.11	554.2	0.04	0.0	0.00	868.3
105341	230.2	0.09	230.2	0.10	554.2	0.04	0.0	0.00	868.3
105349	230.2	0.11	226.5	0.12	554.2	0.04	0.0	0.00	868.3
105330	230.2	0.10	230.2	0.11	554.2	0.04	0.0	0.00	868.3
105329	230.2	0.11	230.2	0.11	554.2	0.04	0.0	0.00	868.3
105343	230.2	0.08	230.2	0.09	554.2	0.03	0.0	0.00	868.3
105350	230.2	0.08	230.2	0.09	554.2	0.03	0.0	0.00	868.3
105371	230.2	0.04	230.2	0.04	554.2	0.02	0.0	0.00	868.3
105394	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105332	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105393	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105327	230.2	0.09	230.1	0.09	554.2	0.04	0.0	0.00	868.3
105396	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105390	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105353	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105338	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105385	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105381	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3

105333	230.2	0.09	230.2	0.09	554.2	0.04	0.0	0.00	868.3
105386	230.2	0.08	230.2	0.08	554.2	0.04	0.0	0.00	868.3
105392	230.2	0.08	230.2	0.08	554.2	0.04	0.0	0.00	868.3
105324	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105354	230.2	0.06	224.3	0.06	554.2	0.02	0.0	0.00	868.3
105348	230.2	0.08	227.8	0.08	554.2	0.03	0.0	0.00	868.3
105388	230.2	0.08	230.2	0.08	554.2	0.03	0.0	0.00	868.3
105383	230.2	0.07	230.2	0.07	554.2	0.03	0.0	0.00	868.3
105378	230.2	0.07	230.1	0.07	554.2	0.03	0.0	0.00	868.3
105379	230.2	0.07	229.7	0.07	554.2	0.03	0.0	0.00	868.3
105373	230.2	0.07	229.7	0.07	554.2	0.03	0.0	0.00	868.3
105368	230.2	0.06	229.5	0.07	554.2	0.03	0.0	0.00	868.3
105331	230.2	0.06	230.2	0.06	554.2	0.03	0.0	0.00	868.3
105351	230.2	0.06	229.0	0.07	554.2	0.03	0.0	0.00	868.3
105372	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105325	230.2	0.05	230.2	0.05	554.2	0.02	0.0	0.00	868.3
105355	230.2	0.04	227.0	0.04	554.2	0.01	0.0	0.00	868.3
105340	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105352	230.2	0.04	230.0	0.04	554.2	0.01	0.0	0.00	868.3
105346	230.2	0.02	228.7	0.02	554.2	0.01	0.0	0.00	868.3
105345	230.2	0.03	229.8	0.03	554.2	0.01	0.0	0.00	868.3
105334	230.2	0.03	230.2	0.03	554.2	0.01	0.0	0.00	868.3
105347	230.2	0.02	229.3	0.02	554.2	0.01	0.0	0.00	868.3
105335	230.2	0.02	230.2	0.02	554.2	0.01	0.0	0.00	868.3
105337	230.2	0.02	229.8	0.02	554.2	0.01	0.0	0.00	868.3
105344	230.2	0.02	229.1	0.02	554.2	0.01	0.0	0.00	868.3
105356	158.1	0.00	157.8	0.00	282.7	0.00	0.0	0.00	447.3
105363	158.1	0.00	157.6	0.00	282.7	0.00	0.0	0.00	447.3
105362	158.1	0.00	157.6	0.00	282.7	0.00	0.0	0.00	447.3
105357	158.1	0.00	157.9	0.00	282.7	0.00	0.0	0.00	447.3
105358	158.1	0.00	157.9	0.00	282.7	0.00	0.0	0.00	447.3
105364	158.1	0.00	158.1	0.00	282.7	0.00	0.0	0.00	447.3
105361	158.1	0.00	158.0	0.00	282.7	0.00	0.0	0.00	447.3
105360	158.1	0.00	158.0	0.00	282.7	0.00	0.0	0.00	447.3
105359	158.1	0.00	158.0	0.00	282.7	0.00	0.0	0.00	447.3
105365	158.1	0.00	158.1	0.00	282.7	0.00	0.0	0.00	447.3
105367	158.1	0.00	158.1	0.00	282.7	0.00	0.0	0.00	447.3
105366	158.1	0.00	158.1	0.00	282.7	0.00	0.0	0.00	447.3

ID / Point	Category E Utilization factor 1	Punching shear resistance [KN]	Category E Utilization factor 2	Combined utilization factor	Design tensile load [KN]	Design shear load [KN]	Utilization factor overall	pretension load [KN]
105382	0.32	6080.1	0.05	0.26	279.6	14.8	0.32	844.2
105387	0.29	6080.1	0.04	0.24	247.9	20.4	0.29	844.2
105377	0.27	6080.1	0.04	0.22	236.2	13.1	0.27	844.2
105391	0.23	6080.1	0.03	0.21	200.6	27.5	0.23	844.2
105375	0.20	6080.1	0.03	0.17	174.8	17.0	0.20	844.2
105328	0.18	6080.1	0.03	0.19	157.7	31.6	0.19	844.2
105395	0.15	6080.1	0.02	0.17	131.0	34.1	0.17	844.2
105380	0.16	6080.1	0.02	0.13	140.5	10.3	0.16	844.2
105326	0.14	6080.1	0.02	0.16	117.2	32.7	0.16	844.2
105384	0.15	6080.1	0.02	0.13	130.1	14.8	0.15	844.2
105336	0.05	6080.1	0.01	0.09	47.0	31.2	0.14	844.2
105376	0.13	6080.1	0.02	0.11	116.5	6.5	0.13	844.2
105370	0.13	6080.1	0.02	0.13	114.2	18.2	0.13	844.2
105369	0.06	6080.1	0.01	0.07	53.4	29.0	0.13	844.2
105323	0.11	6080.1	0.02	0.12	97.1	24.0	0.12	844.2
105339	0.11	6080.1	0.02	0.12	91.9	25.2	0.12	844.2
105374	0.02	6080.1	0.00	0.05	18.1	27.8	0.12	844.2
105389	0.12	6080.1	0.02	0.12	104.0	18.1	0.12	844.2
105342	0.11	6080.1	0.02	0.12	94.7	22.9	0.12	844.2
105341	0.10	6080.1	0.01	0.11	90.4	20.6	0.11	844.2
105349	0.09	6080.1	0.01	0.11	78.2	24.6	0.11	844.2
105330	0.09	6080.1	0.01	0.11	78.4	23.8	0.11	844.2
105329	0.04	6080.1	0.01	0.07	35.5	24.5	0.11	844.2
105343	0.10	6080.1	0.01	0.10	84.4	18.4	0.10	844.2
105350	0.09	6080.1	0.01	0.10	77.4	18.9	0.10	844.2
105371	0.10	6080.1	0.01	0.07	83.1	9.4	0.10	844.2
105394	0.05	6080.1	0.01	0.07	47.2	21.7	0.09	844.2
105332	0.01	6080.1	0.00	0.04	4.5	21.4	0.09	844.2
105393	0.08	6080.1	0.01	0.09	72.4	21.4	0.09	844.2
105327	0.01	6080.1	0.00	0.04	12.7	21.1	0.09	844.2
105396	0.01	6080.1	0.00	0.04	5.9	20.9	0.09	844.2
105390	0.01	6080.1	0.00	0.04	6.0	20.7	0.09	844.2
105353	0.08	6080.1	0.01	0.09	67.9	17.8	0.09	844.2
105338	0.00	6080.1	0.00	0.04	2.6	20.3	0.09	844.2
105385	0.01	6080.1	0.00	0.04	6.5	19.9	0.09	844.2
105381	0.01	6080.1	0.00	0.04	6.4	19.6	0.09	844.2
105333	0.04	6080.1	0.01	0.06	32.0	19.6	0.09	844.2
105386	0.01	6080.1	0.00	0.04	4.7	19.5	0.08	844.2
105392	0.03	6080.1	0.00	0.05	23.9	19.5	0.08	844.2
105324	0.03	6080.1	0.00	0.05	24.8	18.5	0.08	844.2
105354	0.08	6080.1	0.01	0.08	68.1	13.6	0.08	844.2
105348	0.06	6080.1	0.01	0.08	54.3	18.4	0.08	844.2
105388	0.02	6080.1	0.00	0.04	17.6	17.9	0.08	844.2
105383	0.01	6080.1	0.00	0.03	10.2	16.7	0.07	844.2
105378	0.01	6080.1	0.00	0.03	6.8	16.4	0.07	844.2

105379	0.01	6080.1	0.00	0.04	9.1	16.1	0.07	844.2
105373	0.02	6080.1	0.00	0.04	15.6	15.5	0.07	844.2
105368	0.03	6080.1	0.00	0.05	25.0	15.0	0.06	844.2
105331	0.00	6080.1	0.00	0.03	2.2	14.7	0.06	844.2
105351	0.04	6080.1	0.01	0.06	35.9	14.6	0.06	844.2
105372	0.06	6080.1	0.01	0.05	55.1	12.3	0.06	844.2
105325	0.06	6080.1	0.01	0.06	49.3	11.6	0.06	844.2
105355	0.05	6080.1	0.01	0.05	42.5	8.2	0.05	844.2
105340	0.04	6080.1	0.01	0.04	33.4	6.3	0.04	844.2
105352	0.04	6080.1	0.01	0.03	32.5	8.3	0.04	844.2
105346	0.03	6080.1	0.00	0.03	29.9	5.4	0.03	844.2
105345	0.03	6080.1	0.00	0.03	26.5	5.9	0.03	844.2
105334	0.00	6080.1	0.00	0.01	2.0	6.5	0.03	844.2
105347	0.02	6080.1	0.00	0.02	19.2	5.6	0.02	844.2
105335	0.00	6080.1	0.00	0.01	3.8	5.5	0.02	844.2
105337	0.01	6080.1	0.00	0.01	6.8	5.3	0.02	844.2
105344	0.01	6080.1	0.00	0.02	10.5	4.9	0.02	844.2
105356	0.01	7962.1	0.00	0.01	5.5	0.5	0.01	434.8
105363	0.00	7962.1	0.00	0.01	2.2	0.5	0.01	434.8
105362	0.00	7962.1	0.00	0.00	2.2	0.4	0.00	434.8
105357	0.00	7962.1	0.00	0.00	2.1	0.4	0.00	434.8
105358	0.00	7962.1	0.00	0.00	2.1	0.5	0.00	434.8
105364	0.00	7962.1	0.00	0.00	1.4	0.4	0.00	434.8
105361	0.00	7962.1	0.00	0.00	1.2	0.3	0.00	434.8
105360	0.00	7962.1	0.00	0.00	0.7	0.3	0.00	434.8
105359	0.00	7962.1	0.00	0.00	0.7	0.3	0.00	434.8
105365	0.00	7962.1	0.00	0.00	0.6	0.3	0.00	434.8
105367	0.00	7962.1	0.00	0.00	0.7	0.3	0.00	434.8
105366	0.00	7962.1	0.00	0.00	0.7	0.2	0.00	434.8

Fatigue
FG1..Fatigue
1..FEM 1.001 (3rd, 1998)



Check	[S1] 3..Fatigue Summation	**Point**	Total
Fatigue Group	FG1..Fatigue	**Parameter**	Overall Summed Damage
Selection	90397 element(s)	**View**	1..Default View

Check	[S1] 3..Fatigue Summation	**Fatigue Group**	FG1..Fatigue
Parameter	Summed Damage	**Selection**	32 Selections

Selections	X	Y	Z	XY	YZ	ZX	Eqv	Overall
Component '4..Fixed Part Flange'	0.25	0.28		0.07			0.28	0.28
Component '5..Fixed Part Front Plate'	0.03	0.24		0.03			0.25	0.25
Component '6..Fixed Part Back Plate'	0.05	0.23		0.02			0.23	0.23
Component '7..Fixed Part Side Plates'	0.71	0.08		0.07			0.72	0.72
Component '8..Fixed Part Spine'	0.03	0.01		0.01			0.03	0.03
Component '9..Fixed Part Sheave Plate'	0.02	0.02		0.00			0.03	0.03
Component '10..Fixed Part Cylinder Mount Back'	0.06	0.06		0.01			0.13	0.13
Component '11..Fixed Part Eye Plates'	0.04	0.13		0.06			0.16	0.16
Component '12..Fixed Part Cylinder Mount Base'	0.02	0.02		0.04			0.04	0.04
Component '13..Fixed Part Pivot Supports'	0.41	0.40		0.10			0.65	0.65
Component '14..Fixed Part Bottom Plates'	0.28	0.42		0.04			0.45	0.45
Component '15..Fixed Part Horizontals'	0.21	0.02		0.12			0.32	0.32
Component '16..Fixed Part Front Stiffener'	0.23	0.01		0.02			0.24	0.24
Component '17..Fixed Part Pivot Ends'	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01
Component '18..Fixed Part Pivot'	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Component '19..A-Frame Bearing Plates'	0.21	0.64		0.08			0.75	0.75
Component '20..A-Frame Bearings'	0.24	0.18	0.22	0.12	0.20	0.03	0.53	0.53

Component '21..A-Frame Base Plates'	0.08	0.27		0.04			0.28	0.28
Component '22..A-Frame Leg Front and Back'	0.17	0.13		0.02			0.17	0.17
Component '23..A-Frame Leg Side Plates'	0.24	0.25		0.15			0.29	0.29
Component '24..A-Frame Diaphgrams'	0.01	0.15		0.03			0.16	0.16
Component '25..A-Frame Head Lower Plates'	0.11	0.08		0.08			0.20	0.20
Component '26..A-Frame Connecting Plate'	0.23	0.19		0.05			0.25	0.25
Component '27..A-Frame Head Middle Plate'	0.18	0.18		0.10			0.32	0.32
Component '28..A-Frame Head Eye Plates'	0.05	0.03		0.03			0.07	0.07
Component '29..A-Frame Head Top Plate'	0.06	0.35		0.29			0.35	0.35
Component '30..A-Frame Head Back Plate'	0.01	0.02		0.04			0.04	0.04
Component '31..A-Frame Head Vertical Plates'	0.11	0.17		0.04			0.18	0.18
Component '32..Tumbler Bush'	0.36	0.38		0.44			0.60	0.60
Component '33..Tumbler Side Plates'	0.57	0.44		0.07			0.58	0.58
Component '34..Tumbler Top Plate'	0.13	0.34		0.03			0.35	0.35
Component '35..Tumbler Bottom Plate'	0.50	0.86		0.06			0.89	0.89

D

Draghead Gantry Design - Old Methodology

In this appendix, the first draghead gantry design is presented. First the finite element analysis model and its constituents are presented, along with the mesh and boundary conditions used for the analysis. Secondly, structural assessment calculations are presented with their results.

D.1. Load Cases

The load cases for the design were based on the company's experience with the dredging equipment design and BV NR 595 (Bureau Veritas, 2014).

Empirical Case Nominal Force

This loading condition is an empirically defined case. In this case the empty suction pipe is hoisted above the waterline and no inertial effects apart from gravity are considered.

Empirical Case Maximal Force

This loading condition is a second empirically defined case. For this condition the suction pipe filled with water is hoisted above the waterline and no inertial effects apart from gravity are considered.

LC 1 Nominal Operation Static Design Force

In this case, an empty suction pipe is hoisted above the waterline and environmental loads are not considered.

LC 2A Nominal Operation Dynamic Force

For this condition, an empty suction pipe is hoisted above the waterline and environmental inertial loads are considered. This is done through application of the dynamic amplification factor and the duty factor to the load used in LC1. Additionally, environmental effects for the operation are considered.

LC 3 Accidental Condition

This condition is defined based on the maximum brake capacity of the design pulling loads. It is calculated by multiplication of the maximal loading force with winch brake holding factor and the maximum pull factor and divided by an empirical factor for the draghead gantry, based on the company's experience. Additionally, the environmental effects for the operation are considered.

Fatigue
This loading condition is a fatigue loading condition. Fatigue resistance of the gantry is assessed based on the environmental loads from default motion analysis without the LFRD load factors and nominal force when an empty suction pipe is hoisted above the waterline. Since, the area of operation of the vessel is not known yet, the environmental loads are set to an arbitrary sum of $N = 10^8$ cycles. The number of cycles for the pipe load is:

$$N = (1 - d_t) \cdot Y \cdot D \cdot H = (1 - 0.2) \cdot 40 \cdot 365 \cdot 5 = 58400,$$

where d_t is down time, Y are years of operation, D is the number of days in a year and H is the number of hoisting cycles per day. Calculations for this conditions are performed for the model in "Out" position.

D.2. Structural Check Criteria

In this section criteria for acceptance of all of the checks in the design are presented. Structural checks are prepared using the Bureau Veritas rules, while buckling, weld strength and fatigue calculations checks are prepared using the De Norske Veritas rules applicable to the structure. Applicable structural checks are to be calculated for all of the considered gantry positions, while weld calculations, buckling and fatigue are calculated for gantry in the "Out" position. This is due to it being the most critical position.

D.2.1. Structural

The structural check is conducted according to the basis of design supplied by the company. For the finite element analysis model used for the structural check the equivalent Von Mises stress should be lower than allowable stress. For each of the Load Cases for steel S235 and S355 the allowable stresses are presented in Table D.1.

Table D.1: Allowable stresses.

	Empirical Case Nominal Force	Empirical Case Maximal Force	LC 1	LC 2A	LC 3
S355 R_y	355	355	355	355	355
S355 σ_{all}	238	320	234	312	391
S235 R_y	235	235	235	235	235
S235 σ_{all}	173	233	155	207	259

For very fine mesh in hot spot regions these criteria can be replaced. Allowable stresses for each of the Load Cases for steel S235 and S355 are presented in Table D.2.

Table D.2: Allowable stresses for fine mesh model.

	Empirical Case Nominal Force	Empirical Case Maximal Force	LC 1	LC 2A	LC 3
S355 R_y	355	355	355	355	355
S355 σ_{all}	309	415	277	369	462
S235 R_y	235	235	235	235	235
S235 σ_{all}	205	275	183	244	306

D.2.2. Buckling

Plate buckling check is conducted according to the rules by De Norske Veritas, DNV-RP-C201 Buckling of plated structures (De Norske Veritas, 2010a) is used. Material factor $\gamma_M = 1.15$, is used in calculations.

D.2.3. Weld Strength

The double fillet weld strength check is calculated according to the DNV-OS-C201 (De Norske Veritas, 2011) Section 9 C with correction of taking the correlation factor β_w and basic usage factor η_0 according to the Appendix E of DNVGL-ST-N001 (De Norske Veritas, 2021) rules.

D.2.4. Fatigue Calculations

Fatigue calculations are conducted based on the DNV-RP-C203 (De Norske Veritas, 2010b). The structural details are to be first categorised based on the applicable SN-curves from the standard. Then calculation method B is used to find the stress range for each of the details.

D.3. Finite Element Analysis

Finite element analysis is conducted as the base for a design of the gantry. The software used for the analysis are Ansys Workbench 2021 and SDC Verifier 2021 R1. Ansys Workbench is used for modelling, meshing, preparing the model for initial calculations, then SDC Verifier is used to calculate the final results for all of the structural checks and for buckling, weld and fatigue calculations. The steel used for the gantry is S355.

D.3.1. Geometry

For the purposes of this design company provided a base 3D model based on which the finite element model for the draghead gantry was developed. After modifications and simplifications, models of the crane for three positions were developed. All three positions are presented in Figure D.1. The “Out” position, which is the position in which dredging operations are conducted. The “Upright” position, which is the situation when the gantry is not used or in the first period of hoisting while the suction pipe is being lifted from the saddle. Lastly, the “45” position, which is an intermediate point between the other two aforementioned situations, in this case the crane is situated 45 degrees from the “Upright” position.

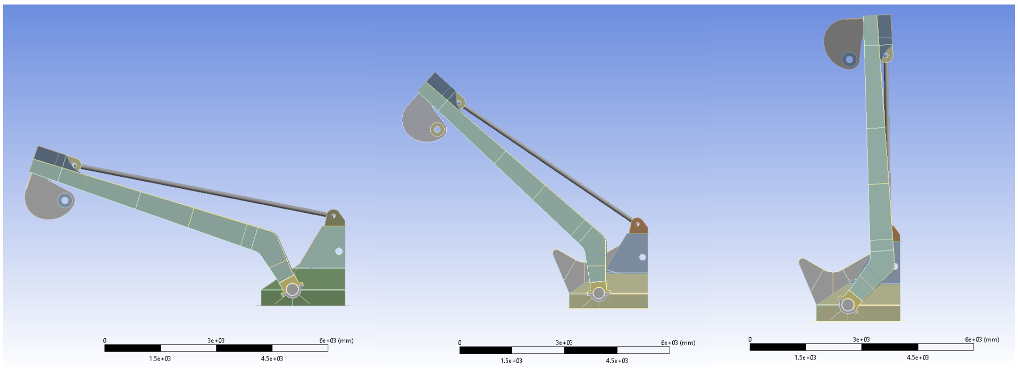


Figure D.1: Draghead gantry model in three positions.

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The gantry model used for the calculations is a mix of shells and solids. Solids are used for the pivot and the bearings, all of the remaining parts of it are modeled as shells. Additionally, one beam element is used to simulate the cylinder used for the positioning of the crane.

D.3.2. Mesh

The meshed gantry is shown in Figure D.2.

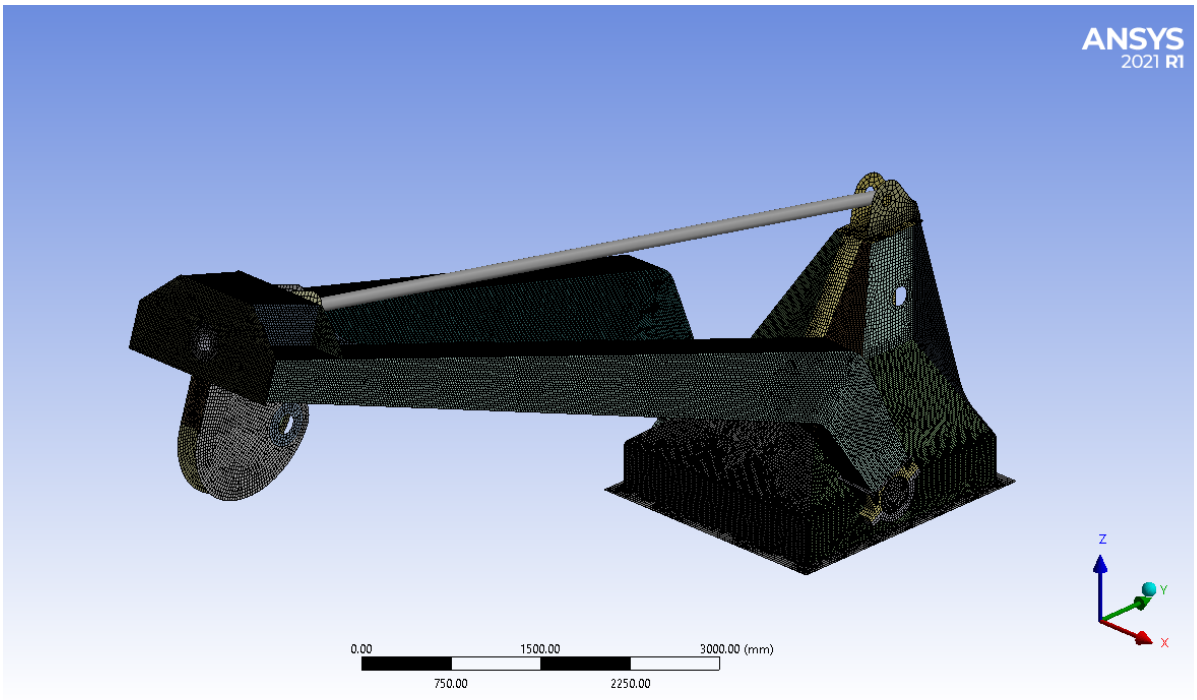

Figure D.2: Meshed model in the “Out” position.

D.3.3. Loads

Each individual load is applied to the model in a separate step. These then can be combined into multiple load sets using the internal capabilities of SDC Verifier.

Load on sheaves

The nominal force on an outer sheave used for calculations is equal to:

$$F = 438kN$$

Dynamic amplification factor is set as:

$$\alpha_{cz} = 1.35.$$

Additionally, the intensity and type of work of the crane were taken into account by implementing a duty factor. Based on the BV rules for lifting appliances (Bureau Veritas, 2017) the crane was categorised as a category II lifting appliance (offshore) - main crane of offshore work unit. The corresponding duty factor for the vertical force on the sheave wheels is

$$\Psi_0 = 1.06.$$

For calculation of an accidental force, additional factors supplied by the company are used, these are:

- Empirical factor for draghead gantry = 1.3,
- Maximum pull factor = 1.2,
- Brake holding factor = 1.2.

Remote Forces applied to the model in "Out" position are presented in Figure D.3.

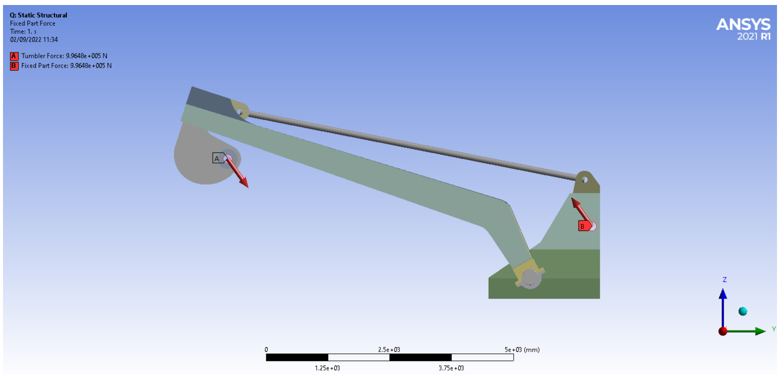

Figure D.3: Remote forces applied to the model in "Out" position.

The acceleration cases are presented in Table D.3.

Table D.3: Acceleration load cases for gantry in all positions calculated based on the default motion analysis and wind loads.

	a_{x+w}	a_{y+w}	a_{-g-z}	a_{-g+z}
Load Case 1	2.1	4.8	-16.8	
Load Case 2	-2.1	4.8	-16.8	
Load Case 3	2.1	-4.8	-16.8	
Load Case 4	-2.1	-4.8	-16.8	
Load Case 5	2.1	4.8		-1.4
Load Case 6	-2.1	4.8		-1.4
Load Case 7	2.1	-4.8		-1.4
Load Case 8	-2.1	-4.8		-1.4

D.3.4. Joints

In order for the modeled structure to behave similarly to the real gantry, joints were created between certain parts of the gantry. They are defined in the same manner for all three of the models. Hence, only joints for the “Out” position are presented as an example. Joints defined in the model are presented in Figure D.4.

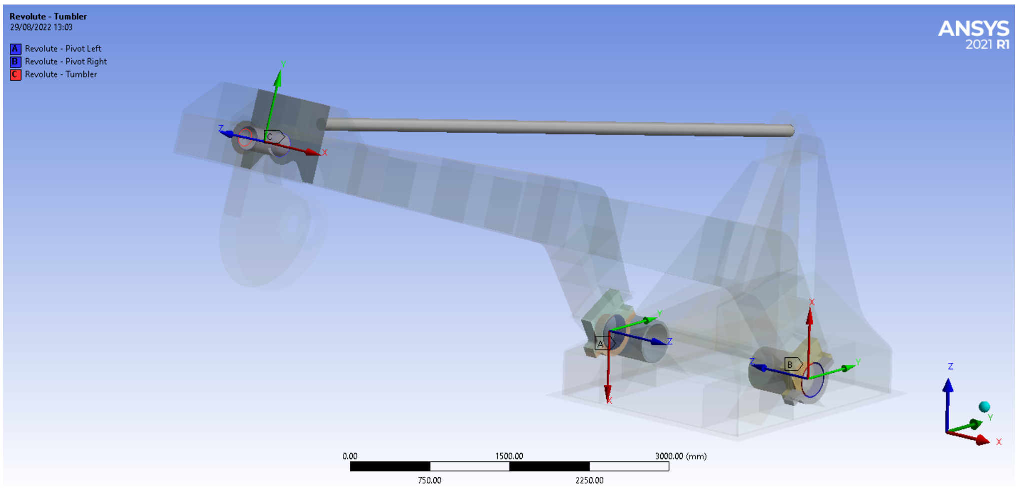

Figure D.4: Revolute joints in the Pivot and Tumbler.

Additionally, in every model, a beam connection is applied between the A-Frame head’s eye plates and Fixed Part’s eye plates. It is used to simulate a cylinder which will be mounted in that place. Similarly to the joints, it is defined in the same manner in each of the models. An example connection beam is presented in Figure D.5.

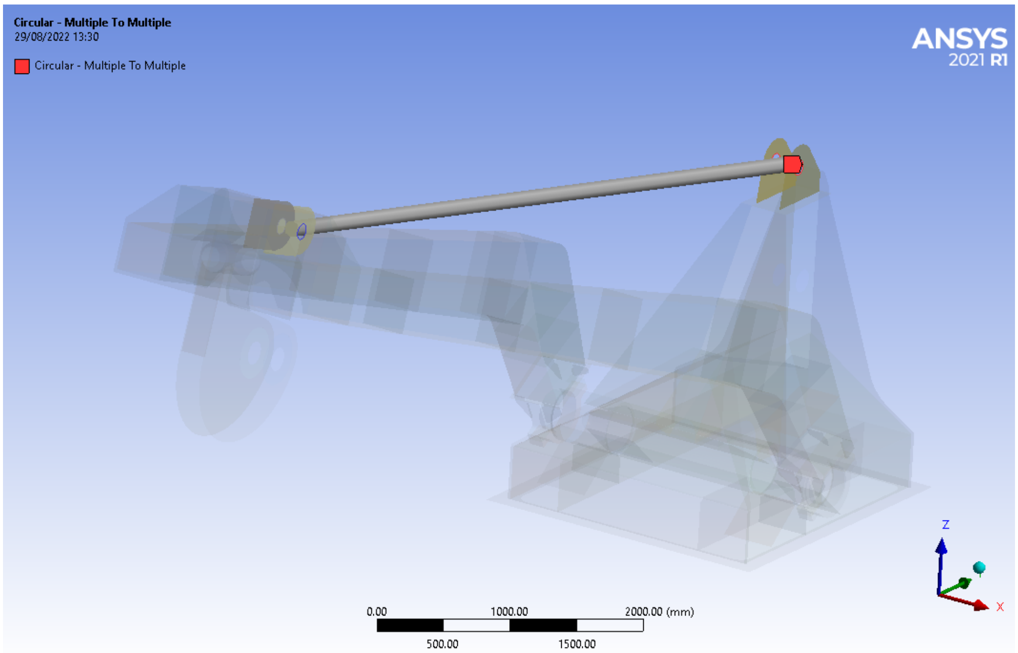

Figure D.5: Beam connection.

D.3.5. Supports

In order to restrain models, fixed support is added to each of the model at the base's face. This is to simulate the bolt connection between the flange around the base and the ship's deck. This connection from one of the models is presented in Figure D.6.

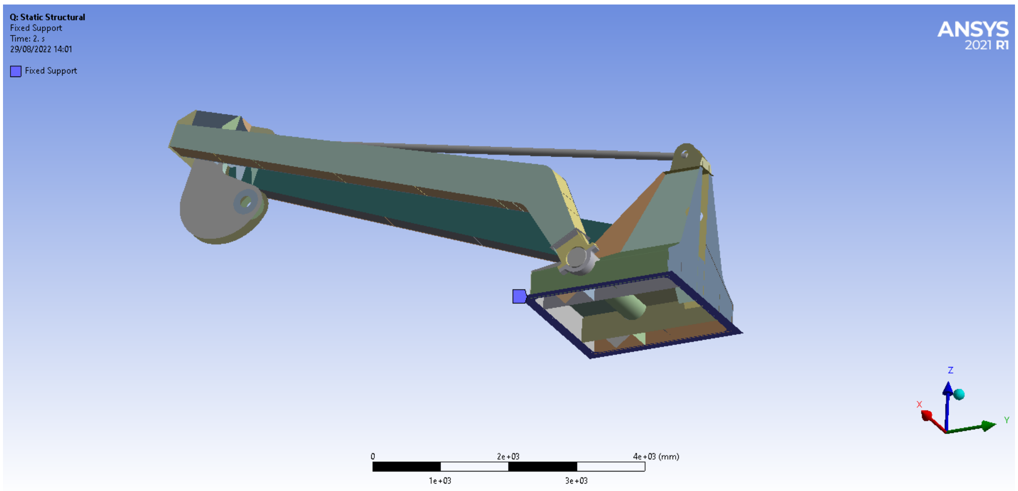

Figure D.6: Beam connection.

D.4. “Out” Model Results

In this section the grouped results for all loading conditions are discussed. Results for the gantry in the “Out” position are calculated using SDC Verifier based on the results obtained in the Ansys simulation. This section covers only part of the calculated results. Legends for all of the plots have twelve levels with the last two being higher than the allowable stress or utilization factor in every case.

D.4.1. Structural Calculations

Most of the model meets the requirements of the structural strength for all of the loading conditions. The summary of equivalent stresses and the unity check are presented in Table D.4. The parts with unity check value over 1 are highlighted in the table. For all of the parts, the unity check is the highest for Loading Conditions 2A. Hence, it can be concluded that this condition is the critical one for the structural design. Plot of equivalent von Mises stresses for LC2A is presented in Figure D.7.

Table D.4: Summary of von Mises stresses and unity checks for all of the parts in the design.

Part	LC 1		LC 2A		LC 3		ECNF		ECMF	
	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.
A-Frame side plates	235	0.99	367	**1.18**	374	0.96	235	0.99	316	0.99
A-Frame top stiffeners	33	0.14	53	0.17	54	0.14	33	0.14	44	0.14
Fixed part front outer plate	95	0.40	161	0.51	164	0.42	95	0.40	129	0.40
Fixed part side outer plates	118	0.50	195	0.62	199	0.51	118	0.50	160	0.50
A-Frame bearing connector plates	115	0.48	182	0.58	186	0.48	115	0.48	155	0.48
Fixed part base	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Fixed part back plate	109	0.46	169	0.54	172	0.44	109	0.46	146	0.46
Fixed part inner side plates	184	0.77	291	0.93	297	0.76	184	0.77	247	0.77
Fixed part cylinder mount horizontal plate	83	0.35	140	0.45	143	0.36	83	0.35	112	0.35
Fixed part cylinder mount vertical back plate	47	0.20	79	0.25	81	0.21	47	0.20	64	0.20
Fixed part cylinder mount vertical plates	68	0.29	117	0.38	119	0.31	68	0.29	94	0.29
A-Frame back plates	86	0.36	147	0.47	150	0.38	86	0.36	117	0.37
A-Frame front plates	224	0.94	349	**1.12**	356	0.91	224	0.94	300	0.94
A-Frame base plates	52	0.22	81	0.26	83	0.21	52	0.22	70	0.22
Fixed part front plates	149	0.63	244	0.78	249	0.64	149	0.63	202	0.63
Fixed part bottom back horizontal side plates	137	0.57	225	0.72	229	0.59	137	0.57	185	0.58

Table D.4: Summary of von Mises stresses and unity checks for all of the parts in the design.

Part	LC 1		LC 2A		LC 3		ECNF		ECMF	
	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.
Fixed part bottom back central plate	22	0.09	34	0.11	34	0.09	22	0.09	29	0.09
Fixed part bottom front horizontal plate	83	0.35	136	0.44	139	0.36	83	0.35	112	0.35
Fixed part front outer plate stiffener	33	0.14	54	0.17	55	0.14	33	0.14	44	0.14
Fixed part front inner side plates stiffener	93	0.39	152	0.49	155	0.40	93	0.39	126	0.39
Fixed part under sheave stiffener	50	0.21	78	0.25	79	0.20	50	0.21	67	0.21
Fixed part pivot supports	100	0.42	172	0.55	176	0.45	100	0.42	137	0.43
Fixed part inner pivot supports	151	0.63	257	0.82	262	0.67	151	0.63	205	0.64
Tumbler side plates	331	**1.39**	489	**1.57**	499	**1.28**	331	**1.39**	439	**1.37**
Tumbler sheave shaft supports	210	0.88	313	**1.00**	319	0.82	210	0.88	279	0.87
Tumbler top stiffener	151	0.63	230	0.74	234	0.60	151	0.63	201	0.63
Tumbler bottom stiffener	215	0.90	320	**1.02**	326	0.83	215	0.90	285	0.89
A-Frame head middle plate	233	0.98	339	**1.09**	346	0.89	233	0.98	307	0.96
A-Frame head bottom plate	76	0.32	118	0.38	121	0.31	76	0.32	101	0.32
A-Frame head top plate	182	0.76	275	0.88	280	0.72	182	0.76	242	0.76
A-Frame head top plate insert	158	0.66	233	0.75	238	0.61	158	0.66	209	0.65
A-Frame head vertical connector plate	186	0.78	273	0.87	278	0.71	186	0.78	245	0.77
A-Frame head back plate	90	0.38	142	0.46	145	0.37	90	0.38	121	0.38

Table D.4: Summary of von Mises stresses and unity checks for all of the parts in the design.

Part	LC 1		LC 2A		LC 3		ECNF		ECMF	
	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.	σ_{VM} $[MPa]$	U.C.
A-Frame head triangular stiffeners	50	0.21	78	0.25	79	0.20	50	0.21	67	0.21
A-Frame head cylinder mount plates	94	0.39	138	0.44	141	0.36	94	0.39	123	0.39
A-Frame head front vertical stiffeners	176	0.74	265	0.85	270	0.69	176	0.74	234	0.73
A-Frame head back vertical stiffeners	84	0.35	128	0.41	131	0.33	84	0.35	112	0.35
A-Frame head back bottom plates	73	0.31	114	0.37	117	0.30	73	0.31	98	0.31
A-Frame stiffener plates	86	0.36	139	0.44	141	0.36	86	0.36	115	0.36
Tumbler shaft sleeve	187	0.79	283	0.91	289	0.74	187	0.79	250	0.78
Bearings	98	0.41	159	0.51	162	0.41	98	0.41	132	0.41
Pivot	106	0.45	171	0.55	175	0.45	106	0.45	143	0.45

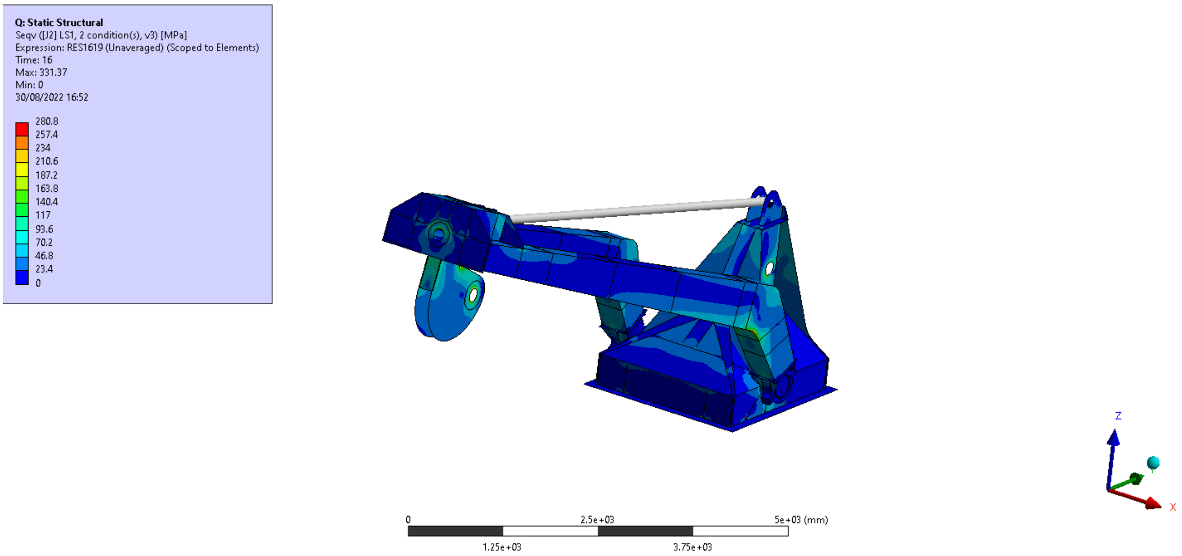

Figure D.7: Equivalent von Mises stress plot for the Loading Conditions 2A.

Since some of the parts do not pass the basic structural check, an additional check for fine mesh is performed for these parts. First the elements for which the calculated equivalent von Mises stress is higher than the allowable values are localised using the Peak Finder tool in SDC Verifier, then plots of mean elemental values of von Mises stress with close ups of the hot spot areas are created. These checks are presented in Appendix E.3.2. Based on results presented in Table D.4 and the additional checks given in the aforementioned appendix, it is concluded that the gantry's structural design is adequate for operations and conditions in the “Out” position.

D.4.2. Buckling Calculations

In order to perform buckling calculations, plate sections between the stiffeners were recognised using SDC Verifier. Then erroneously recognised plates were corrected. The overview of recognition results are presented in Figure D.8.

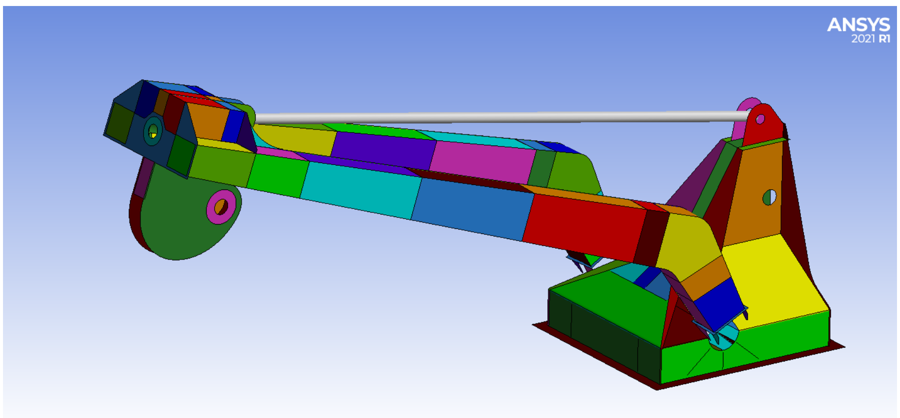

Figure D.8: Recognition step of buckling calculations, an overview of recognised plates.

Results of the buckling checks calculated with SDC Verifier according to the basis of design are presented in the Table D.5. Buckling factor for each of the loading conditions is the highest buckling factor obtained for the one of the unstiffened plates in each of the sections. For each of the loading conditions and sections, buckling factor is divided by the allowable utilization factor. The highest value for each section is written in bold.

Table D.5: Buckling check results.

	LC1	LC2A	LC3	ECNF	ECMF
Section	U.C.	U.C.	U.C.	U.C.	U.C.
1	0.65	**0.83**	0.67	0.58	0.59
2	0.61	**0.78**	0.63	0.55	0.55
3	0.78	**0.93**	0.77	0.70	0.70
4	0.26	**0.29**	0.23	0.23	0.23
5	0.26	**0.29**	0.23	0.23	0.22
6	0.26	**0.29**	0.24	0.23	0.23
7	0.26	**0.28**	0.23	0.23	0.22
8	0.83	**0.98**	0.80	0.74	0.74
9	0.61	**0.78**	0.64	0.55	0.56
10	0.64	**0.80**	0.66	0.57	0.58
11	0.20	**0.25**	0.21	0.18	0.18
12	0.45	**0.58**	0.47	0.40	0.40
13	0.49	**0.58**	0.47	0.44	0.43
14	0.00	**0.00**	0.00	0.00	0.00
15	0.58	**0.72**	0.58	0.52	0.52
16	0.26	**0.33**	0.27	0.23	0.24
17	0.81	**0.96**	0.77	0.73	0.72
18	0.78	**0.96**	0.78	0.70	0.69
19	0.81	**0.96**	0.77	0.73	0.71
20	0.35	**0.43**	0.36	0.31	0.31
21	0.75	**0.90**	0.73	0.68	0.67
22	0.13	**0.15**	0.12	0.12	0.12
23	0.23	**0.27**	0.23	0.21	0.21
24	0.19	**0.22**	0.18	0.17	0.16
25	0.19	**0.21**	0.17	0.17	0.16
26	0.19	**0.23**	0.18	0.17	0.16
27	0.12	**0.13**	0.10	0.10	0.10
28	0.30	**0.39**	0.31	0.27	0.28
29	0.64	**0.73**	0.59	0.57	0.57
30	0.25	**0.32**	0.25	0.22	0.22
31	0.57	**0.71**	0.58	0.51	0.51
32	0.57	**0.72**	0.59	0.51	0.51
33	0.26	**0.33**	0.26	0.23	0.23
34	0.12	**0.13**	0.10	0.10	0.11
35	0.25	**0.28**	0.23	0.22	0.21
36	0.32	**0.37**	0.30	0.29	0.28
37	0.32	**0.37**	0.30	0.29	0.29
38	0.38	**0.49**	0.39	0.34	0.34
39	0.28	**0.35**	0.28	0.25	0.25
40	0.06	**0.12**	0.10	0.05	0.05
41	0.13	**0.23**	0.18	0.12	0.13

D.4.3. Weld Calculations

In order to perform weld strength calculations, welds between plates in the model were recognised using SDC Verifier. The overview of all welds in the model is presented in Figure D.9.

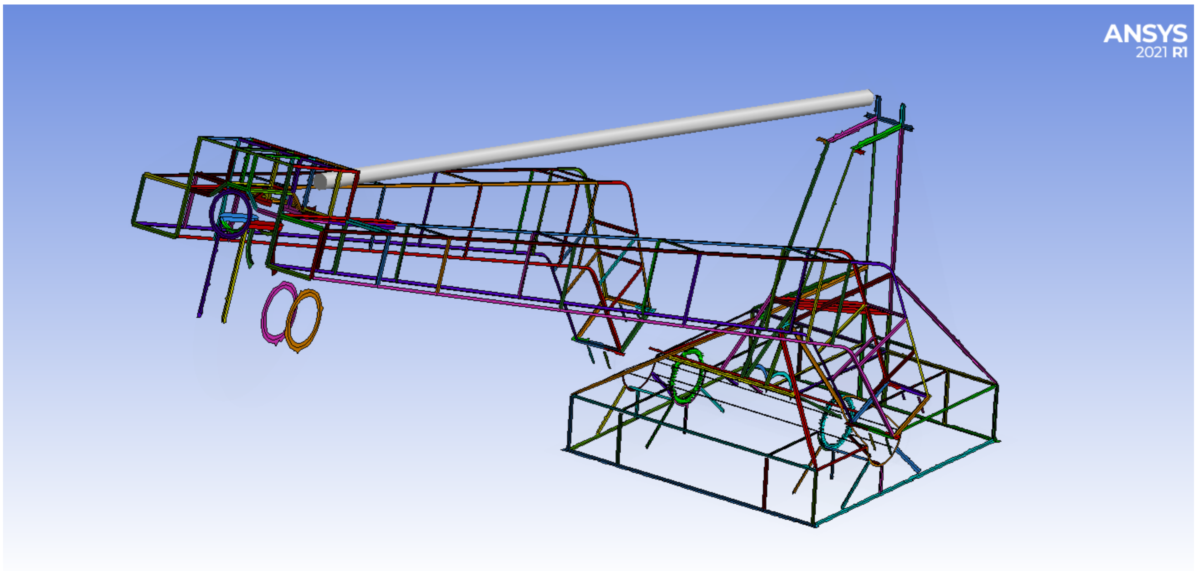

Figure D.9: Welds in the model.

Results of the fillet weld checks calculated with SDC Verifier according to the basis of design for each of the loading conditions are presented in Table D.6. Allowable utilization factor is equal to 1 for each of the welds presented in the table.

Table D.6: Weld strength check results

LC1 η	LC2A η	LC3 η	ECNF η	ECMF η	Weld ID	LC1 η	LC2A η	LC3 η	ECNF η	ECMF η	Weld ID
4	0.08	0.13	0.13	0.08	0.1	128	0.21	0.32	0.33	0.21	0.28
5	0.08	0.13	0.13	0.08	0.11	129	0.21	0.32	0.33	0.21	0.28
21	0.04	0.06	0.06	0.04	0.05	130	0.05	0.07	0.07	0.05	0.06
22	0.03	0.04	0.04	0.03	0.03	131	0.06	0.09	0.10	0.06	0.08
23	0.03	0.04	0.04	0.03	0.03	132	0.12	0.20	0.20	0.12	0.16
24	0.04	0.06	0.06	0.04	0.06	133	0.06	0.10	0.10	0.06	0.08
26	0.02	0.03	0.03	0.02	0.02	134	0.11	0.17	0.17	0.11	0.14
27	0.02	0.03	0.03	0.02	0.02	135	0.11	0.17	0.18	0.11	0.14
31	0.04	0.07	0.07	0.04	0.06	136	0.09	0.14	0.14	0.09	0.12
32	0.15	0.25	0.26	0.15	0.20	137	0.01	0.02	0.02	0.01	0.02
34	0.02	0.04	0.04	0.02	0.03	138	0.02	0.03	0.03	0.02	0.03
36	0.38	0.66	0.67	0.38	0.52	139	0.04	0.06	0.06	0.04	0.05
37	0.04	0.07	0.07	0.04	0.06	140	0.07	0.12	0.12	0.07	0.09
38	0.15	0.25	0.26	0.15	0.20	141	0.02	0.03	0.03	0.02	0.02
43	0.02	0.04	0.04	0.02	0.03	146	0.12	0.18	0.19	0.12	0.16
44	0.35	0.60	0.61	0.35	0.48	147	0.12	0.18	0.19	0.12	0.16
46	0.08	0.13	0.14	0.08	0.11	206	0.04	0.07	0.07	0.04	0.06
47	0.08	0.13	0.14	0.08	0.11	245	0.13	0.20	0.21	0.13	0.17
48	0.02	0.03	0.04	0.02	0.03	267	0.13	0.20	0.21	0.13	0.17
49	0.02	0.03	0.03	0.02	0.03	324	0.08	0.13	0.13	0.08	0.11
51	0.01	0.01	0.01	0.01	0.01	326	0.05	0.07	0.07	0.05	0.06

Table D.6: Weld strength check results

LC1 η	LC2A η	LC3 η	ECNF η	ECMF η	Weld ID	LC1 η	LC2A η	LC3 η	ECNF η	ECMF η	Weld ID
52	0.01	0.02	0.02	0.01	0.01	351	0.03	0.07	0.07	0.03	0.05
53	0.02	0.03	0.03	0.02	0.03	352	0.17	0.29	0.29	0.17	0.23
54	0.27	0.46	0.47	0.27	0.37	353	0.11	0.26	0.27	0.11	0.16
55	0.01	0.03	0.03	0.01	0.02	354	0.29	0.47	0.48	0.29	0.39
56	0.01	0.01	0.02	0.01	0.01	355	0.17	0.29	0.3	0.17	0.23
57	0.01	0.02	0.02	0.01	0.01	356	0.03	0.07	0.07	0.03	0.04
58	0.02	0.03	0.03	0.02	0.03	357	0.11	0.26	0.26	0.11	0.15
59	0.27	0.46	0.47	0.27	0.37	358	0.28	0.46	0.47	0.28	0.38
60	0.01	0.03	0.03	0.01	0.02	361	0.16	0.27	0.27	0.16	0.22
61	0.07	0.11	0.11	0.07	0.10	362	0.19	0.33	0.34	0.19	0.27
62	0.07	0.11	0.11	0.07	0.10	363	0.09	0.16	0.16	0.09	0.13
66	0.03	0.05	0.05	0.03	0.05	364	0.09	0.15	0.16	0.09	0.13
67	0.11	0.17	0.17	0.11	0.15	365	0.19	0.32	0.32	0.19	0.25
68	0.11	0.18	0.18	0.11	0.15	366	0.16	0.27	0.27	0.16	0.22
69	0.06	0.09	0.09	0.06	0.08	369	0.03	0.06	0.06	0.03	0.05
70	0.11	0.16	0.17	0.11	0.14	370	0.13	0.22	0.22	0.13	0.18
71	0.02	0.04	0.04	0.02	0.03	371	0.04	0.07	0.07	0.04	0.06
72	0.06	0.10	0.10	0.06	0.09	372	0.13	0.22	0.22	0.13	0.18
73	0.05	0.08	0.08	0.05	0.07	373	0.01	0.03	0.03	0.01	0.02
74	0.13	0.22	0.22	0.13	0.17	374	0.09	0.15	0.15	0.09	0.12
75	0.03	0.04	0.05	0.03	0.04	377	0.12	0.18	0.19	0.12	0.16
76	0.05	0.07	0.07	0.05	0.06	378	0.12	0.19	0.19	0.12	0.16
77	0.02	0.04	0.04	0.02	0.03	381	0.01	0.02	0.02	0.01	0.01
78	0.06	0.10	0.10	0.06	0.08	382	0.01	0.02	0.02	0.01	0.02
79	0.06	0.10	0.10	0.06	0.09	385	0.06	0.10	0.11	0.06	0.09
80	0.09	0.14	0.15	0.09	0.12	386	0.06	0.11	0.11	0.06	0.09
81	0.08	0.12	0.12	0.08	0.11	387	0.28	0.48	0.49	0.28	0.38
83	0.03	0.04	0.04	0.03	0.04	389	0.23	0.39	0.40	0.23	0.32
84	0.03	0.04	0.04	0.03	0.03	390	0.11	0.19	0.19	0.11	0.15
85	0.01	0.03	0.03	0.01	0.02	391	0.11	0.19	0.19	0.11	0.15
87	0.08	0.12	0.12	0.08	0.11	392	0.23	0.39	0.40	0.23	0.32
88	0.11	0.17	0.17	0.11	0.14	393	0.27	0.43	0.44	0.27	0.37
89	0.06	0.09	0.09	0.06	0.08	394	0.28	0.44	0.45	0.28	0.37
90	0.05	0.07	0.07	0.05	0.06	395	0.33	0.51	0.52	0.33	0.44
91	0.03	0.04	0.04	0.03	0.03	400	0.30	0.45	0.46	0.30	0.40
92	0.12	0.20	0.20	0.12	0.16	401	0.04	0.07	0.07	0.04	0.05
94	0.01	0.02	0.02	0.01	0.01	402	0.13	0.21	0.22	0.13	0.17
95	0.11	0.17	0.17	0.11	0.14	403	0.15	0.23	0.23	0.15	0.20
96	0.11	0.17	0.17	0.11	0.15	404	0.13	0.21	0.22	0.13	0.17
97	0.05	0.08	0.08	0.05	0.07	405	0.06	0.10	0.10	0.06	0.08
98	0.06	0.09	0.10	0.06	0.08	406	0.06	0.10	0.10	0.06	0.08

Table D.6: Weld strength check results

LC1 η	LC2A η	LC3 η	ECNF η	ECMF η	Weld ID	LC1 η	LC2A η	LC3 η	ECNF η	ECMF η	Weld ID
99	0.05	0.07	0.07	0.05	0.06	411	0.15	0.22	0.23	0.15	0.19
100	0.13	0.22	0.22	0.13	0.18	416	0.06	0.09	0.09	0.06	0.08
101	0.02	0.04	0.04	0.02	0.03	417	0.15	0.23	0.23	0.15	0.19
102	0.04	0.06	0.06	0.04	0.05	419	0.05	0.07	0.07	0.05	0.06
103	0.07	0.12	0.12	0.07	0.09	420	0.16	0.25	0.25	0.16	0.21
104	0.02	0.03	0.03	0.02	0.03	426	0.21	0.35	0.36	0.21	0.28
105	0.12	0.19	0.20	0.12	0.16	427	0.07	0.13	0.14	0.07	0.10
106	0.01	0.02	0.02	0.01	0.02	428	0.16	0.24	0.25	0.16	0.21
107	0.02	0.04	0.04	0.02	0.03	429	0.07	0.14	0.14	0.07	0.10
108	0.04	0.06	0.06	0.04	0.05	430	0.20	0.33	0.33	0.20	0.27
110	0.05	0.12	0.13	0.05	0.07	432	0.05	0.07	0.07	0.05	0.06
111	0.24	0.38	0.39	0.24	0.32	433	0.51	0.75	0.76	0.51	0.67
113	0.05	0.12	0.12	0.05	0.07	434	0.00	0.01	0.01	0.00	0.00
114	0.25	0.39	0.40	0.25	0.33	435	0.03	0.05	0.05	0.03	0.04
116	0.41	0.61	0.62	0.41	0.54	437	0.05	0.09	0.09	0.05	0.07
117	0.29	0.43	0.44	0.29	0.39	438	0.07	0.11	0.11	0.07	0.09
118	0.01	0.02	0.02	0.01	0.01	442	0.02	0.03	0.03	0.02	0.02
119	0.42	0.62	0.64	0.42	0.55	443	0.13	0.20	0.20	0.13	0.17
120	0.23	0.36	0.36	0.23	0.31	444	0.02	0.03	0.03	0.02	0.02
122	0.12	0.19	0.20	0.12	0.16	445	0.13	0.20	0.20	0.13	0.17
123	0.23	0.36	0.36	0.23	0.31	446	0.20	0.32	0.32	0.20	0.27
124	0.34	0.53	0.54	0.34	0.45	447	0.13	0.21	0.22	0.13	0.18
125	0.35	0.53	0.54	0.35	0.46	448	0.13	0.22	0.22	0.13	0.18
127	0.30	0.47	0.48	0.30	0.40	449	0.21	0.32	0.33	0.21	0.28

D.4.4. Fatigue Calculations

In order to perform fatigue calculations first the SN-Curves are assigned to parts of the model according to DNV-RP-C203 (De Norske Veritas, 2010b), using SDC Verifier. Curves for fatigue in the air environment are used. The overview of the classification of structural details in the direction perpendicular to the welds is presented in Figure D.10.

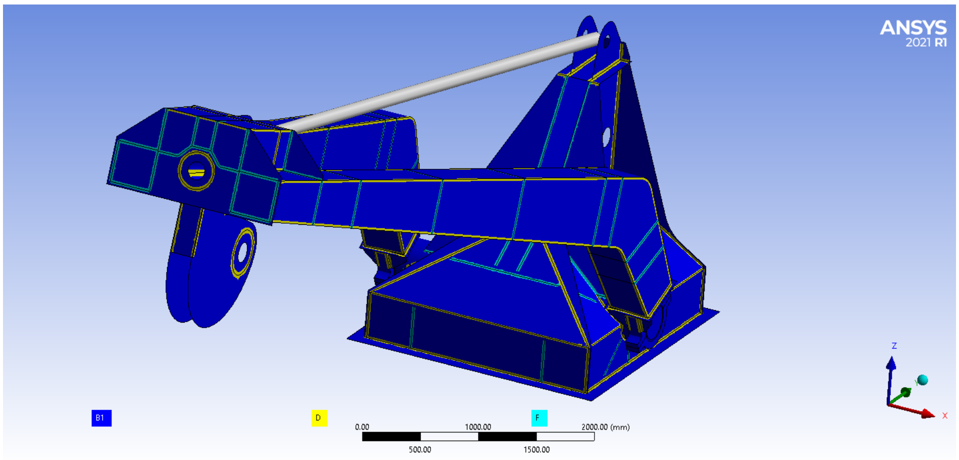

Figure D.10: Model with structural details classified for fatigue, SN-Curves for stresses in direction perpendicular to the weld.

Fillet welds are classified as F-curve details in the direction perpendicular to the weld and as a E-curve in the shear direction. Full penetration welds are classified as D-curve details in the perpendicular direction and as C2-curve detail in the shear direction. All of the welds are classified as C2-curve details in the direction parallel to the weld and the rest of the model is classified as B2-curve detail in all directions.

Results of the fatigue check are presented in Table D.7. The parts which have to be individually assessed are highlighted. The individual checks are given in Appendix F.7.

Table D.7: Fatigue check results.

Part	Fatigue Damage	DFF	Allowable Damage	Unity Check
A-Frame side plates	**0.90**	**3**	**0.33**	**2.70**
A-Frame top stiffeners	0.00	3	0.33	0.00
Fixed part front outer plate	0.19	3	0.33	0.57
Fixed part side outer plates	0.21	3	0.33	0.63
A-Frame bearing connector plates’	**1.46**	**1**	**1.00**	**1.46**
Fixed part base	0.00	3	0.33	0.00
Fixed part back plate	0.08	3	0.33	0.24
Fixed part inner side plates	0.16	3	0.33	0.48
Fixed part cylinder mount horizontal plate	0.09	1	1.00	0.09
Fixed part cylinder mount vertical back plate	0.01	1	1.00	0.01
Fixed part cylinder mount vertical plates	0.03	1	1.00	0.03
A-Frame back plates	0.07	3	0.33	0.21
A-Frame front plates	0.51	1	1.00	0.51
A-Frame base plates	0.01	3	0.33	0.03
Fixed part front plates	**0.47**	**3**	**0.33**	**1.41**
Fixed part bottom back horizontal side plates	**0.99**	**3**	**0.33**	**2.97**
Fixed part bottom back central plate	0.00	3	0.33	0.00
Fixed part bottom front horizontal plate	0.26	3	0.33	0.78
Fixed part front outer plate stiffener	0.00	3	0.33	0.00
Fixed part front inner side plates stiffener	0.24	3	0.33	0.72
Fixed part under sheave stiffener	0.01	1	1.00	0.01
Fixed part pivot supports	0.22	3	0.33	0.66
Fixed part inner pivot supports	**0.37**	**3**	**0.33**	**1.11**
Tumbler side plates	**1.54**	**1**	**1.00**	**1.54**
Tumbler sheave shaft supports	0.11	1	1.00	0.11
Tumbler top stiffener	0.18	1	1.00	0.18
Tumbler bottom stiffener	0.26	1	1.00	0.26
A-Frame head middle plate	**0.65**	**3**	**0.33**	**1.95**
A-Frame head bottom plate	0.05	1	1.00	0.05
A-Frame head top plate	0.48	1	1.00	0.48
A-Frame head top plate insert	0.13	1	1.00	0.13
A-Frame head vertical connector plate	0.64	1	1.00	0.64
A-Frame head back plate	0.03	3	0.33	0.09
A-Frame head triangular stiffeners	0.01	1	1.00	0.01
A-Frame head cylinder mount plates	0.05	3	0.33	0.15
A-Frame head front vertical stiffeners	0.83	1	1.00	0.83
A-Frame head back vertical stiffeners	0.08	3	0.33	0.24
A-Frame head back bottom plates	0.04	3	0.33	0.12
A-Frame stiffener plates	0.12	3	0.33	0.36
Tumbler shaft sleeve	0.09	1	1.00	0.09
Bearings	0.02	1	1.00	0.02
Pivot	0.09	3	0.33	0.27

Most of the unity checks in the table are below 1 and the ones which are above it are checked in Appendix F.7. The results of individual checks are confirming that all of the individually assessed areas are safe from fatigue induced failure.

D.4.5. Summary

Overall, based on the results obtained for the model in “Out” position, it is concluded that the crane has an adequate structural strength. Moreover, the results of the checks confirm that the structure has sufficient resistance to buckling and fatigue and also that welds chosen for each of the plates have acceptable strength. A summary with the results of structural and buckling checks for the ruling loading condition LC2A and a fatigue check for each of the parts is presented in Table D.8. Results in this table were corrected to incorporate the individual structural and fatigue checks.

Table D.8: Summary of the results of structural, buckling and fatigue checks for the ruling condition (LC2A). Individual check results are incorporated.

Part	Structural	Buckling	Fatigue	Maximum
A-Frame side plates	0.84	0.96	0.78	0.96
A-Frame top stiffeners	0.17	0.14	0.00	0.17
Fixed part front outer plate	0.51	0.54	0.57	0.57
Fixed part side outer plates	0.62	0.96	0.63	0.96
A-Frame bearing connector plates	0.58	0.49	0.78	0.78
Fixed part base	0.00	0.00	0.00	0.00
Fixed part back plate	0.54	0.58	0.24	0.58
Fixed part inner side plates	0.93	0.98	0.48	0.98
Fixed part cylinder mount horizontal plate	0.45	0.33	0.09	0.45
Fixed part cylinder mount vertical back plate	0.25	0.22	0.01	0.25
Fixed part cylinder mount vertical plates	0.38	0.49	0.03	0.49
A-Frame back plates	0.47	0.45	0.21	0.47
A-Frame front plates	0.84	0.90	0.51	0.90
A-Frame base plates	0.26	0.13	0.03	0.26
Fixed part front plates	0.78	0.61	0.32	0.78
Fixed part bottom back horizontal side plates	0.72	0.72	0.94	0.94
Fixed part bottom back central plate	0.11	0.11	0.00	0.11
Fixed part bottom front horizontal plate	0.44	0.46	0.78	0.78
Fixed part front outer plate stiffener	0.17	0.15	0.00	0.17
Fixed part front inner side plates stiffener	0.49	0.36	0.72	0.72
Fixed part under sheave stiffener	0.25	0.12	0.01	0.25
Fixed part pivot supports	0.55	0.72	0.66	0.72
Fixed part inner pivot supports	0.82	0.78	0.85	0.85
Tumbler side plates	1.00	0.13	0.99	1.00
Tumbler sheave shaft supports	0.79	0.29	0.11	0.79
Tumbler top stiffener	0.74	0.73	0.18	0.74
Tumbler bottom stiffener	0.99	0.70	0.26	0.99
A-Frame head middle plate	0.70	0.40	0.65	0.70
A-Frame head bottom plate	0.38	0.32	0.05	0.38
A-Frame head top plate	0.88	0.38	0.48	0.88
A-Frame head top plate insert	0.75	0.13	0.13	0.75
A-Frame head vertical connector plate	0.87	0.76	0.64	0.87
A-Frame head back plate	0.46	0.38	0.09	0.46
A-Frame head triangular stiffeners	0.25	0.20	0.01	0.25
A-Frame head cylinder mount plates	0.44	0.23	0.15	0.44
A-Frame head front vertical stiffeners	0.85	0.39	0.83	0.85
A-Frame head back vertical stiffeners	0.41	0.29	0.24	0.41
A-Frame head back bottom plates	0.37	0.20	0.12	0.37
A-Frame stiffener plates	0.44	0.39	0.36	0.44
Tumbler shaft sleeve	0.91		0.09	0.91
Bearings	0.51		0.02	0.51
Pivot	0.55		0.27	0.55

D.5. “45” Model Results

In this section structural calculations for the “45” position model for the relevant loading conditions are presented. Similarly to the Section D.4, legends for the plots have twelve levels with the last two being over the limit of allowed stresses or utilization factor. Results are calculated using SDC Verifier based on the results obtained in the Ansys Mechanical simulation.

D.5.1. Structural Calculations

Most of the model meets the requirements of the structural strength for both checked loading conditions. The summary of equivalent stresses and the unity check are presented in Table D.9. For all of the parts, the unity check is the highest for loading condition ECMF. Hence, it can be concluded that this condition is the critical one for the structural design. Plot of equivalent von Mises stresses for EMCF is presented in Figure D.11.

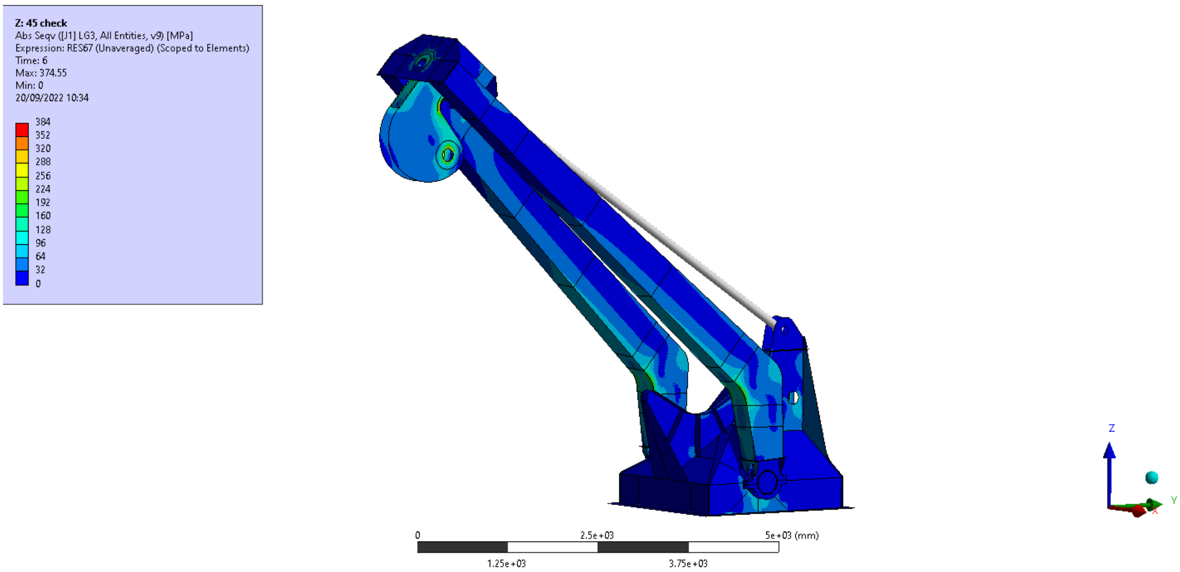

Figure D.11: Equivalent von Mises stress plot for the ECMF.

Few of the parts do not pass the basic structural check, therefore an additional check for fine mesh is performed for these parts. The areas of elements for which the the equivalent von Mises stress exceeds the allowable stress are located using the Peak Finder tool in SDC Verifier, then plots of average elemental von Mises stress with close ups of the hot spot areas are generated. Checks are presented in Appendix E.3.2. Based on these results the gantry is sufficiently strong for the structure to perform correctly in the “45” position.

D.6. “Upright” Model Results

In this section structural calculations for the “Upright” position model for the relevant loading conditions are presented. Similarly to the previous sections, legends for the plots have twelve levels with the last two being over the limit of allowed stresses or utilization factor. Results are calculated using SDC Verifier and Ansys Mechanical.

D.6.1. Structural Calculations

In most of the parts in the model the equivalent von Mises stress is lower than the allowable stress for each of the loading conditions. The summary of equivalent stresses and the unity check are presented in Table D.10. Each of the parts is stressed more in loading condition ECMF. Hence, this condition is the critical one for the structural design. Plot of equivalent von Mises stresses for EMCF is presented in Figure D.12.

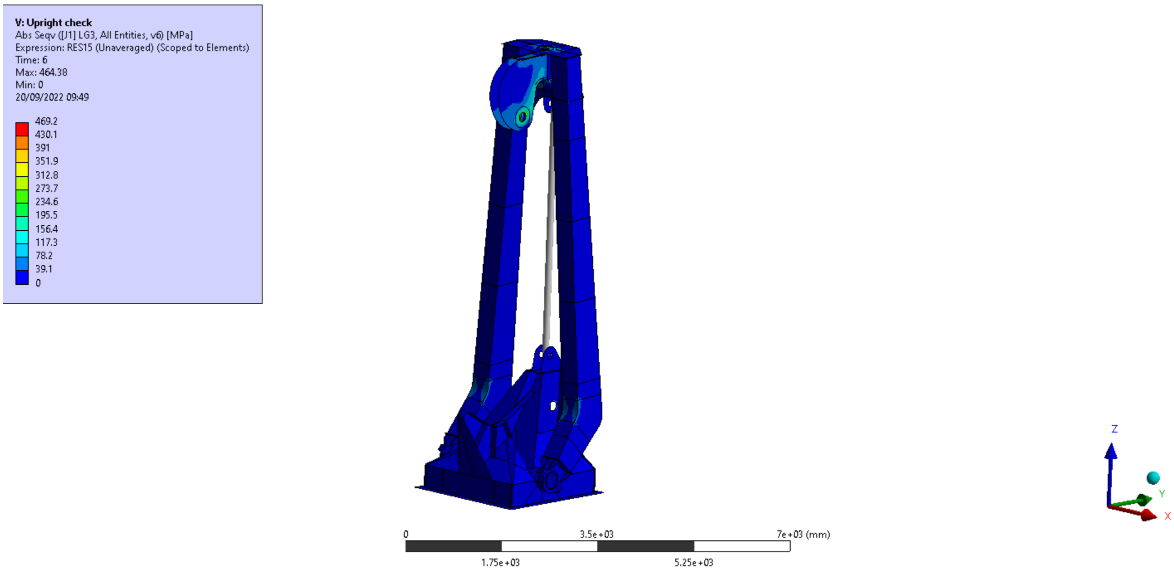

Figure D.12: Equivalent von Mises stress plot for the ECMF.

Table D.10: Summary of von Mises stresses and unity checks for all of the parts in the “Upright” model.

	LC3		ECMF	
Part	σ_{VM} [MPa]	U.C.	σ_{VM} [MPa]	U.C.
A-Frame side plates	134	0.34	96	0.30
A-Frame top stiffeners	78	0.20	63	0.20
Fixed part front outer plate	12	0.03	8	0.03
Fixed part side outer plates	75	0.19	49	0.15
A-Frame bearing connector plates	59	0.15	37	0.12
Fixed part base	0	0.00	0	0.00
Fixed part back plate	67	0.17	46	0.14
Fixed part inner side plates	119	0.30	81	0.25
Fixed part cylinder mount horizontal plate	16	0.04	13	0.04
Fixed part cylinder mount vertical back plate	31	0.08	25	0.08
Fixed part cylinder mount vertical plates	43	0.11	29	0.09
A-Frame back plates	46	0.12	33	0.10
A-Frame front plates	128	0.33	92	0.29
A-Frame base plates	29	0.07	21	0.07
Fixed part front plates	39	0.10	23	0.07
Fixed part bottom back horizontal side plates	10	0.02	6	0.02
Fixed part bottom back central plate	8	0.02	6	0.02
Fixed part bottom front horizontal plate	24	0.06	14	0.04
Fixed part front outer plate stiffener	11	0.03	6	0.02
Fixed part front inner side plates stiffener	11	0.03	7	0.02
Fixed part under sheave stiffener	30	0.08	23	0.07
Fixed part pivot supports	76	0.19	51	0.16
Fixed part inner pivot supports	22	0.06	13	0.04
Tumbler side plates	292	0.75	248	0.77
Tumbler sheave shaft supports	400	1.02	345	1.08
Tumbler top stiffener	111	0.28	89	0.28
Tumbler bottom stiffener	184	0.47	154	0.48
A-Frame head middle plate	430	1.10	377	1.18
A-Frame head bottom plate	44	0.11	37	0.11
A-Frame head top plate	172	0.44	154	0.48
A-Frame head top plate insert	186	0.48	164	0.51
A-Frame head vertical connector plate	534	1.37	464	1.45
A-Frame head back plate	71	0.18	54	0.17
A-Frame head triangular stiffeners	17	0.04	13	0.04
A-Frame head cylinder mount plates	271	0.69	237	0.74
A-Frame head front vertical stiffeners	191	0.49	164	0.51
A-Frame head back vertical stiffeners	48	0.12	42	0.13
A-Frame head back bottom plates	54	0.14	43	0.13
A-Frame stiffener plates	55	0.14	34	0.11
Tumbler shaft sleeve	95	0.24	75	0.24
Bearings	62	0.16	41	0.13
Pivot	55	0.14	35	0.11
Saddle	8	0.02	6	0.02

For the parts which did not pass the basic check, an individual check is performed, in the same manner as in the previous cases. Checks are presented in Appendix E.3.2. Based on these results the gantry is sufficiently strong for the “Upright” position.

D.7. Mass

Final mass of the gantry in this design is 13311.6 kg.

Table D.9: Summary of von Mises stresses and unity checks for all of the parts in the “45” model.

	LC3		ECMF	
Part	σ_{VM} [MPa]	U.C.	σ_{VM} [MPa]	U.C.
A-Frame side plates	318	0.81	262	0.82
A-Frame top stiffeners	34	0.09	27	0.08
Fixed part front outer plate	84	0.22	66	0.21
Fixed part side outer plates	160	0.41	126	0.39
A-Frame bearing connector plates	151	0.39	123	0.38
Fixed part base	0	0.00	0	0.00
Fixed part back plate	207	0.53	173	0.54
Fixed part inner side plates	339	0.87	284	0.89
Fixed part cylinder mount horizontal plate	91	0.23	69	0.21
Fixed part cylinder mount vertical back plate	49	0.12	37	0.12
Fixed part cylinder mount vertical plates	95	0.24	69	0.22
A-Frame back plates	102	0.26	85	0.27
A-Frame front plates	304	0.78	251	0.78
A-Frame base plates	73	0.19	60	0.19
Fixed part front plates	137	0.35	107	0.34
Fixed part bottom back horizontal side plates	118	0.30	94	0.29
Fixed part bottom back central plate	24	0.06	20	0.06
Fixed part bottom front horizontal plate	172	0.44	133	0.42
Fixed part front outer plate stiffener	62	0.16	49	0.15
Fixed part front inner side plates stiffener	66	0.17	51	0.16
Fixed part under sheave stiffener	63	0.16	53	0.16
Fixed part pivot supports	169	0.43	128	0.40
Fixed part inner pivot supports	173	0.44	126	0.39
Tumbler side plates	427	1.09	375	1.17
Tumbler sheave shaft supports	370	0.95	325	1.02
Tumbler top stiffener	145	0.37	127	0.40
Tumbler bottom stiffener	276	0.71	241	0.75
A-Frame head middle plate	373	0.95	330	1.03
A-Frame head bottom plate	85	0.22	71	0.22
A-Frame head top plate	263	0.67	227	0.71
A-Frame head top plate insert	221	0.57	193	0.60
A-Frame head vertical connector plate	298	0.76	259	0.81
A-Frame head back plate	87	0.22	70	0.22
A-Frame head triangular stiffeners	155	0.40	137	0.43
A-Frame head cylinder mount plates	263	0.67	227	0.71
A-Frame head front vertical stiffeners	239	0.61	207	0.65
A-Frame head back vertical stiffeners	91	0.23	78	0.24
A-Frame head back bottom plates	82	0.21	69	0.21
A-Frame stiffener plates	97	0.25	77	0.24
Tumbler shaft sleeve	149	0.38	130	0.41
Bearings	145	0.37	120	0.38
Pivot	138	0.35	109	0.34
Saddle	96	0.25	73	0.23

E

Hot Spot Checks

This appendix contains plots of peak stress zones which did not satisfy the basic criteria presented in Appendix D.7 Section D.2.1. For each of the hot spots, mean elemental von Mises stresses are calculated and the check is performed according to the fine mesh criteria.

E.1. Model “Out”

E.1.1. Loading Conditions 1

Table E.1: Hot spot areas for the Loading Condition 1.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	331.37	E.1	E.4
Zone 2	330.47	E.2	E.5
Zone 3	235.42	E.3	E.6

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Loading Condition 1.

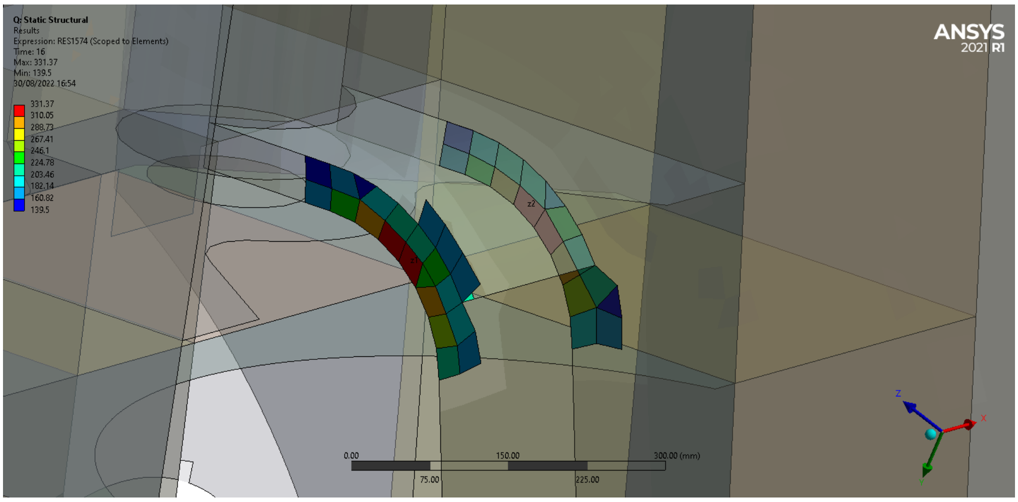

Figure E.1: Equivalent von Mises stress plot Zone 1 hot spot.

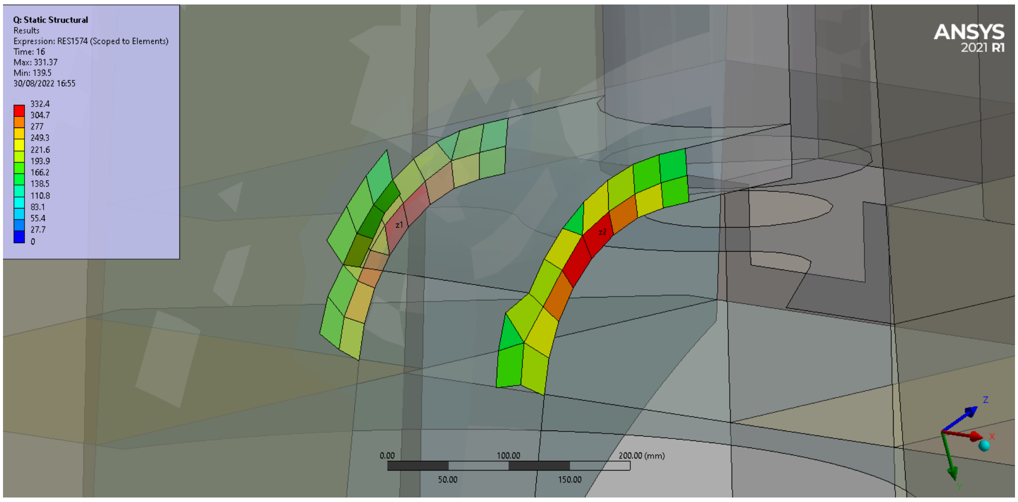

Figure E.2: Equivalent von Mises stress plot for Zone 2 hot spot.

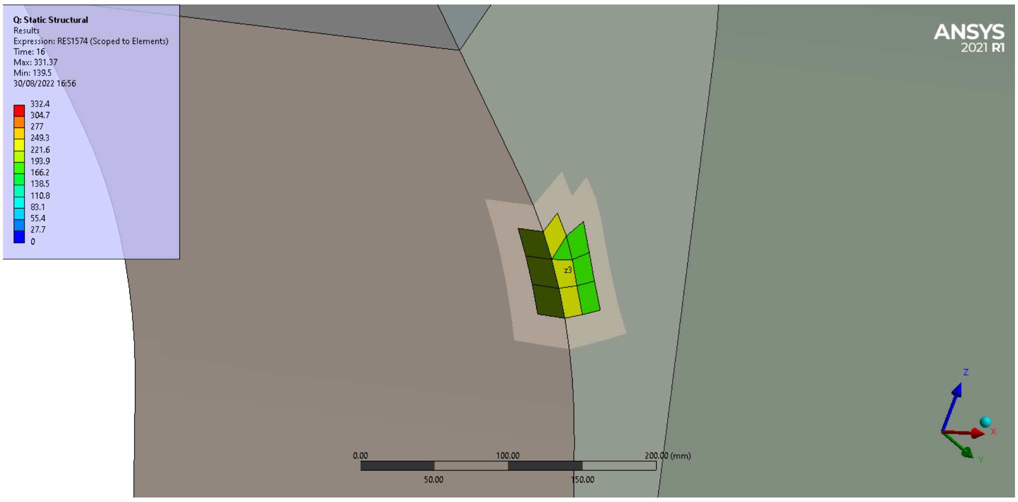

Figure E.3: Equivalent von Mises stress plot for Zone 3 hot spot.

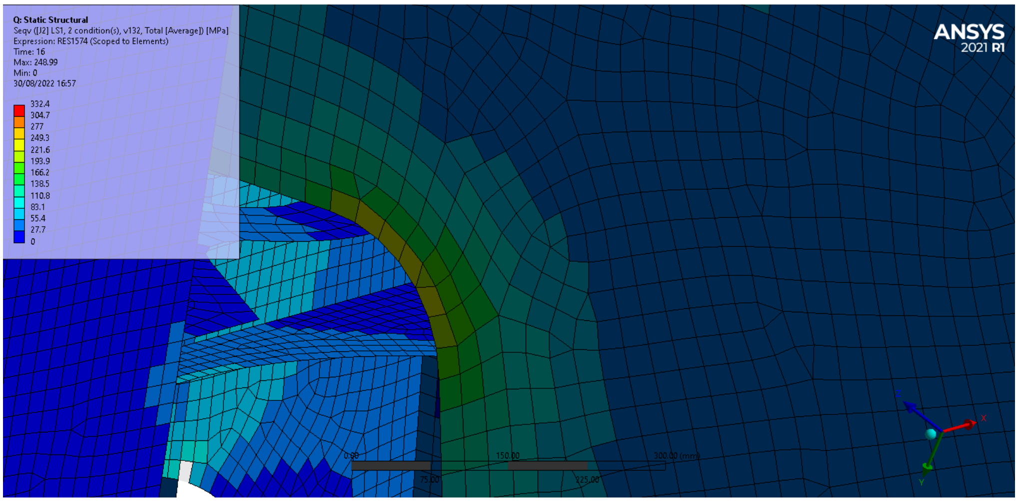

Figure E.4: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

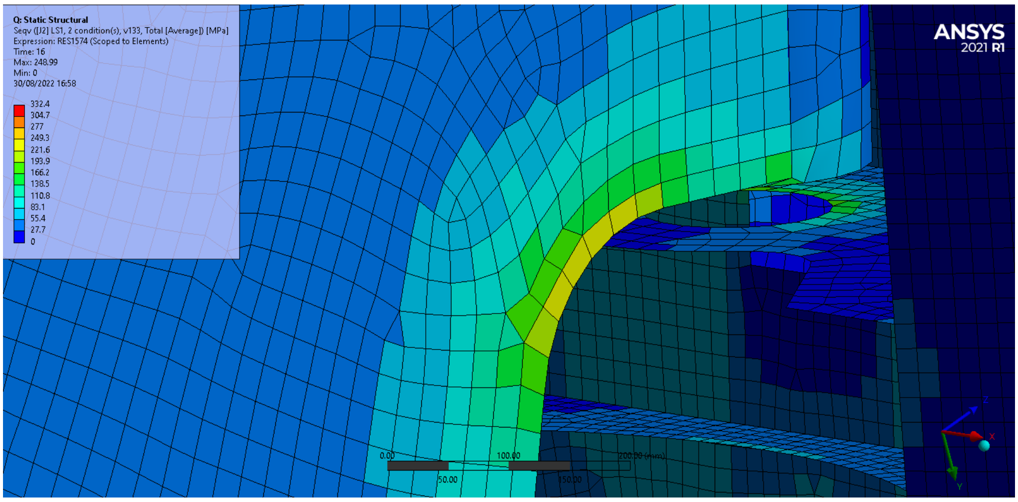

Figure E.5: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

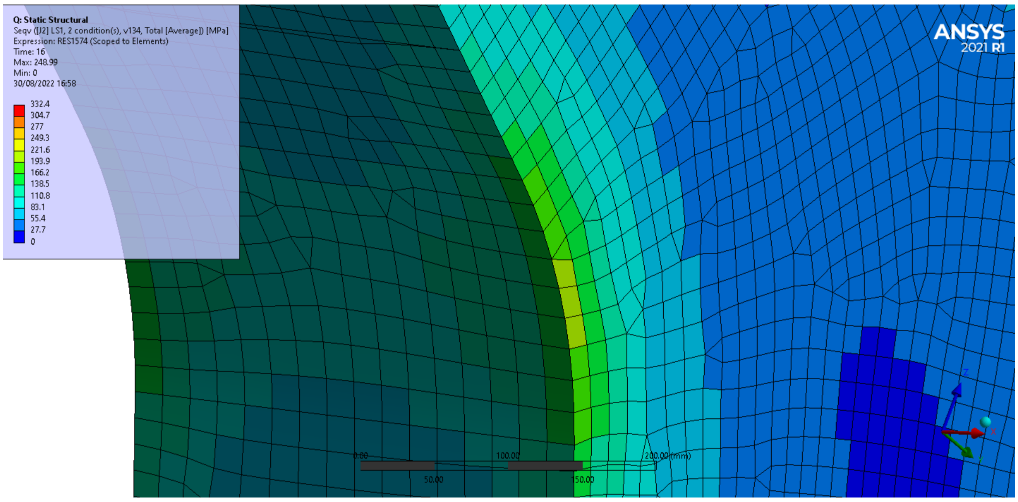

Figure E.6: Equivalent von Mises elemental mean stress plot Zone 3 hot spot.

E.1.2. Loading Conditions 2A

Table E.2: Hot spot areas for the Loading Condition 2A.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	489.38	E.7	E.15
Zone 2	488.87	E.8	E.16
Zone 3	367.17	E.9	E.17
Zone 4	360.87	E.10	E.18
Zone 5	359.47	E.11	E.19
Zone 6	358.35	E.12	E.20
Zone 7	339.37	E.13	E.21
Zone 8	322.47	E.13	E.21
Zone 9	312.99	E.14	E.22

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Loading Conditions 2A.

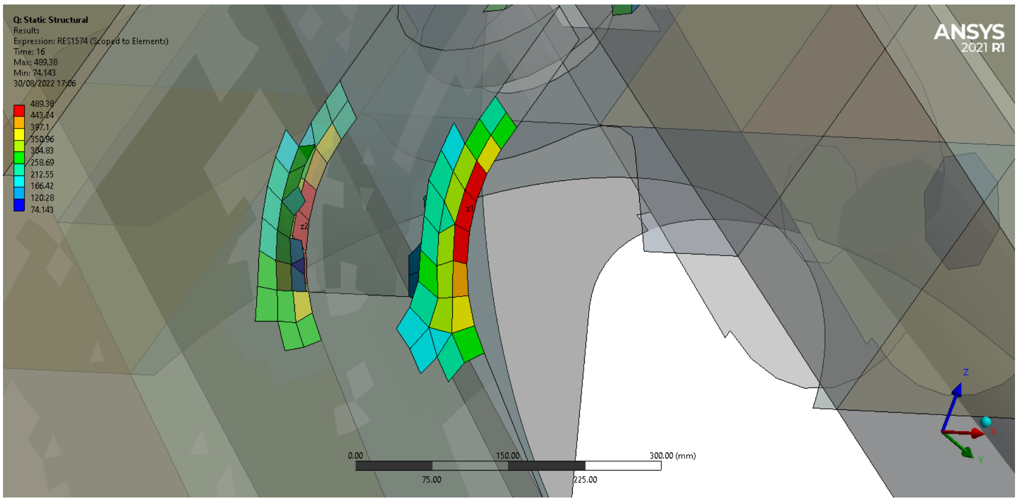

Figure E.7: Equivalent von Mises stress plot for Zone 1 hot spot.

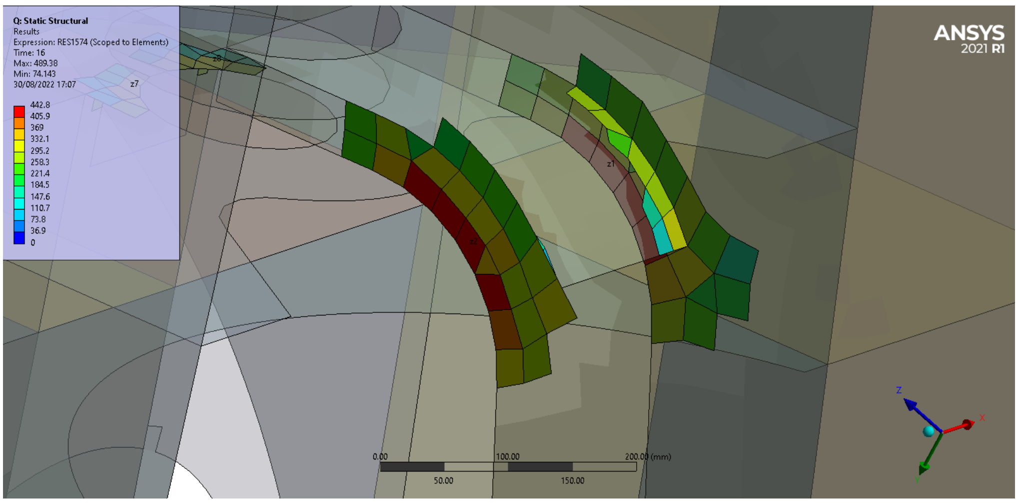

Figure E.8: Equivalent von Mises stress plot for Zone 2 hot spot.

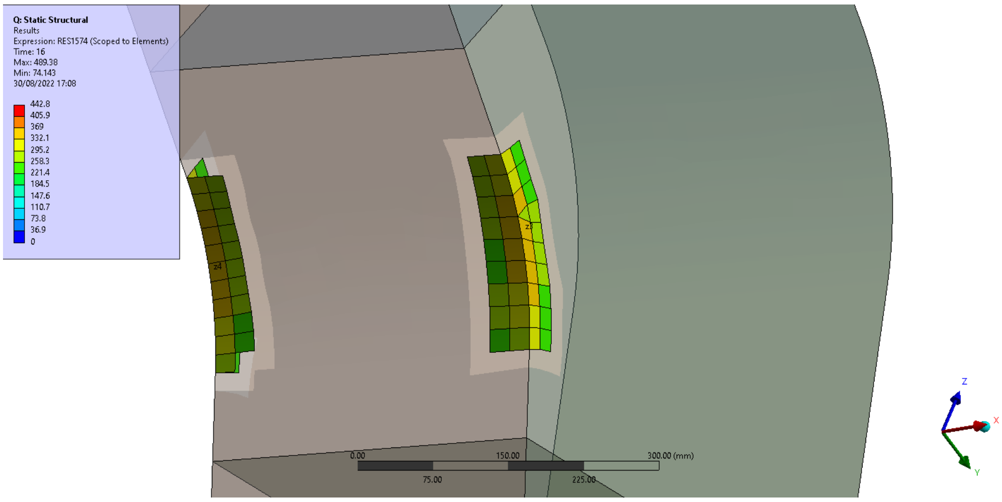

Figure E.9: Equivalent von Mises stress plot for Zone 3 hot spot.

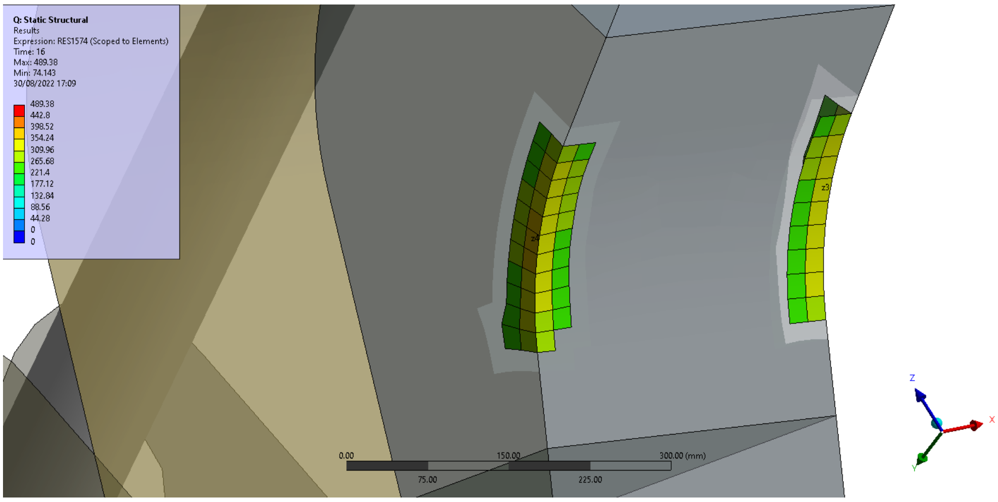

Figure E.10: Equivalent von Mises stress plot for Zone 4 hot spot.

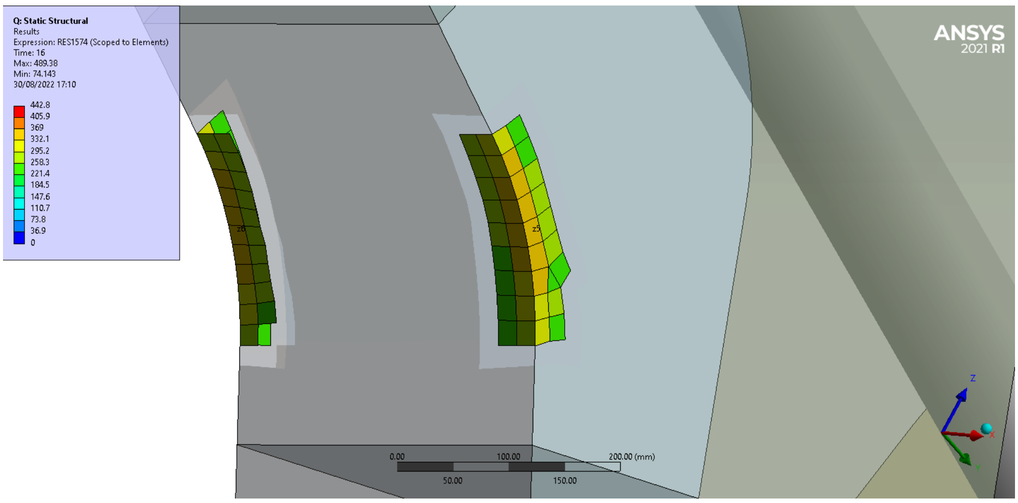

Figure E.11: Equivalent von Mises stress plot for Zone 5 hot spot.

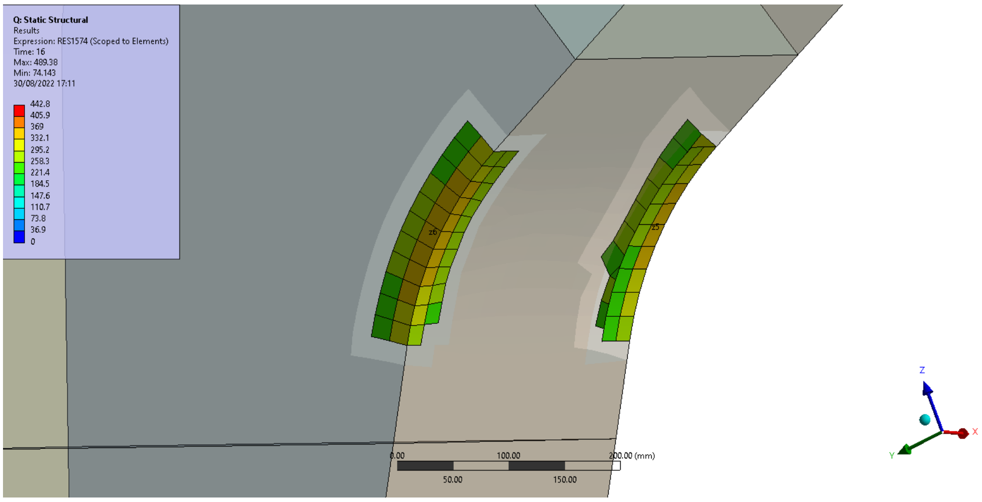

Figure E.12: Equivalent von Mises stress plot for Zone 6 hot spot.

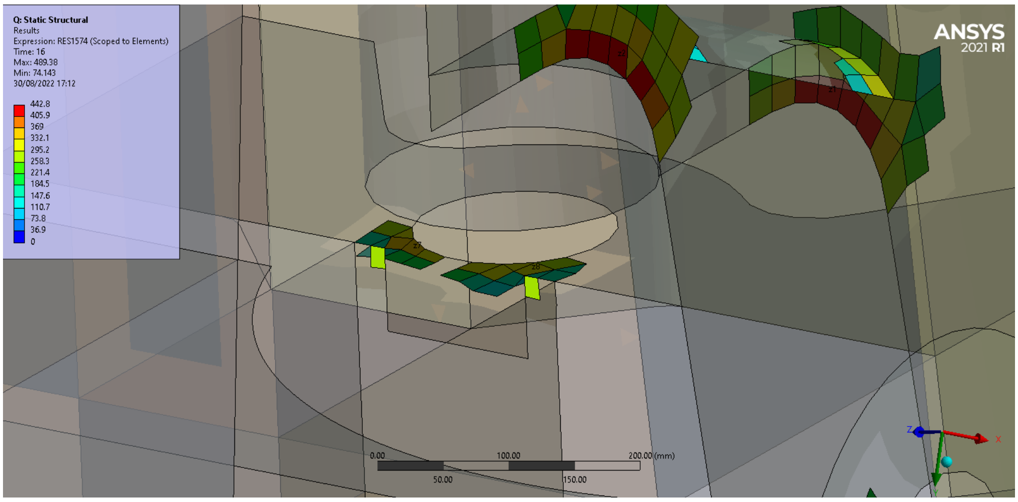

Figure E.13: Equivalent von Mises stress plot for Zones 7 and 8 hot spots.

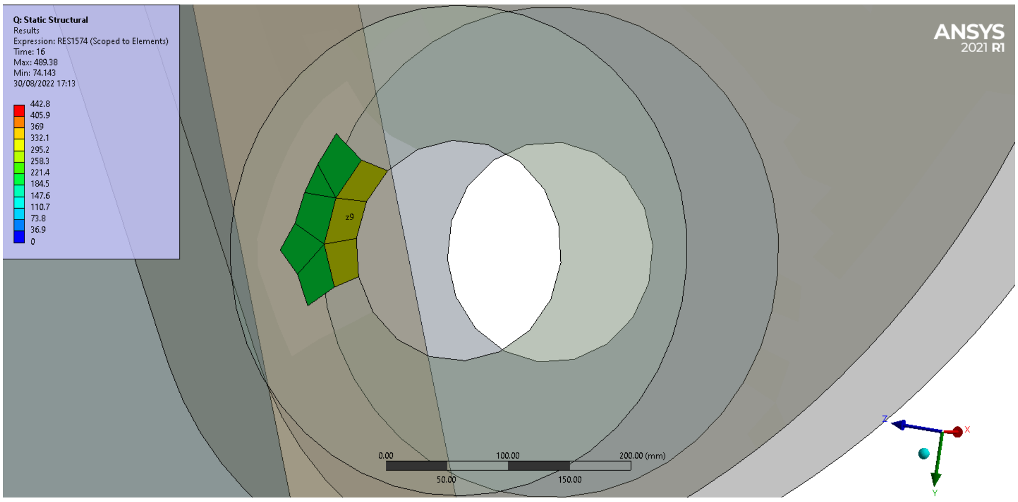

Figure E.14: Equivalent von Mises stress plot for Zone 9 hot spot.

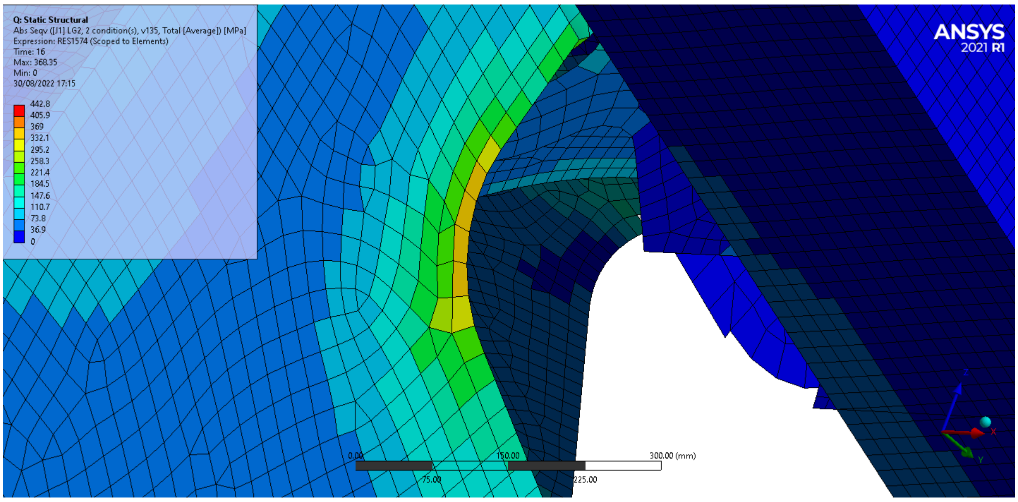

Figure E.15: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

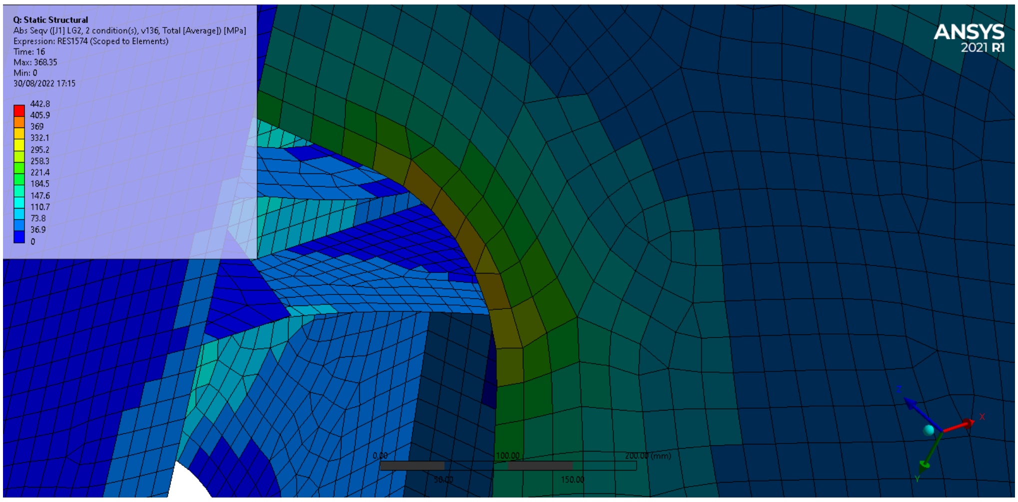

Figure E.16: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

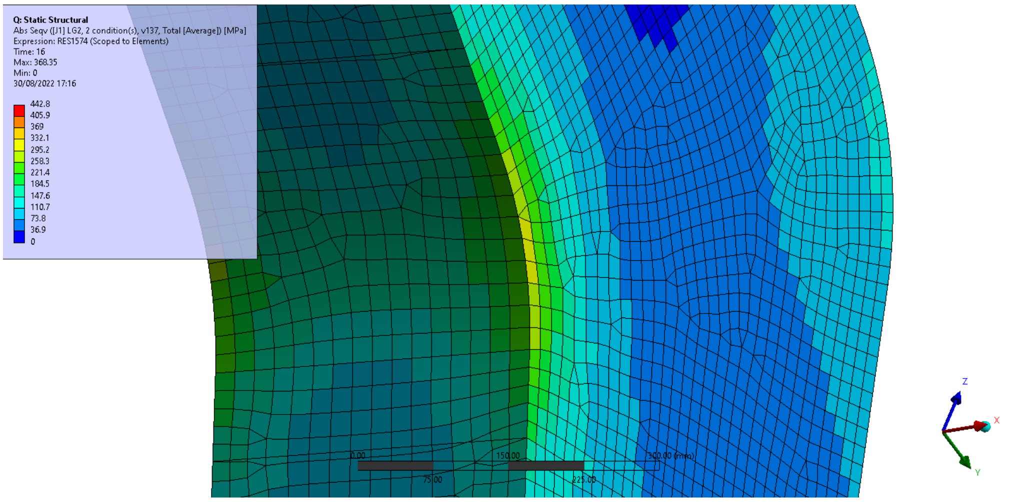

Figure E.17: Equivalent von Mises elemental mean stress plot Zone 3 hot spot.

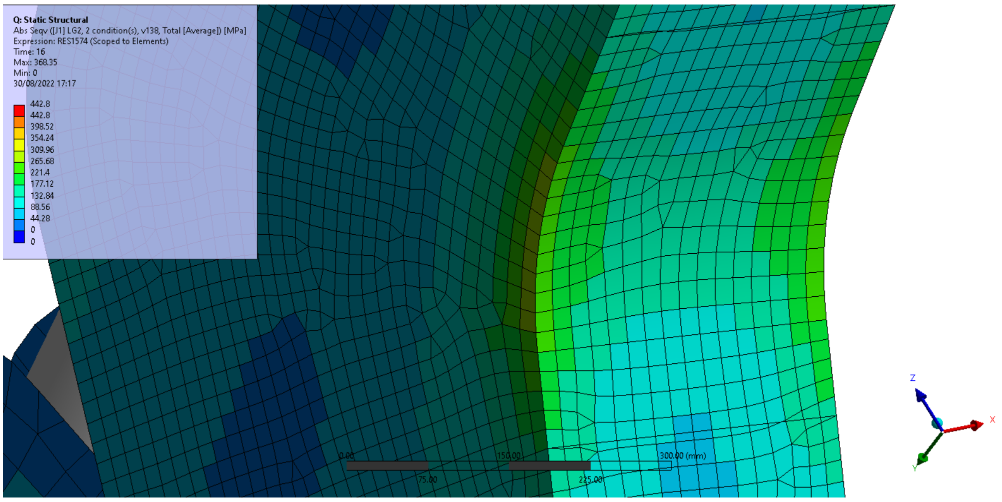

Figure E.18: Equivalent von Mises elemental mean stress plot Zone 4 hot spot.

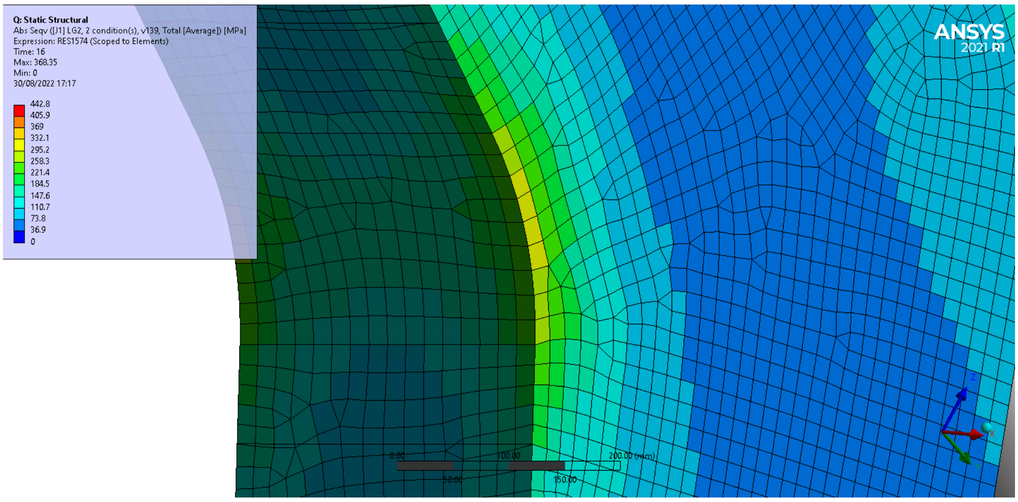

Figure E.19: Equivalent von Mises elemental mean stress plot Zone 5 hot spot.

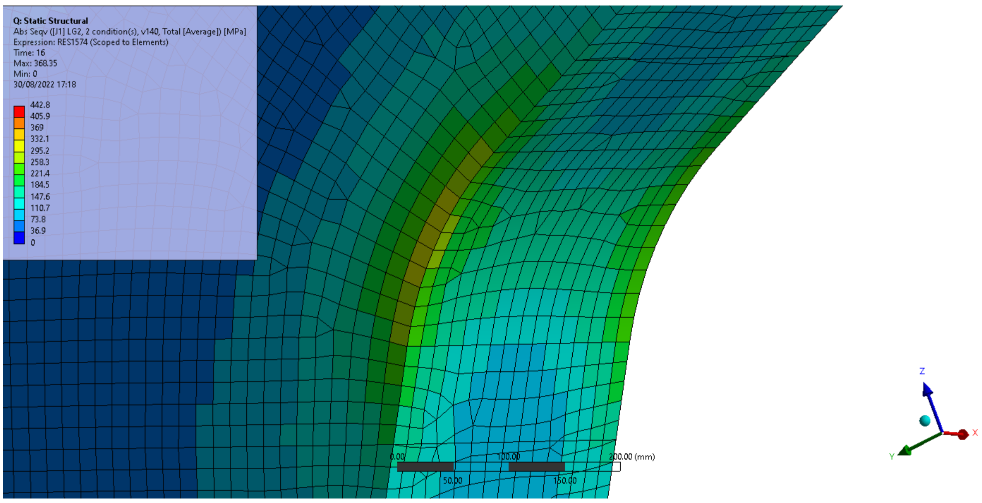

Figure E.20: Equivalent von Mises elemental mean stress plot Zone 6 hot spot.

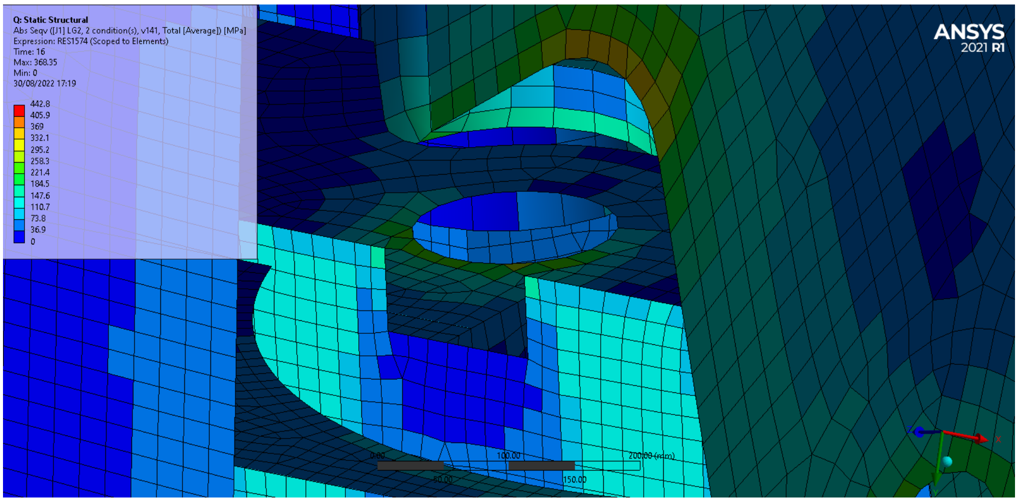

Figure E.21: Equivalent von Mises elemental mean stress plot Zones 7 and 8 hot spots.

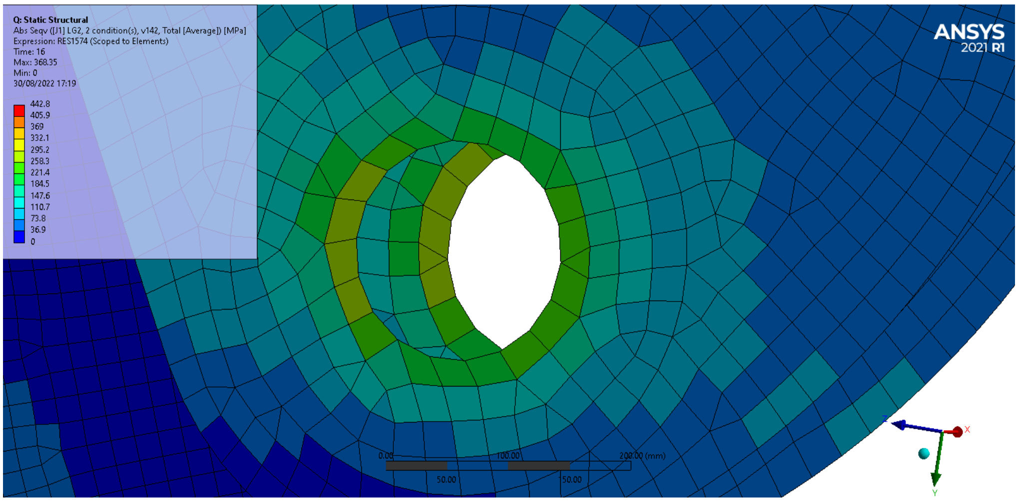

Figure E.22: Equivalent von Mises elemental mean stress plot Zone 9 hot spot.

E.1.3. Loading Conditions 3

Table E.3: Hot spot areas for the Loading Condition 3.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	499.17	E.23	E.25
Zone 2	498.67	E.24	E.26

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Loading Conditions 3.

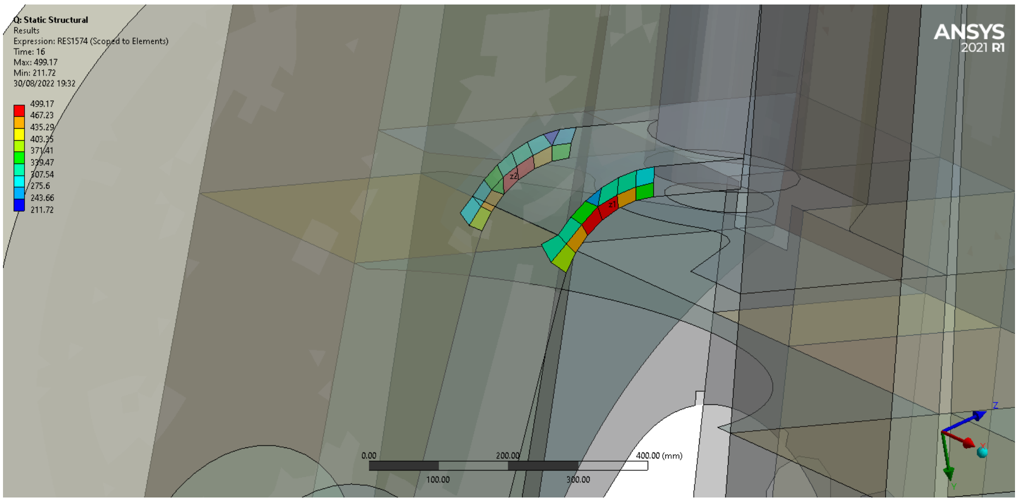

Figure E.23: Equivalent von Mises stress plot Zone 1 hot spot.

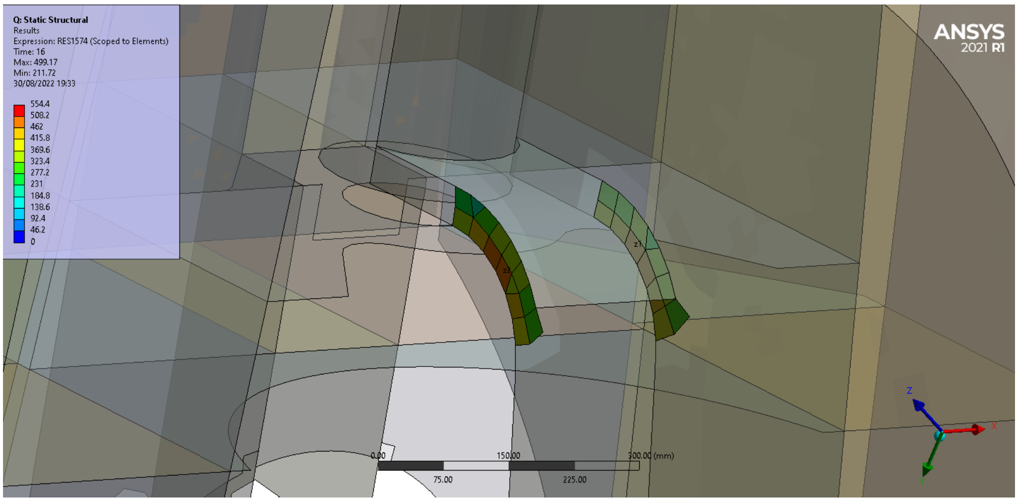

Figure E.24: Equivalent von Mises stress plot for Zone 2 hot spot.

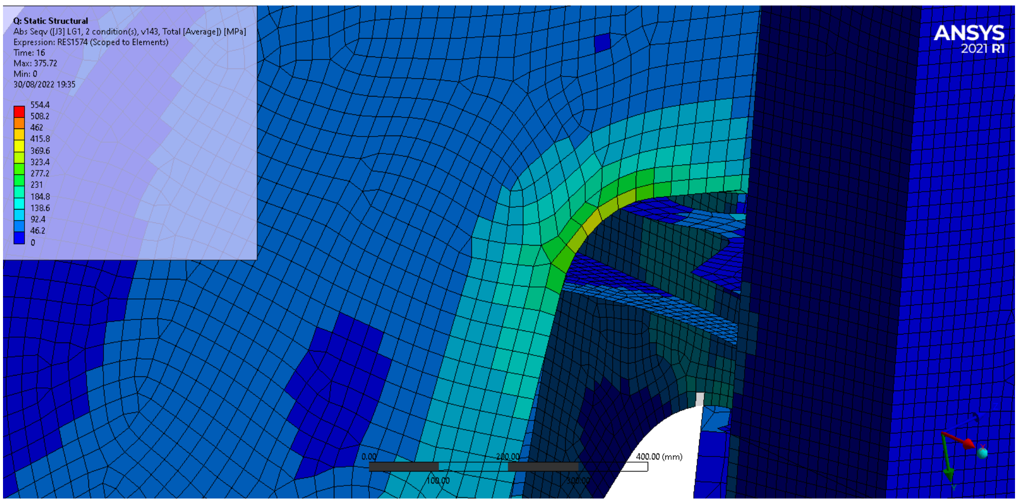

Figure E.25: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

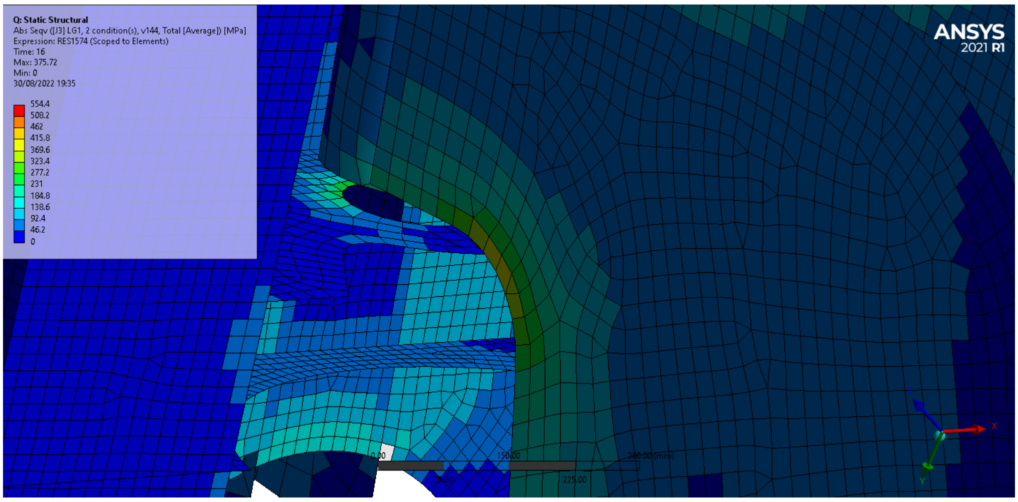

Figure E.26: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

E.1.4. Empirical Case Nominal Force

Table E.4: Hot spot areas for Empirical Case Nominal Force.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	331.37	E.27	E.29
Zone 2	330.47	E.28	E.30

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Empirical Case Nominal Force.

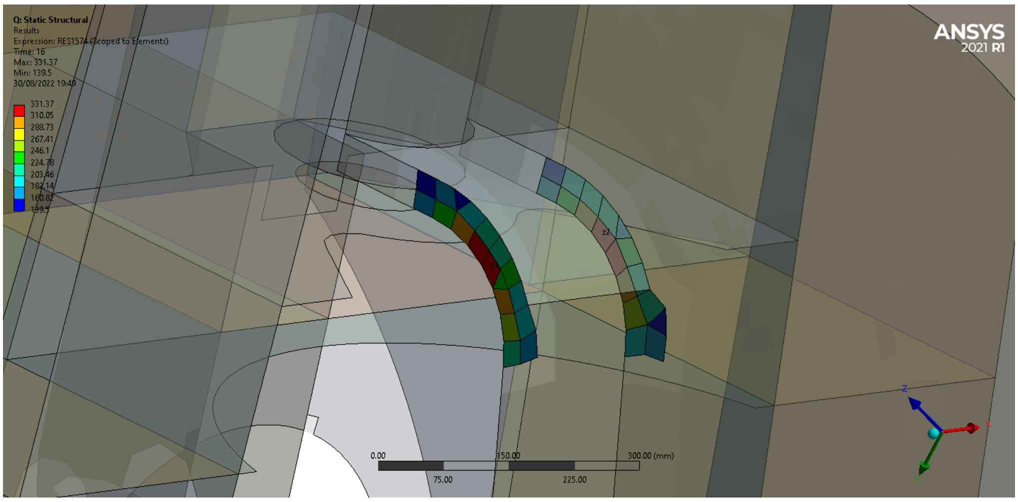

Figure E.27: Equivalent von Mises stress plot Zone 1 hot spot.

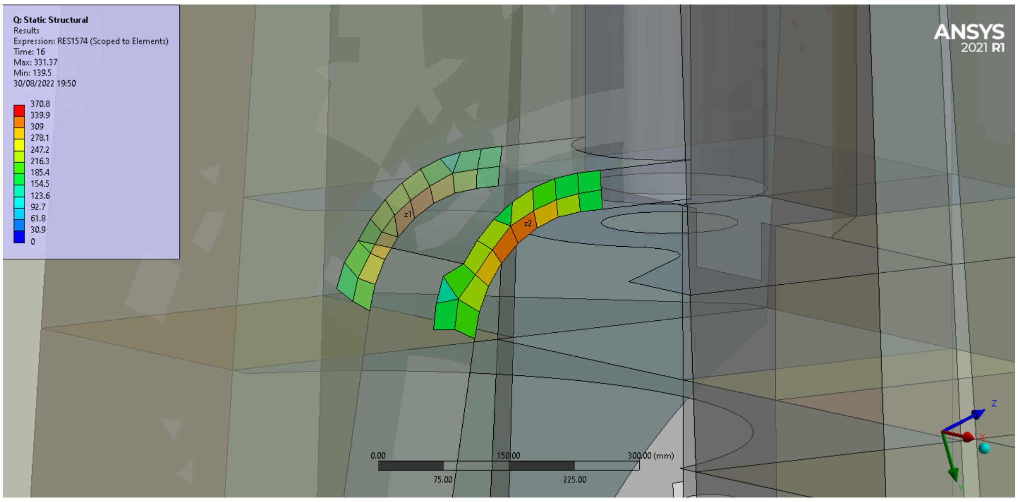

Figure E.28: Equivalent von Mises stress plot for Zone 2 hot spot.

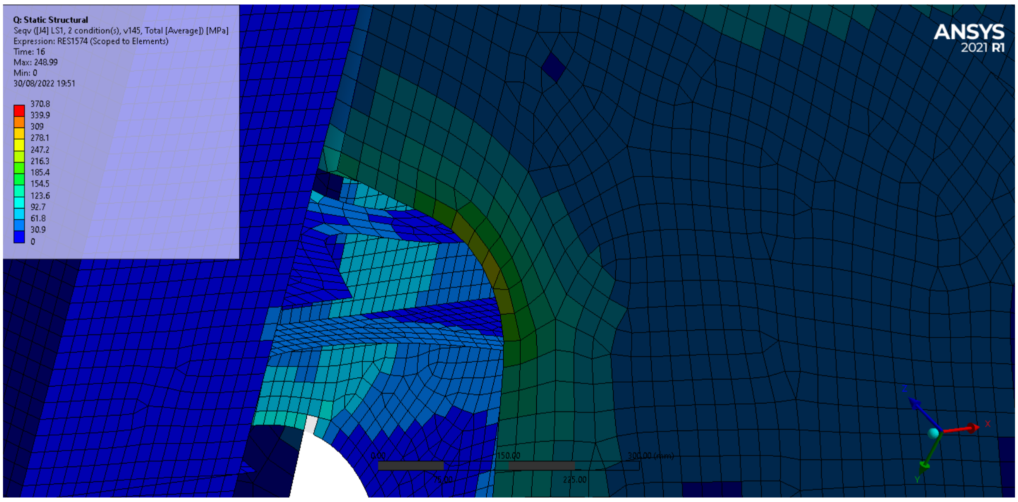

Figure E.29: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

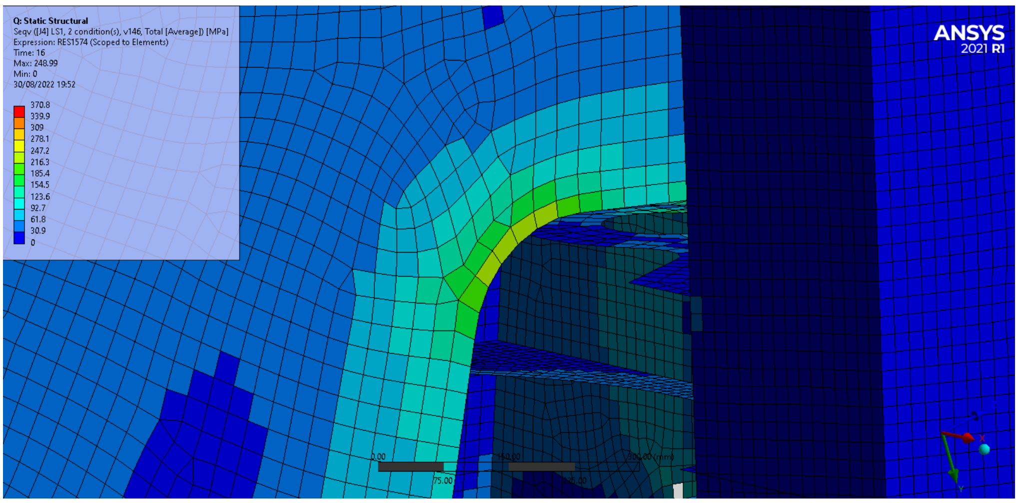

Figure E.30: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

E.1.5. Empirical Case Maximal Force

Table E.5: Hot spot areas for Empirical Case Maximal Force.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	439.15	E.31	E.33
Zone 2	438.18	E.32	E.34

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Empirical Case Maximal Force.

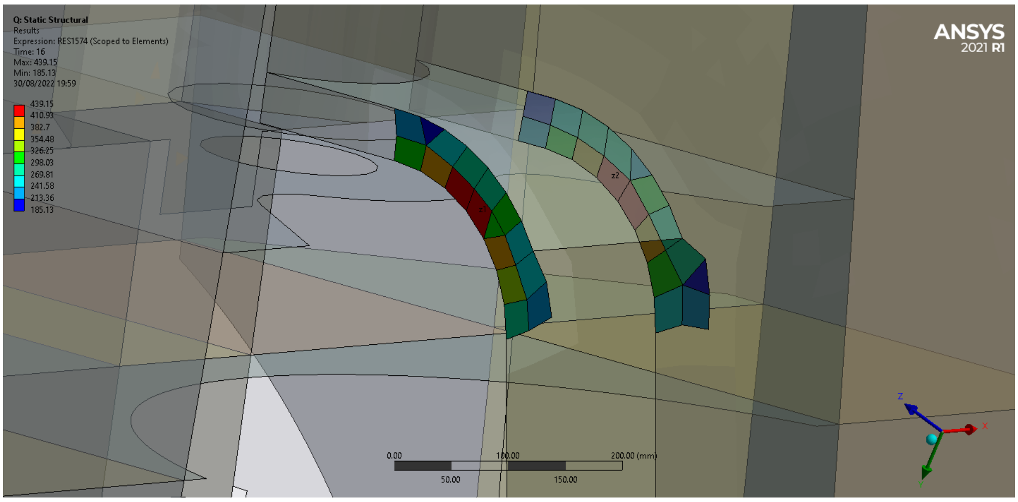

Figure E.31: Equivalent von Mises stress plot Zone 1 hot spot.

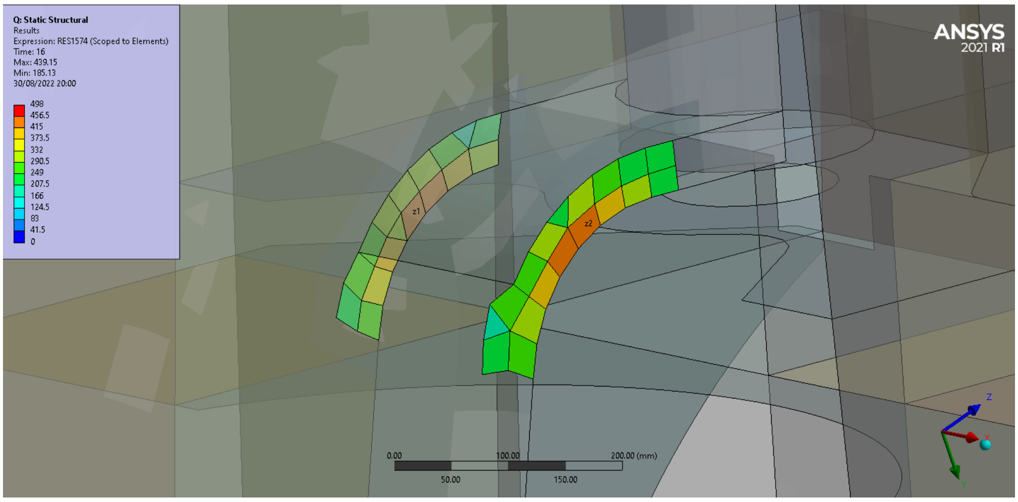

Figure E.32: Equivalent von Mises stress plot for Zone 2 hot spot.

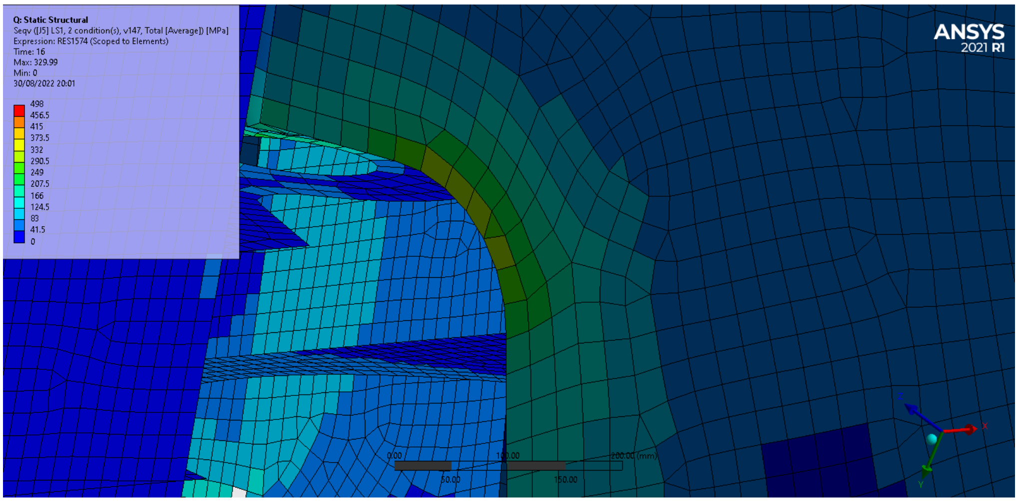

Figure E.33: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

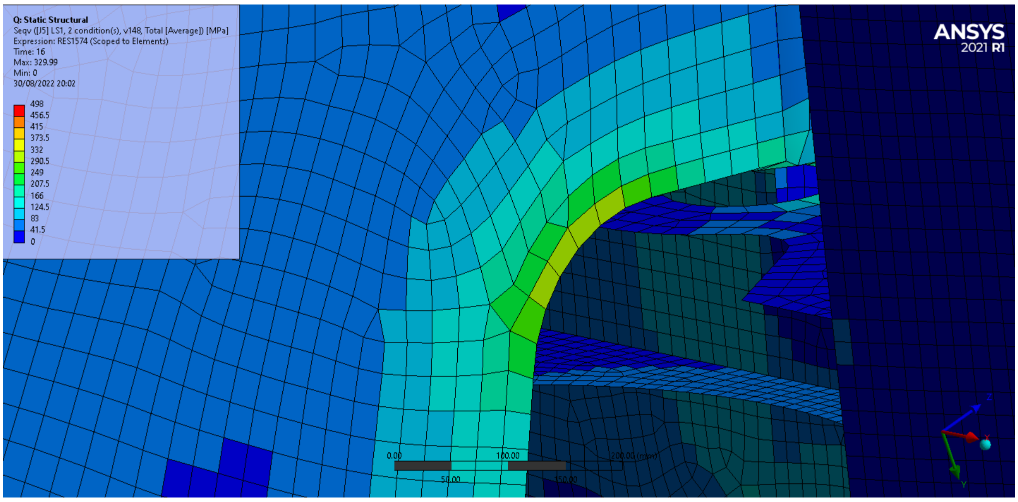

Figure E.34: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

E.2. Model "45"

E.2.1. Loading Conditions 3

Table E.6: Hot spot areas for Loading Conditions 3.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	426.52	E.35	E.37
Zone 2	425.47	E.36	E.38

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Loading Conditions 3.

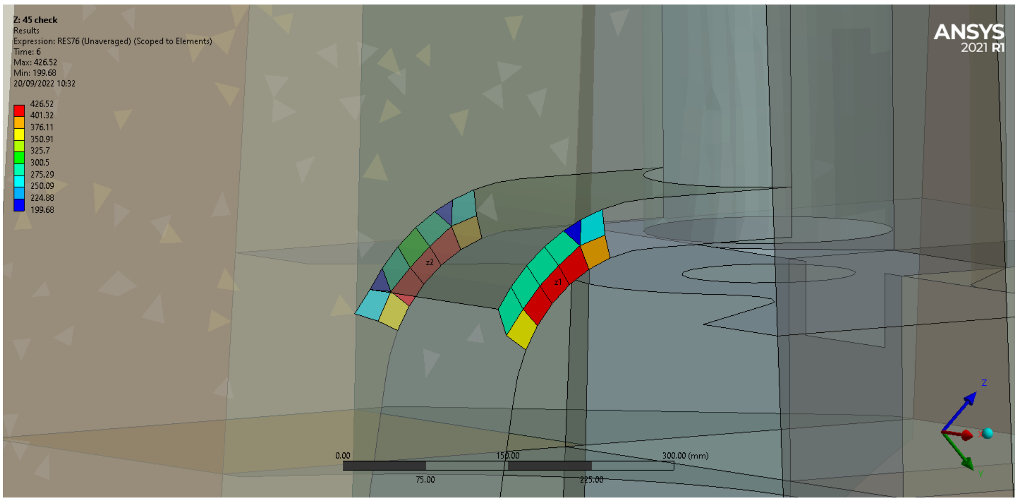

Figure E.35: Equivalent von Mises stress plot Zone 1 hot spot.

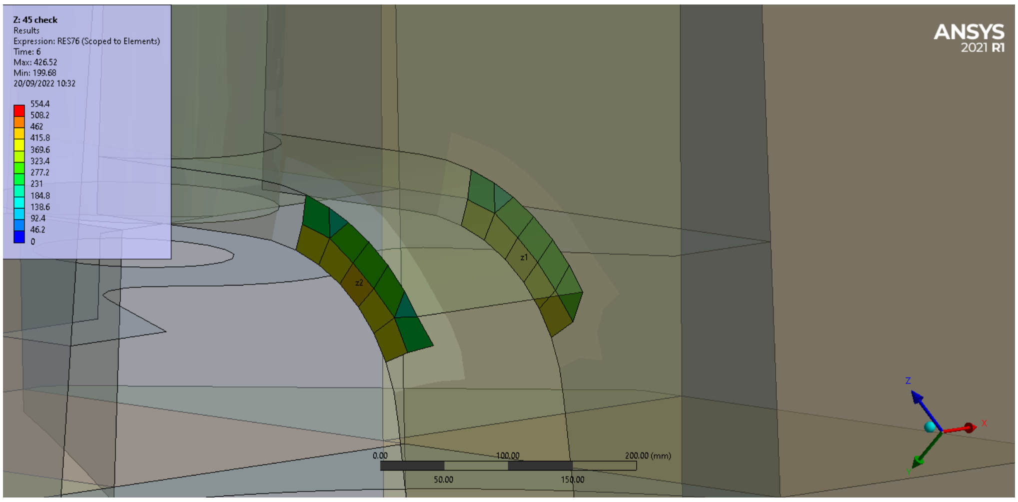

Figure E.36: Equivalent von Mises stress plot for Zone 2 hot spot.

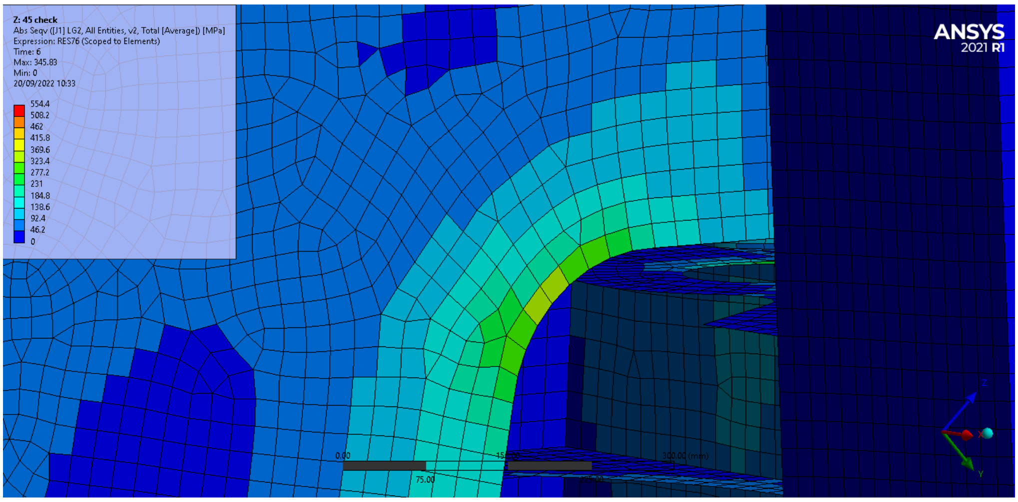

Figure E.37: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

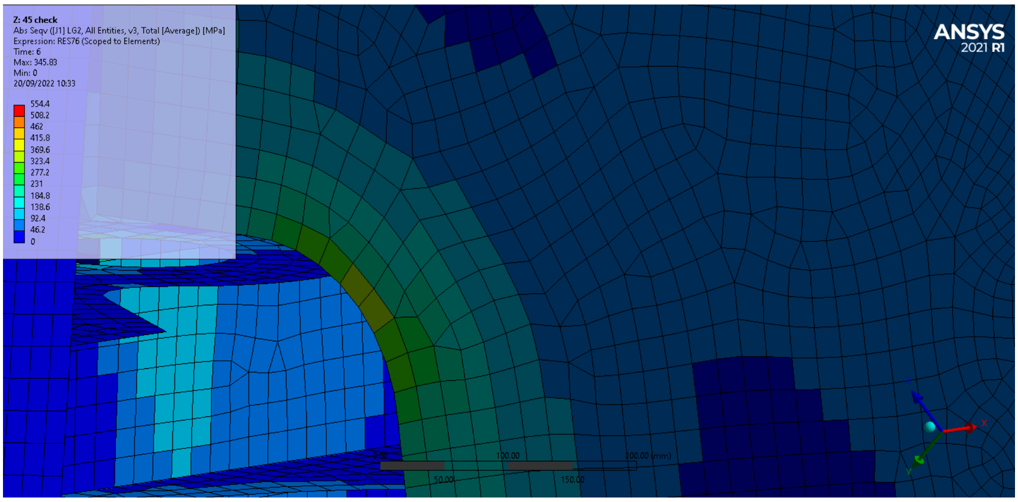

Figure E.38: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

E.2.2. Empirical Case Maximal Force

Table E.7: Hot spot areas for empirical case maximal force.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	374.55	E.39	E.43
Zone 2	373.62	E.40	E.44
Zone 3	329.95	E.41	E.45
Zone 4	325.23	E.42	E.46

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Empirical Case Maximal Force.

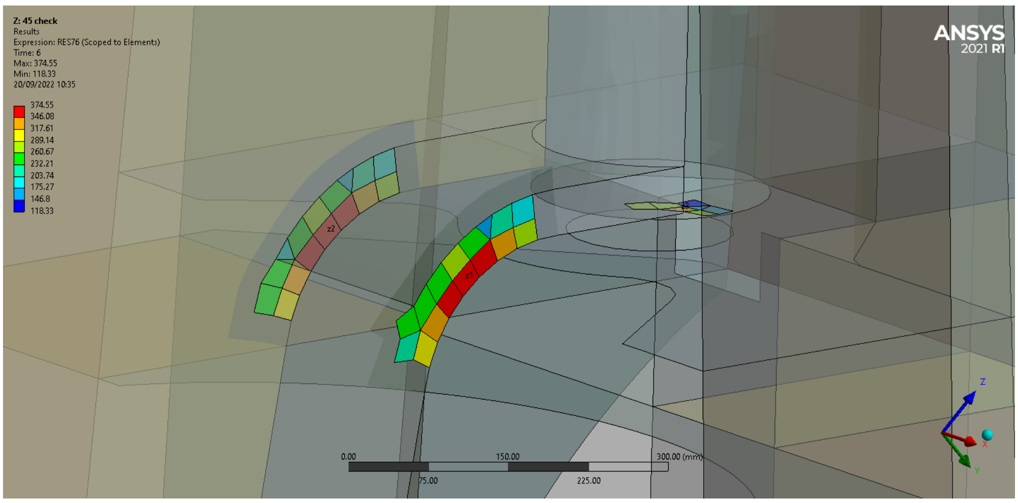

Figure E.39: Equivalent von Mises stress plot Zone 1 hot spot.

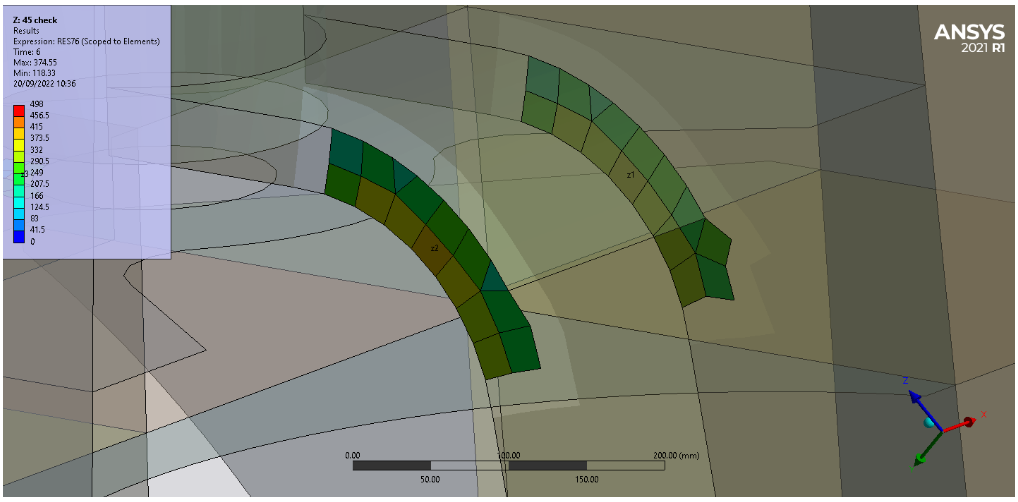

Figure E.40: Equivalent von Mises stress plot for Zone 2 hot spot.

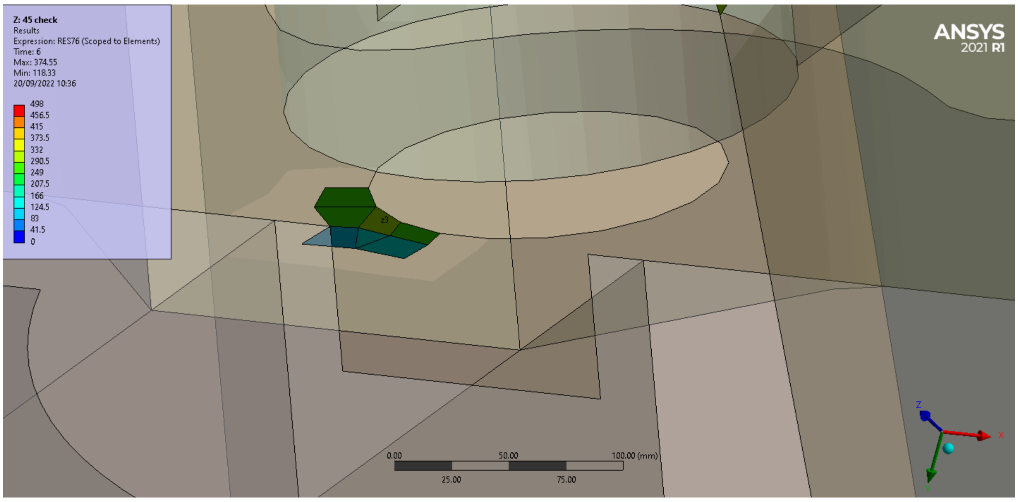

Figure E.41: Equivalent von Mises stress plot Zone 3 hot spot.

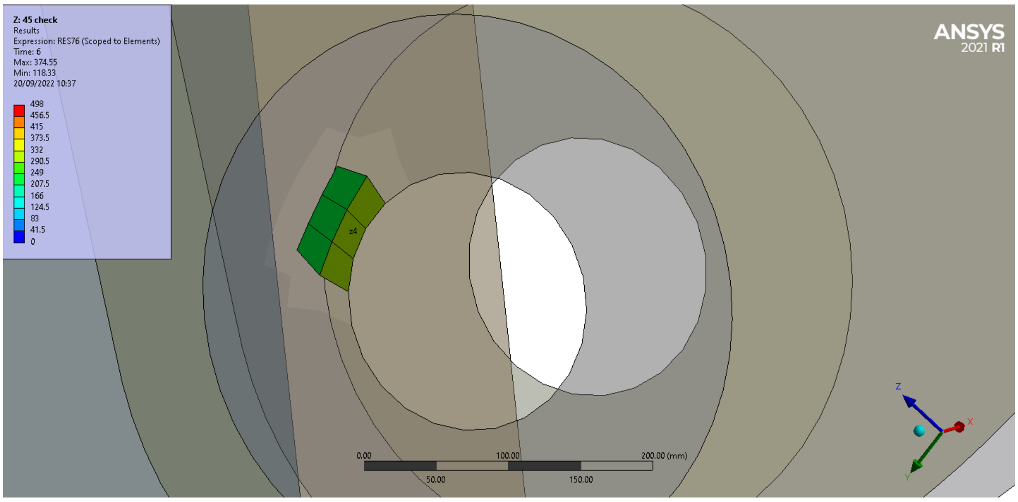

Figure E.42: Equivalent von Mises stress plot for Zone 4 hot spot.

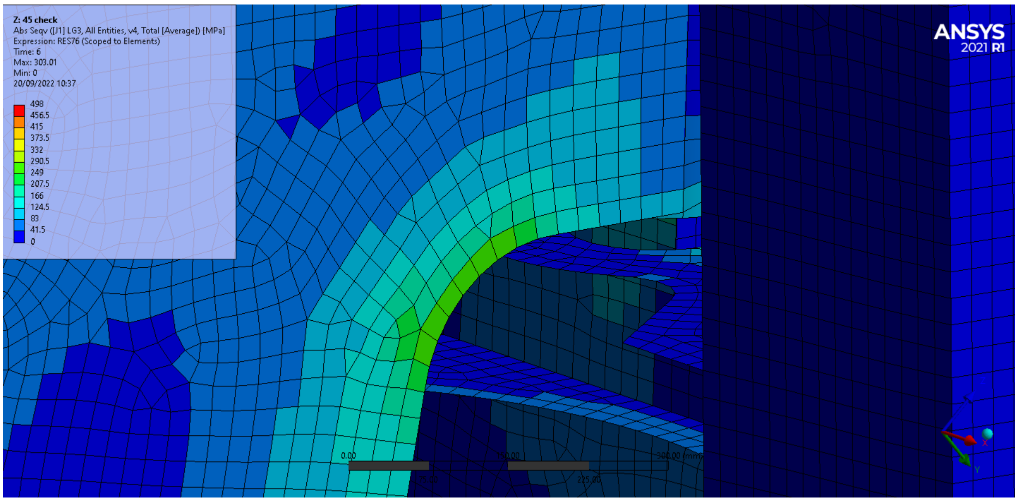

Figure E.43: Equivalent von Mises elemental mean stress plot Zone 1 hot spot.

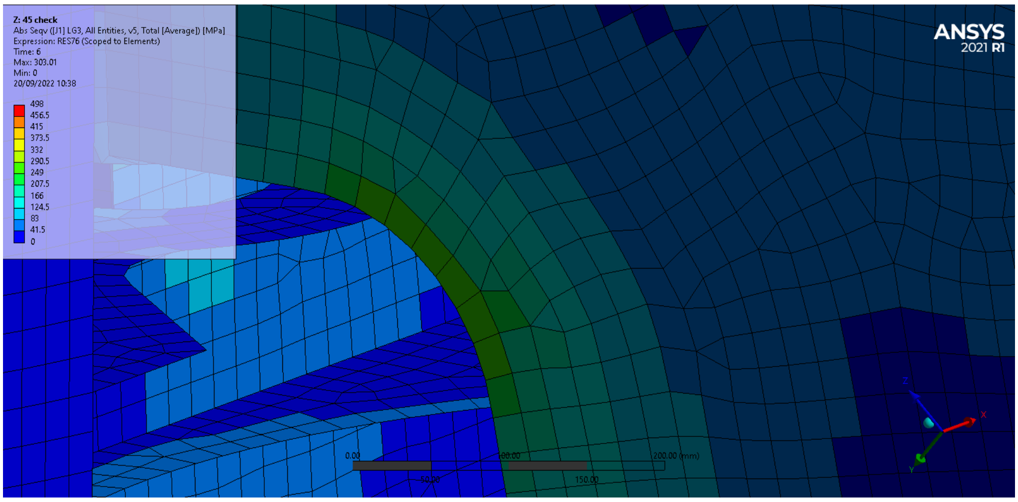

Figure E.44: Equivalent von Mises elemental mean stress plot Zone 2 hot spot.

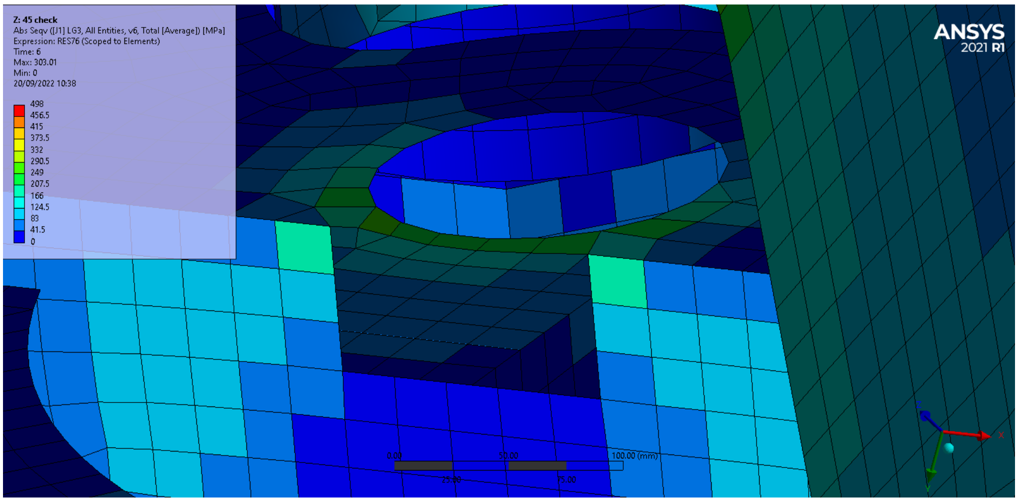

Figure E.45: Equivalent von Mises elemental mean stress plot Zone 3 hot spot.

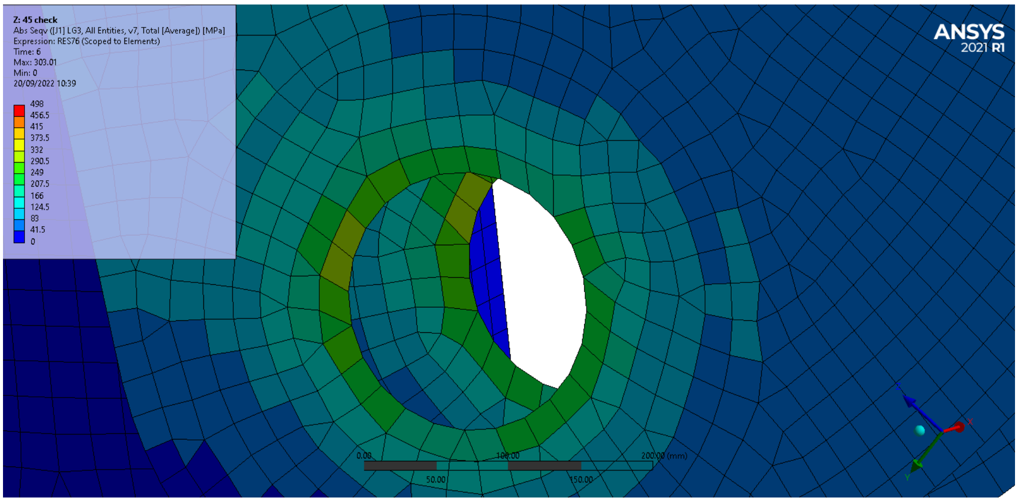

Figure E.46: Equivalent von Mises elemental mean stress plot Zone 4 hot spot.

E.3. Model “Upright”

E.3.1. Loading Conditions 3

Table E.8: Hot spot areas for Loading Conditions 3.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	523.35	E.47	E.50
Zone 2	492.67	E.47	E.50
Zone 3	399.65	E.48	E.51
Zone 4	392.68	E.49	E.52

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Loading Conditions 3.

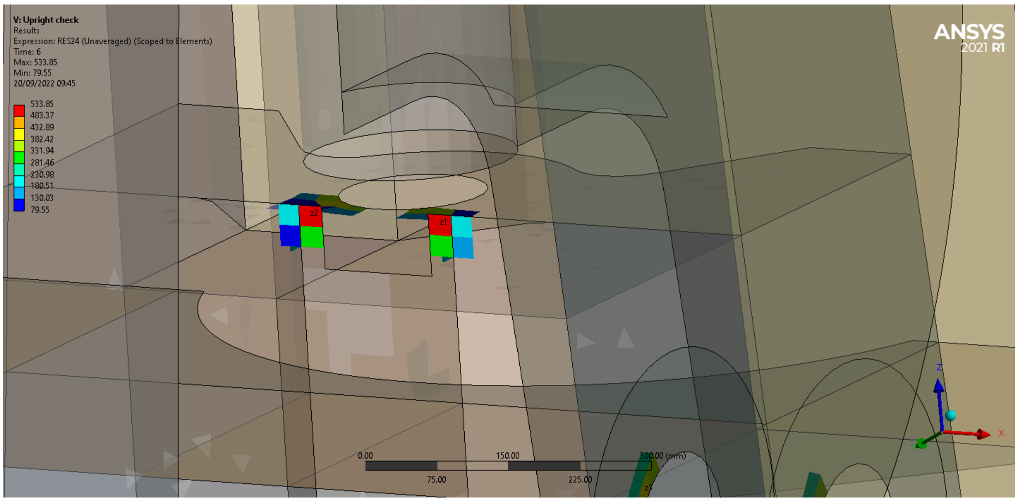

Figure E.47: Equivalent von Mises stress plot for Zone 1 and Zone 2 hot spots.

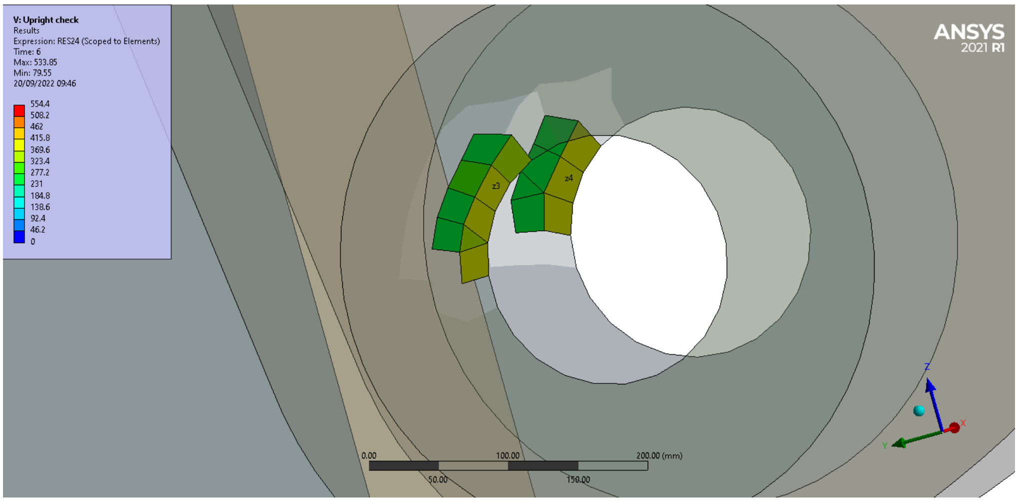

Figure E.48: Equivalent von Mises stress plot for Zone 3 hot spot.

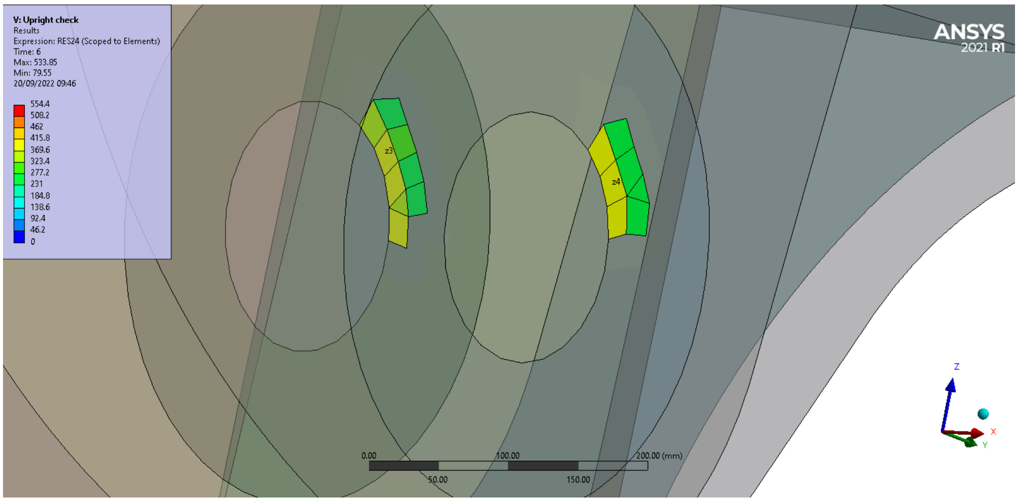

Figure E.49: Equivalent von Mises stress plot Zone 4 hot spot.

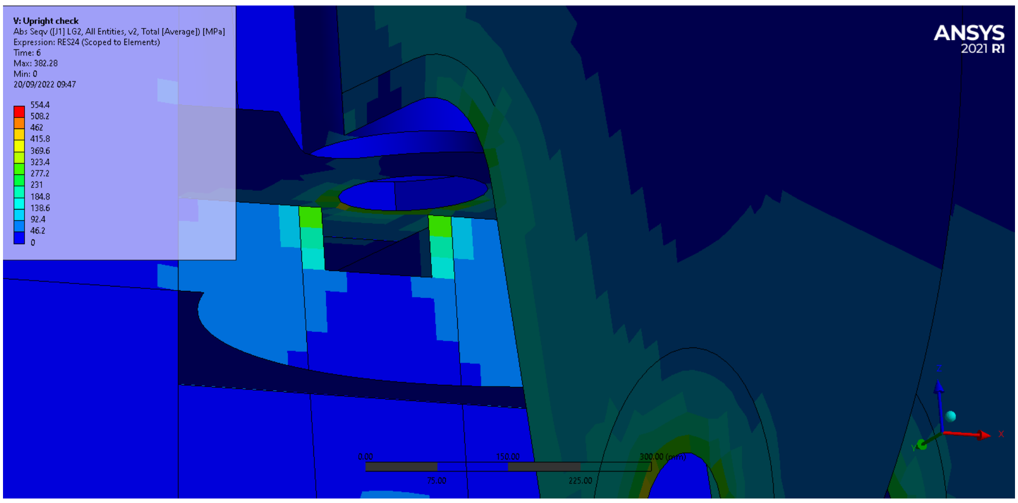

Figure E.50: Equivalent von Mises elemental mean stress plot for Zone 1 and Zone 2 hot spots.

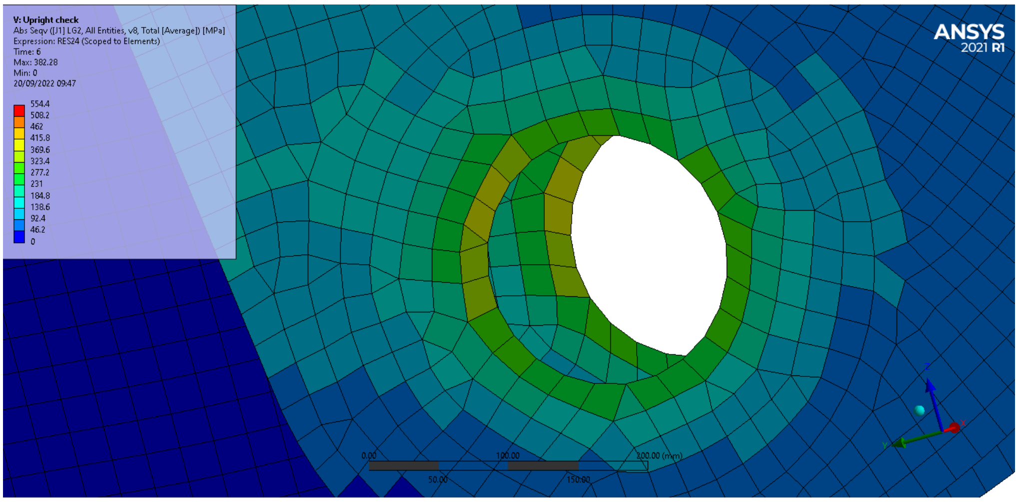

Figure E.51: Equivalent von Mises elemental mean stress plot Zone 3 hot spot.

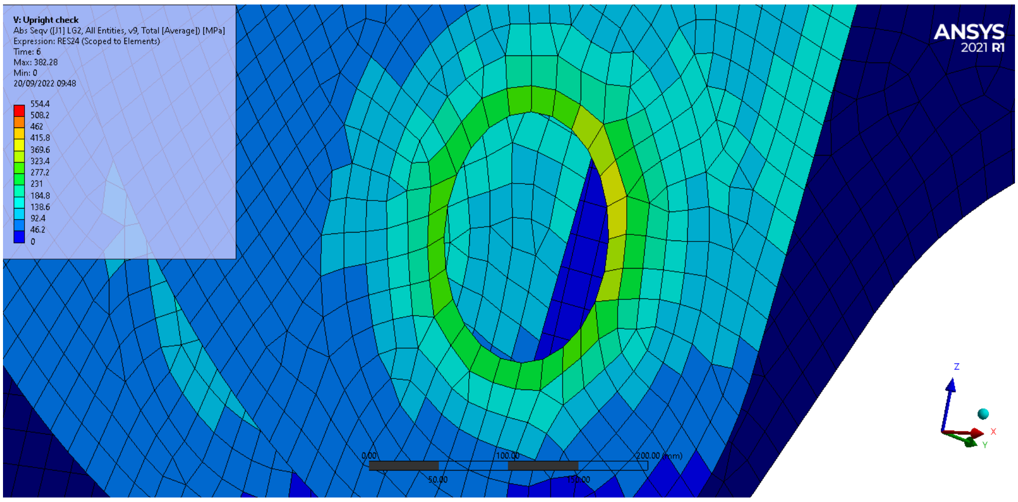

Figure E.52: Equivalent von Mises elemental mean stress plot Zone 4 hot spot.

E.3.2. Empirical Case Maximal Force

Table E.9: Hot spot areas for empirical case maximal force.

Zone	Peak Value [MPa]	Figure	Check
Zone 1	456.54	E.53	E.56
Zone 2	429.73	E.53	E.56
Zone 3	344.44	E.54	E.57
Zone 4	338.79	E.55	E.58

Based on the results presented in the check figures, it is concluded that all of the hot spot stress zones are sufficiently strong to prevent yielding for Empirical Case Maximal Force.

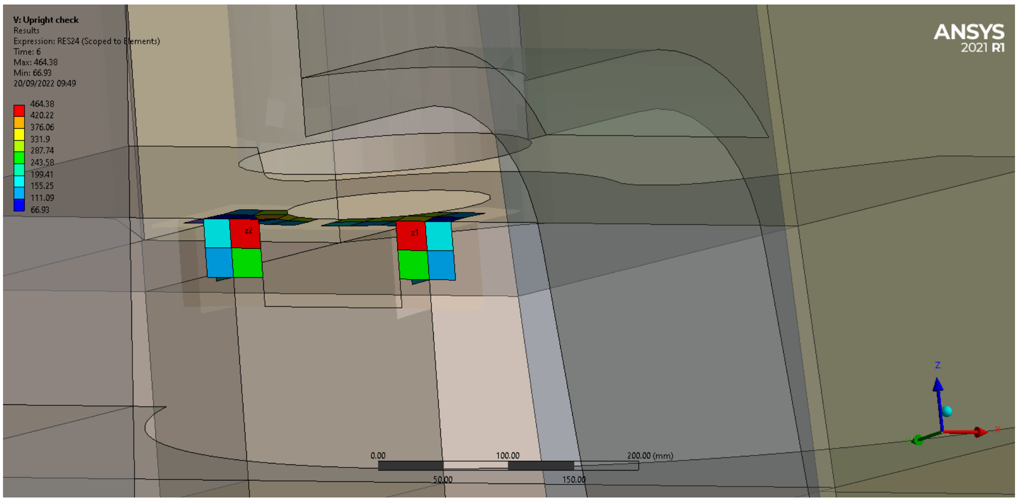

Figure E.53: Equivalent von Mises stress plot Zones 1 and 2 hot spots.

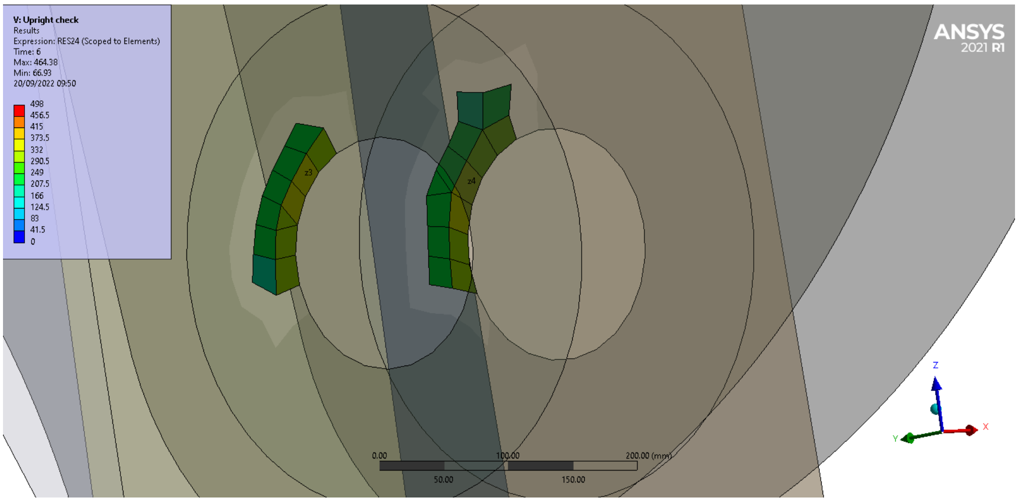

Figure E.54: Equivalent von Mises stress plot for Zone 3 hot spot.

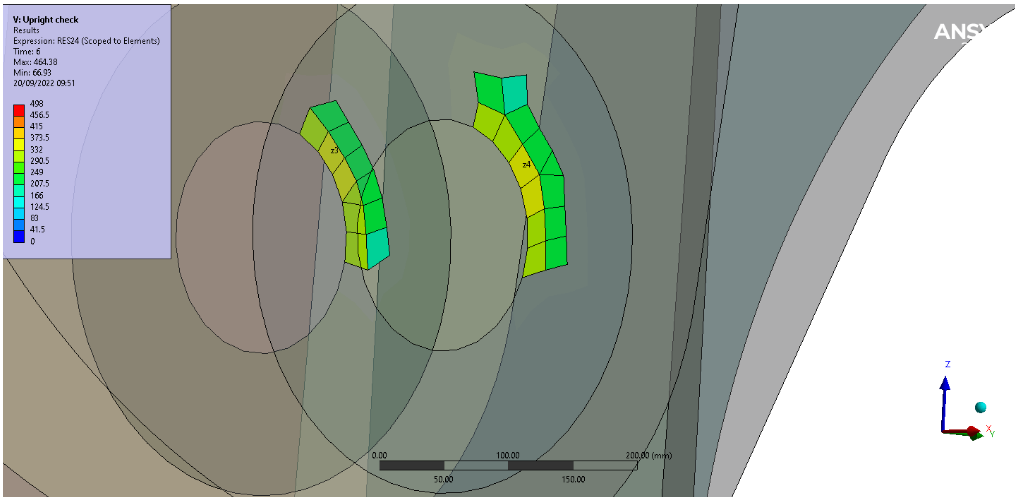

Figure E.55: Equivalent von Mises stress plot Zone 4 hot spot.

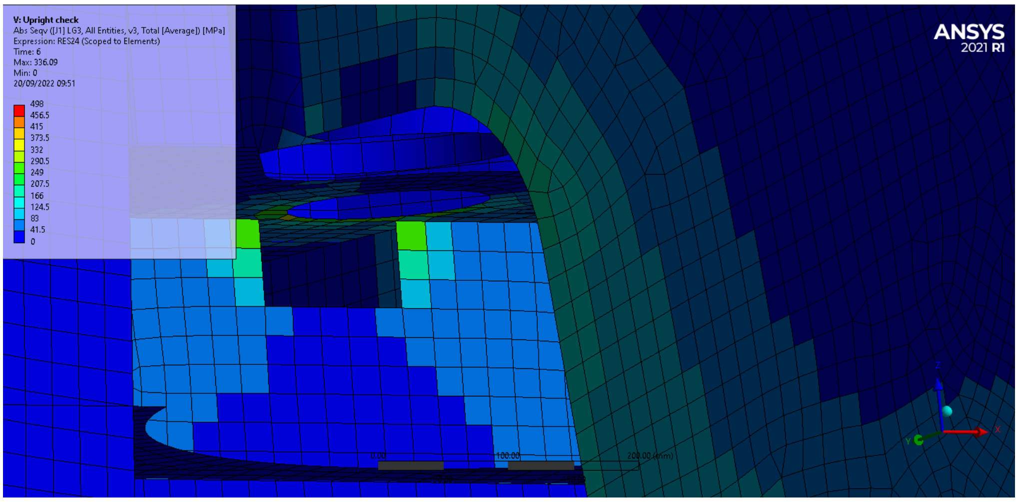

Figure E.56: Equivalent von Mises elemental mean stress plot Zone 1 and 2 hot spots.

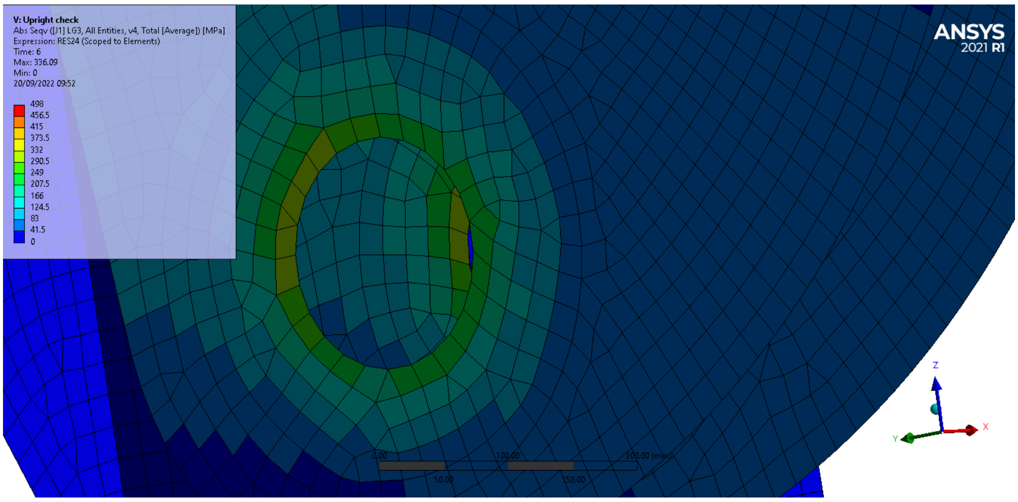

Figure E.57: Equivalent von Mises elemental mean stress plot Zone 3 hot spot.

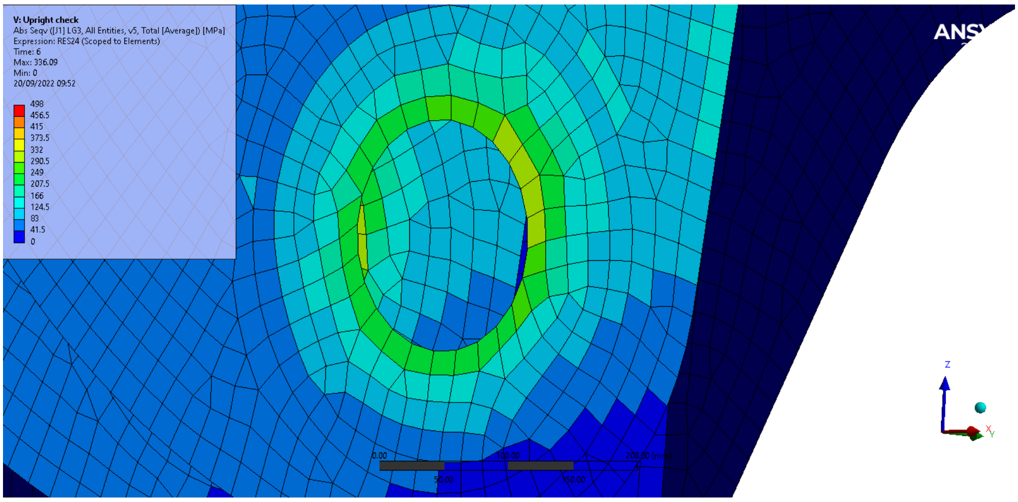

Figure E.58: Equivalent von Mises elemental mean stress plot Zone 4 hot spot.

F

Fatigue Checks

In this appendix individual fatigue assessment of the parts which are not passing the fatigue check is performed. Areas where fatigue damage is higher than the lowest allowable damage are discussed.

F.1. A-Frame Side Plates

The first zone is presented in Figure F.1. Presented elements are located on the weld on the A-Frame sections. Welds between the front plates and the side plates are made from the outside, the front plate is the last plate which is welded in this section. These are therefore accessible and available for inspection, which means that the DFF in this are is equal to 1 and fatigue damage is lower than the allowable damage of 1.

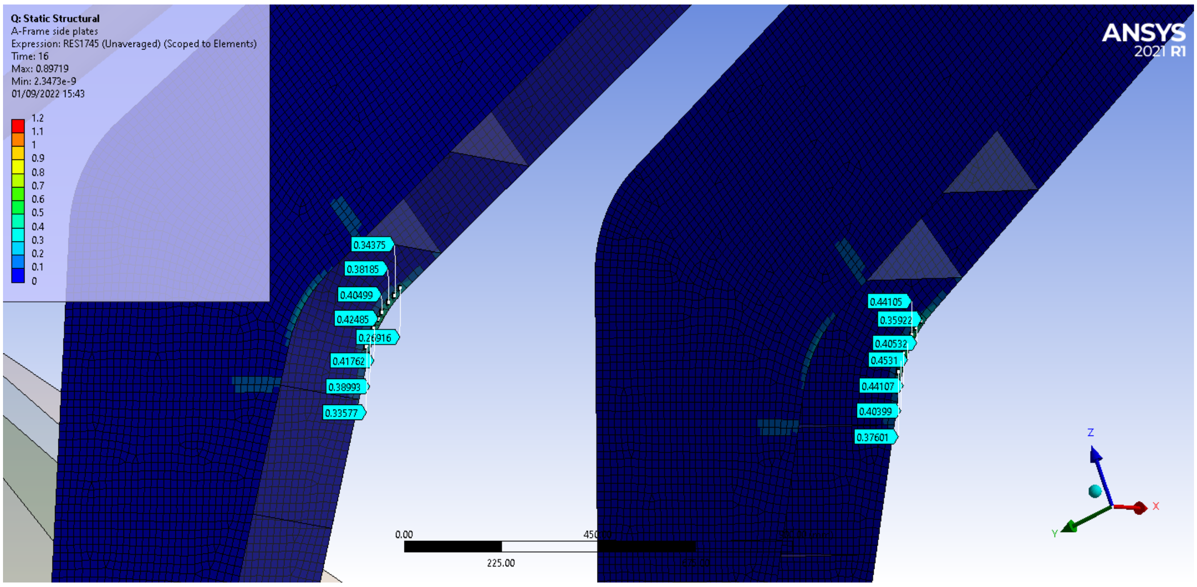

Figure F.1: High fatigue area 1.

The second and third zones are presented in Figures F.2 and F.3. These are parts of the welds which are located on the outside of the A-Frame section and are available for inspection. Therefore the DFF for these areas is equal to 1 as does the allowable fatigue damage. Based on this individual check of the A-Frame side plates, it is concluded that this part is sufficiently resistant to fatigue.

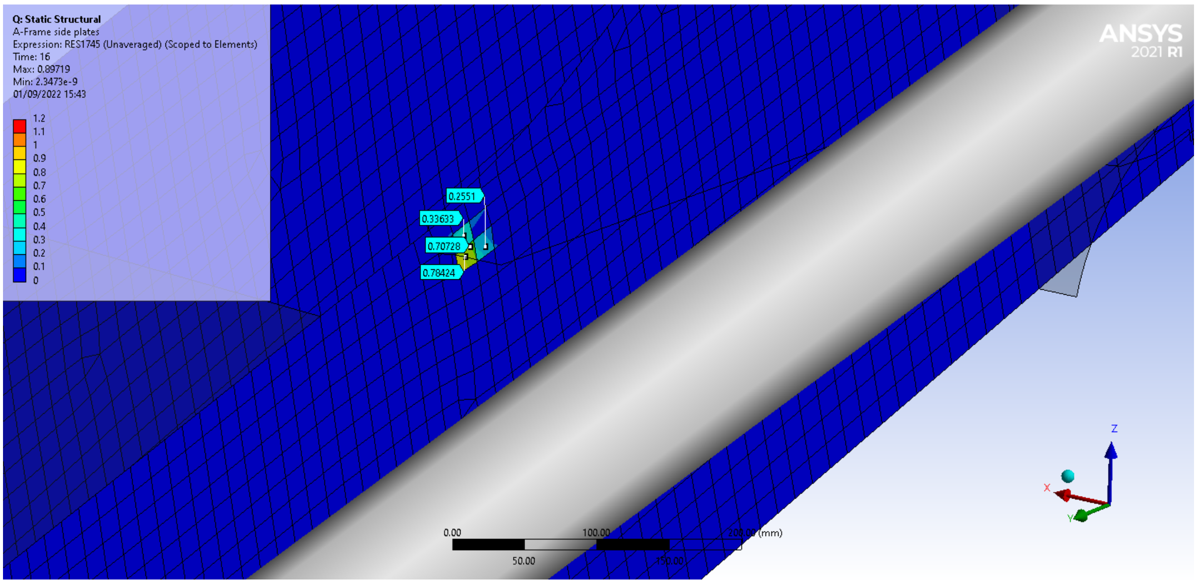

Figure F.2: High fatigue area 2.

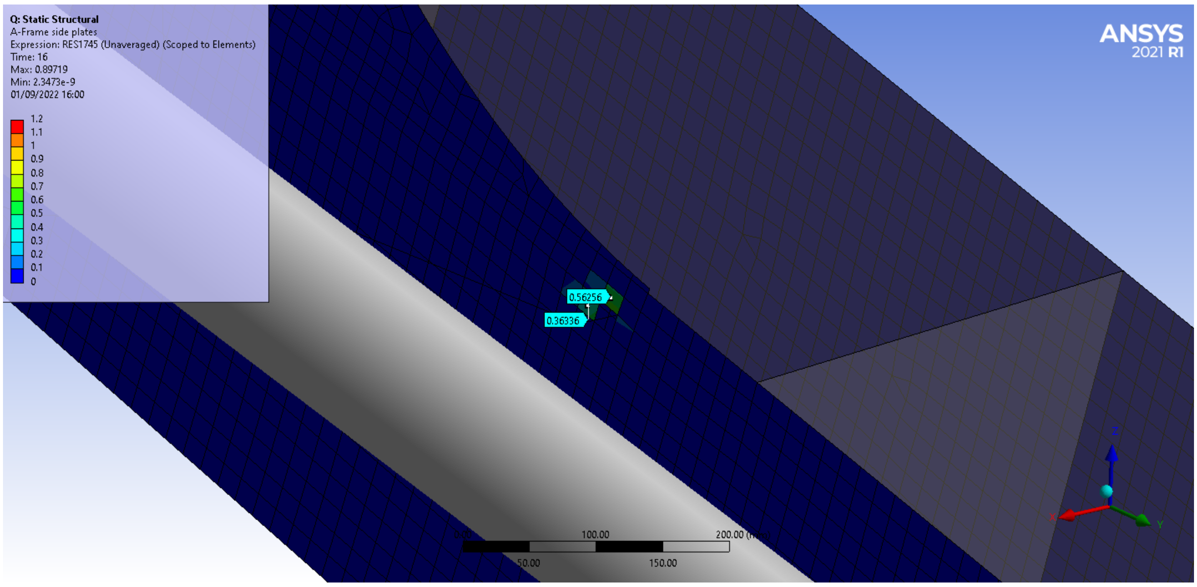

Figure F.3: High fatigue area 3.

F.2. A-Frame Bearing Connector Plates

Bearing connector plates with fatigue hot spots marked are presented in Figures F.4 and F.5. The maximal fatigue damage in this case is much higher than the correct value of $0.78 < 1$ read 0.5t away from hot spot. Based on this individual check of the A-Frame bearing connector plates, it is concluded that this part is sufficiently resistant to fatigue.

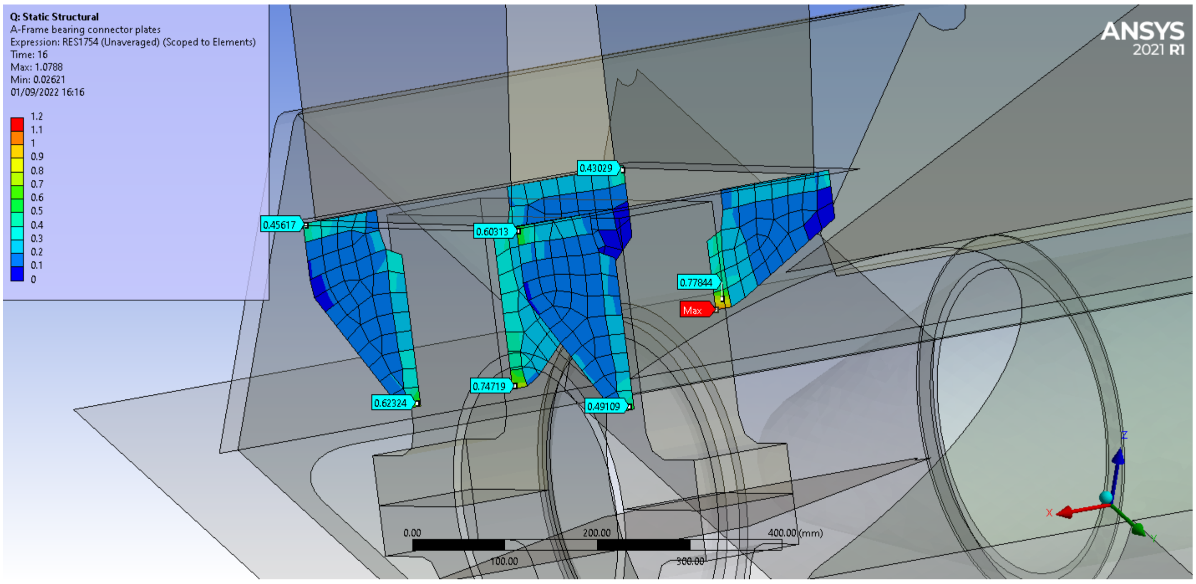

Figure F.4: High fatigue area 1.

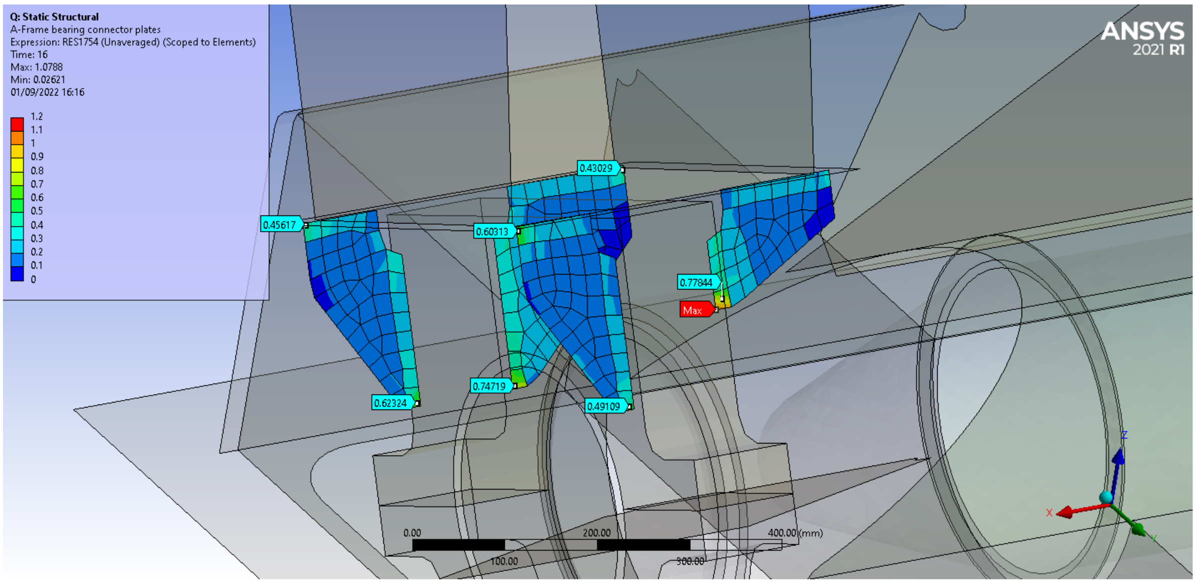

Figure F.5: High fatigue area 2.

F.3. Fixed Part Front Plates

Fixed part front plates with fatigue hot spots marked are presented in Figure F.6. The maximal damage is higher than the correctly read value of $0.32 < 0.33$, Moreover, this part of the plates is easily accessible for inspection. Hence the DFF for this area is equal to 1. Based on this check it is concluded that fixed part front plates are sufficiently resistant to fatigue.

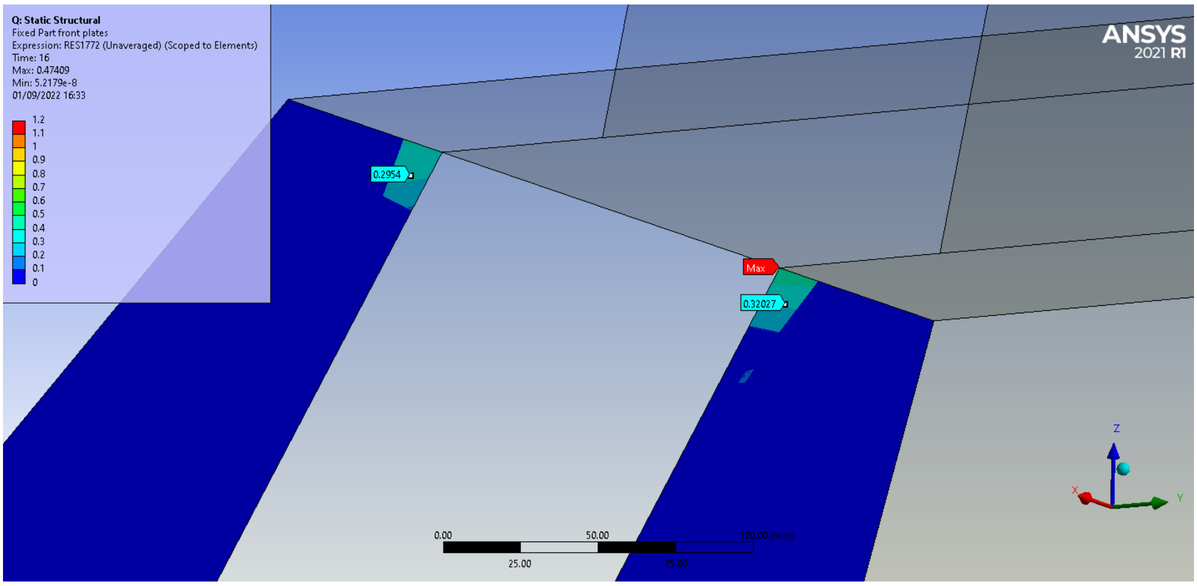

Figure F.6: High fatigue area.

F.4. Fixed Part Bottom Back Horizontal Side Plates

Fatigue hot spots for horizontal side plates in the fixed part are presented in Figures F.7 and F.8. The fatigue damage is in that case $0.31 < 0.33$. Therefore these parts are sufficiently resistant to fatigue.

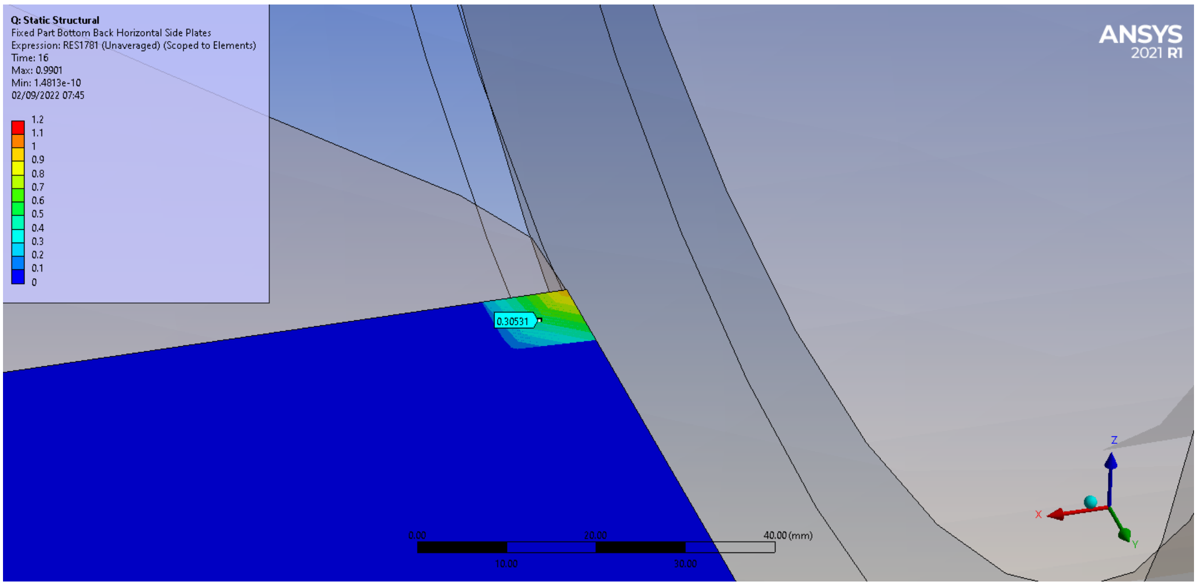

Figure F.7: High fatigue area 1.

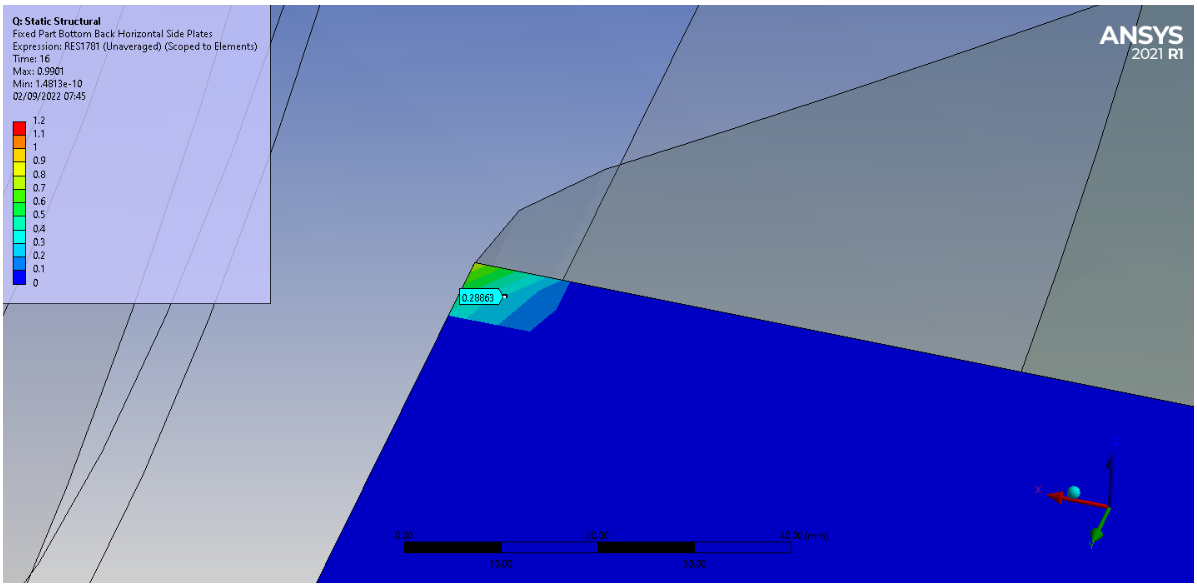

Figure F.8: High fatigue area 2.

F.5. Fixed Part Inner Pivot Supports

The fatigue check results for inner pivot supports in the fixed part are presented in Figures F.9 and F.10. The fatigue damage is equal to $0.28 < 0.33$. Hence the part is deemed to be adequately protected against fatigue.

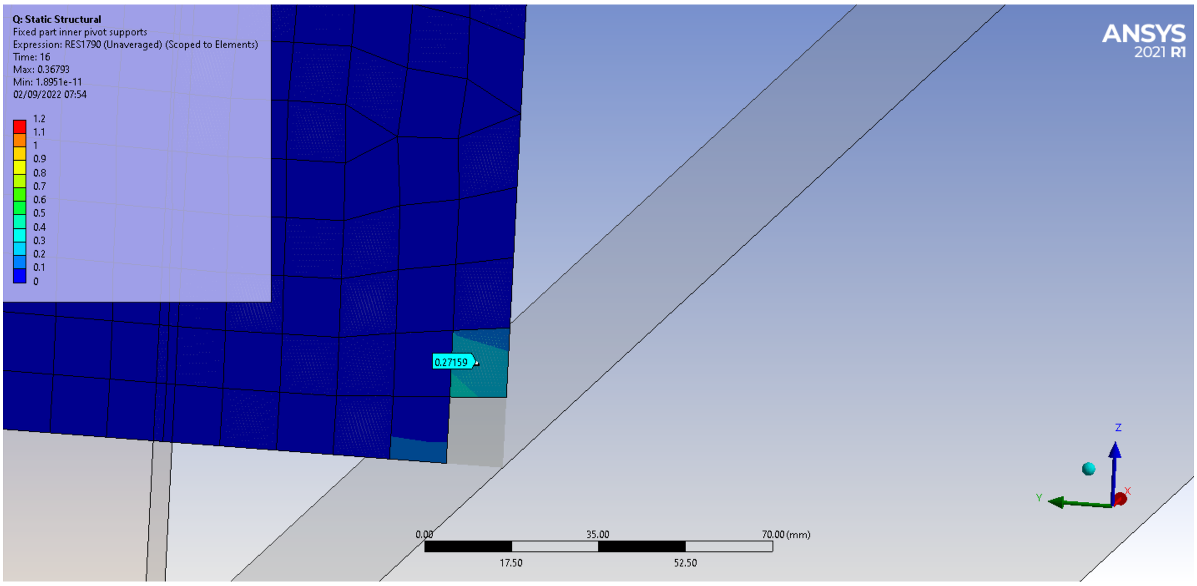

Figure F.9: High fatigue area 1.

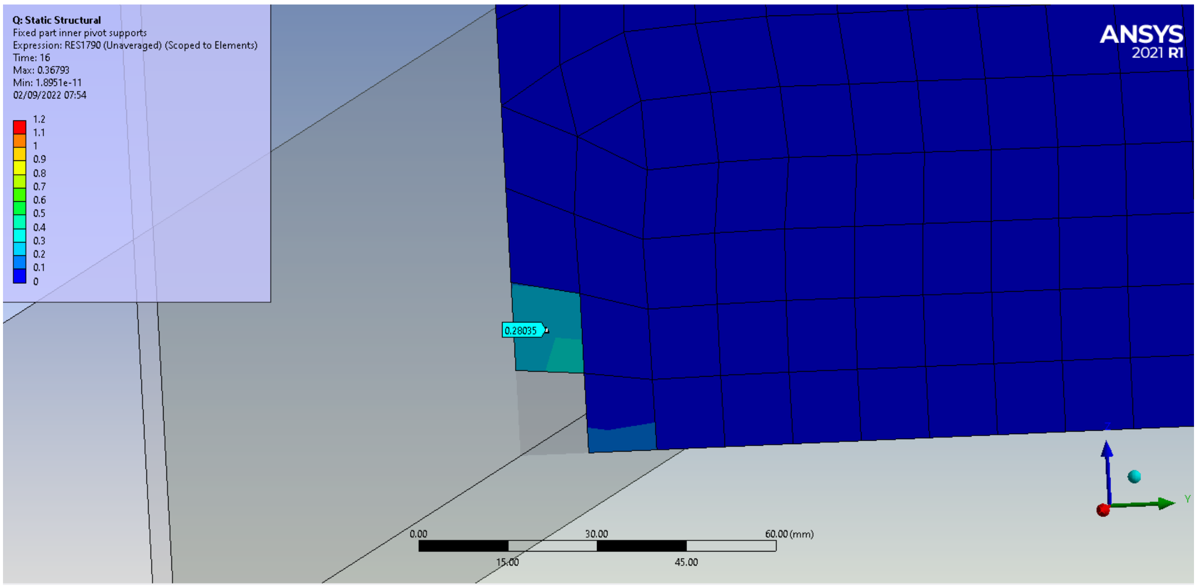

Figure F.10: High fatigue area 2.

F.6. Tumbler Side Plates

The fatigue check results for tumbler side plates are presented in Figures F.11 and F.12. In this case the fatigue damage is equal to $0.99 < 1$. Therefore, it is concluded that tumbler sideplates are sufficiently resistant to fatigue.

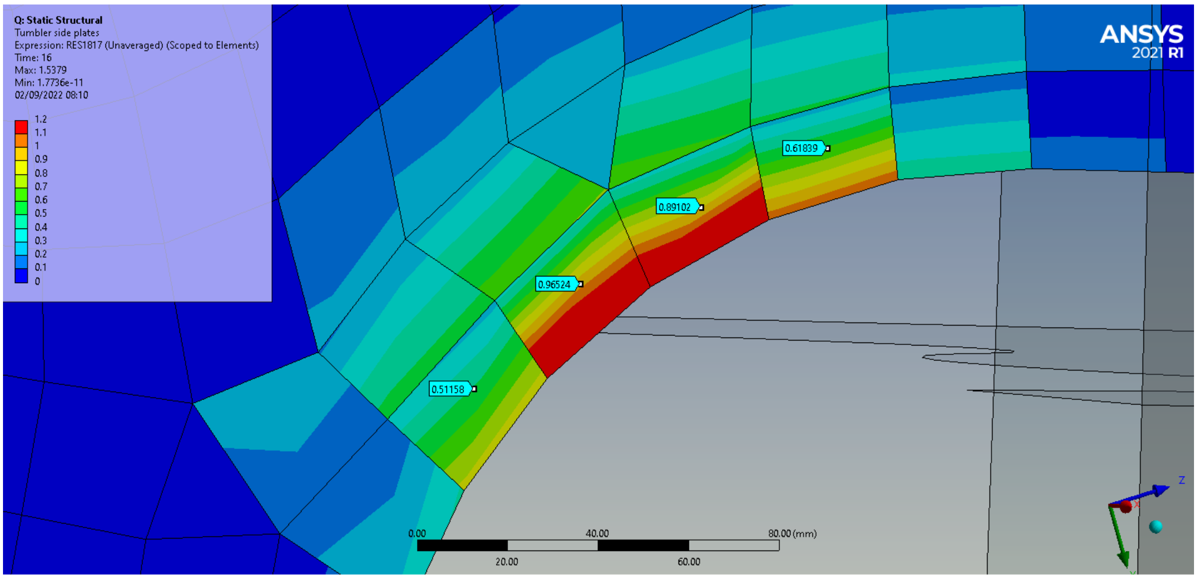

Figure F.11: High fatigue area 1.

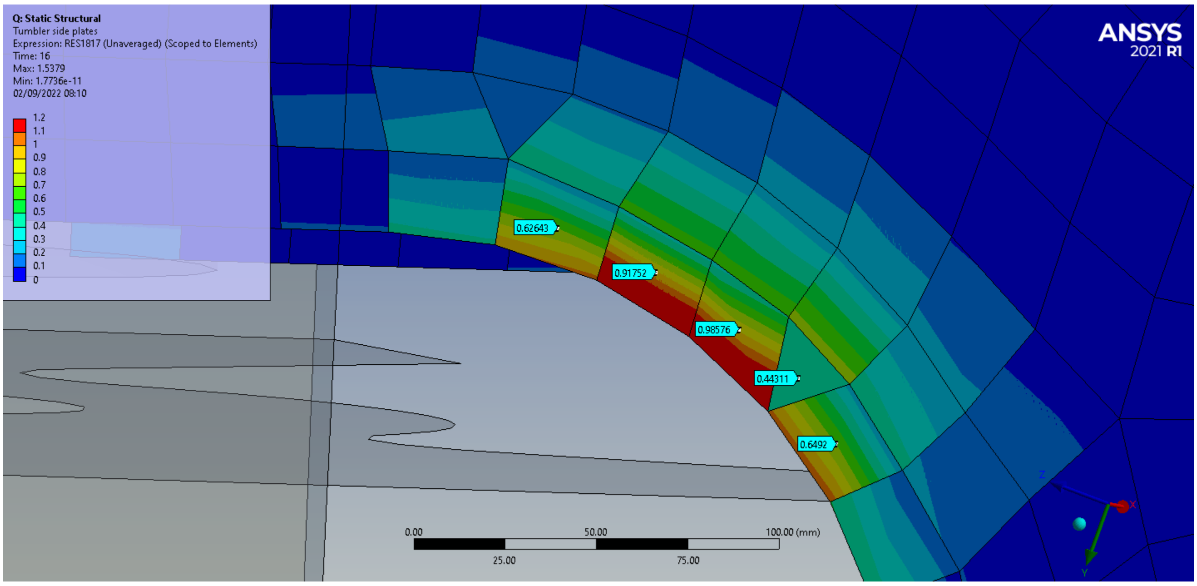

Figure F.12: High fatigue area 2.

F.7. A-Frame Head Middle Plate

The fatigue check results for the middle plate in the A-frame head are presented in the Figure F.13. The area in which fatigue occurs is not the part of the plate which is welded shut. It is accessible for inspection and its DFF should be equal to 1. Therefore, the maximal fatigue of $0.65 < 1.00$, which means that this part is sufficiently resistant to fatigue.

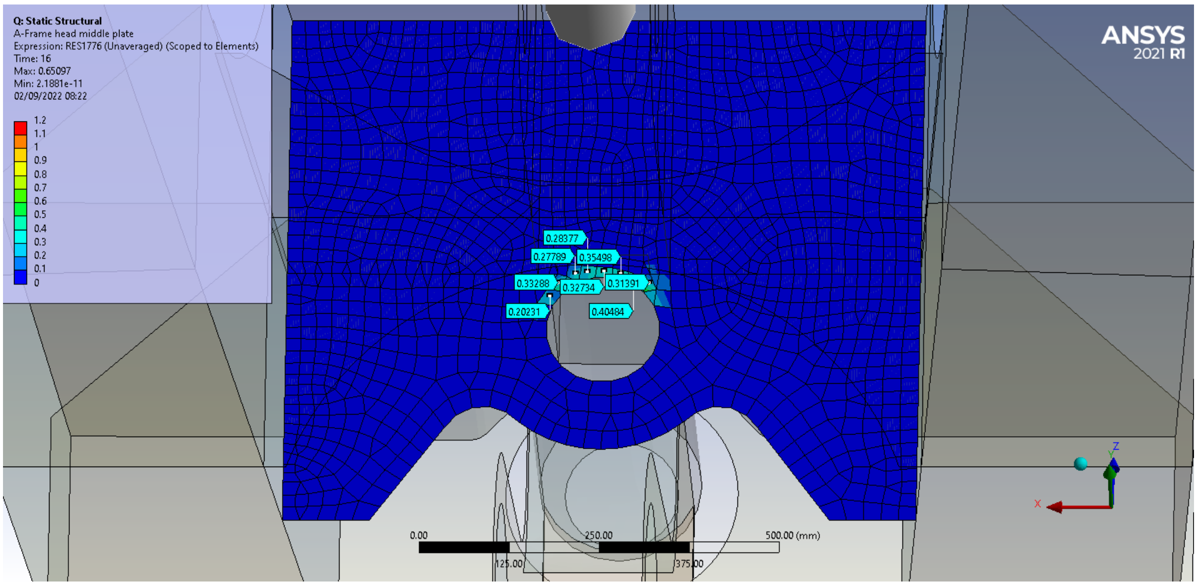

Figure F.13: High fatigue area.

G

Results of load calculations for the new design

Loads on sheaves				Outer sheave			Fixed part sheave		
				Load	422 kN		Load	443 kN	
LC	Angle	Trim	Heel	Fx [kN]	Fy [kN]	Fz [kN]	Fx [kN]	Fy [kN]	Fz [kN]
1	1	0	0	0	-7	-844	0	-8	-886
1	1	0	5	0	-44	-842	0	-8	-886
1	1	0	-5	0	29	-843	0	-8	-886
2	1	0	8	0	-62	-839	0	-8	-886
2	1	0	-8	0	48	-841	0	-8	-886
3	1	0	27	0	-197	-795	0	-8	-886
3	1	0	-27	0	184	-802	0	-8	-886
1	1	2	0	15	-7	-844	0	-8	-886
1	1	-2	0	-15	-7	-844	0	-8	-886
2	1	3	0	22	-7	-843	0	-8	-886
2	1	-3	0	-22	-7	-843	0	-8	-886
3	1	10	0	73	-7	-838	0	-8	-886
3	1	-10	0	-73	-7	-838	0	-8	-886
1	11	0	0	0	-81	-836	0	-85	-878
1	11	0	5	0	-116	-828	0	-85	-878
1	11	0	-5	0	-44	-842	0	-85	-878
2	11	0	8	0	-134	-822	0	-85	-878
2	11	0	-8	0	-26	-843	0	-85	-878
3	11	0	27	0	-259	-755	0	-85	-878
3	11	0	-27	0	116	-828	0	-85	-878
1	11	2	0	15	-81	-836	0	-85	-878
1	11	-2	0	-15	-81	-836	0	-85	-878
2	11	3	0	22	-81	-836	0	-85	-878
2	11	-3	0	-22	-81	-836	0	-85	-878
3	11	10	0	73	-81	-830	0	-85	-878
3	11	-10	0	-73	-81	-830	0	-85	-878
1	22	0	0	0	-158	-813	0	-166	-854
1	22	0	5	0	-192	-798	0	-166	-854
1	22	0	-5	0	-123	-826	0	-166	-854
2	22	0	8	0	-208	-789	0	-166	-854
2	22	0	-8	0	-106	-831	0	-166	-854
3	22	0	27	0	-318	-699	0	-166	-854
3	22	0	-27	0	36	-842	0	-166	-854
1	22	2	0	15	-158	-813	0	-166	-854
1	22	-2	0	-15	-158	-813	0	-166	-854
2	22	3	0	22	-158	-813	0	-166	-854
2	22	-3	0	-22	-158	-813	0	-166	-854
3	22	10	0	73	-158	-807	0	-166	-854
3	22	-10	0	-73	-158	-807	0	-166	-854
1	33	0	0	0	-230	-776	0	-241	-815
1	33	0	5	0	-260	-755	0	-241	-815
1	33	0	-5	0	-198	-795	0	-241	-815
2	33	0	8	0	-274	-743	0	-241	-815
2	33	0	-8	0	-182	-803	0	-241	-815
3	33	0	27	0	-365	-634	0	-241	-815
3	33	0	-27	0	-45	-842	0	-241	-815
1	33	2	0	15	-230	-776	0	-241	-815

Loads on sheaves				Outer sheave			Fixed part sheave		
				Load	422 kN		Load	443 kN	
LC	Angle	Trim	Heel	Fx [kN]	Fy [kN]	Fz [kN]	Fx [kN]	Fy [kN]	Fz [kN]
1	33	-2	0	-15	-230	-776	0	-241	-815
2	33	3	0	22	-230	-775	0	-241	-815
2	33	-3	0	-22	-230	-775	0	-241	-815
3	33	10	0	73	-230	-770	0	-241	-815
3	33	-10	0	-73	-230	-770	0	-241	-815
1	43	0	0	0	-288	-731	1	-302	-767
1	43	0	5	0	-314	-704	2	-302	-767
1	43	0	-5	0	-260	-755	3	-302	-767
2	43	0	8	0	-326	-690	4	-302	-767
2	43	0	-8	0	-245	-766	5	-302	-767
3	43	0	27	0	-396	-567	6	-302	-767
3	43	0	-27	0	-117	-827	7	-302	-767
1	43	2	0	15	-288	-730	8	-302	-767
1	43	-2	0	-15	-288	-730	9	-302	-767
2	43	3	0	22	-288	-730	10	-302	-767
2	43	-3	0	-22	-288	-730	11	-302	-767
3	43	10	0	73	-288	-724	12	-302	-767
3	43	-10	0	-73	-288	-724	13	-302	-767
1	52	0	0	0	-333	-682	14	-349	-716
1	52	0	5	0	-354	-652	15	-349	-716
1	52	0	-5	0	-309	-710	16	-349	-716
2	52	0	8	0	-364	-636	17	-349	-716
2	52	0	-8	0	-296	-723	18	-349	-716
3	52	0	27	0	-414	-503	19	-349	-716
3	52	0	-27	0	-179	-804	20	-349	-716
1	52	2	0	15	-333	-682	21	-349	-716
1	52	-2	0	-15	-333	-682	22	-349	-716
2	52	3	0	22	-333	-681	23	-349	-716
2	52	-3	0	-22	-333	-681	24	-349	-716
3	52	10	0	73	-333	-676	25	-349	-716
3	52	-10	0	-73	-333	-676	26	-349	-716
1	61	0	0	0	-369	-627	27	-387	-658
1	61	0	5	0	-386	-594	28	-387	-658
1	61	0	-5	0	-350	-658	29	-387	-658
2	61	0	8	0	-393	-577	30	-387	-658
2	61	0	-8	0	-339	-673	31	-387	-658
3	61	0	27	0	-422	-437	32	-387	-658
3	61	0	-27	0	-237	-771	33	-387	-658
1	61	2	0	15	-369	-626	34	-387	-658
1	61	-2	0	-15	-369	-626	35	-387	-658
2	61	3	0	22	-369	-626	36	-387	-658
2	61	-3	0	-22	-369	-626	37	-387	-658
3	61	10	0	73	-369	-620	38	-387	-658
3	61	-10	0	-73	-369	-620	39	-387	-658
1	70	0	0	0	-397	-566	40	-416	-595
1	70	0	5	0	-408	-531	41	-416	-595
1	70	0	-5	0	-382	-600	42	-416	-595

Loads on sheaves				Outer sheave			Fixed part sheave		
				Load	422	kN	Load	443	kN
LC	Angle	Trim	Heel	Fx [kN]	Fy [kN]	Fz [kN]	Fx [kN]	Fy [kN]	Fz [kN]
2	70	0	8	0	-412	-513	43	-416	-595
2	70	0	-8	0	-374	-617	44	-416	-595
3	70	0	27	0	-419	-371	45	-416	-595
3	70	0	-27	0	-288	-730	46	-416	-595
1	70	2	0	15	-397	-566	47	-416	-595
1	70	-2	0	-15	-397	-566	48	-416	-595
2	70	3	0	22	-397	-566	49	-416	-595
2	70	-3	0	-22	-397	-566	50	-416	-595
3	70	10	0	73	-397	-560	51	-416	-595
3	70	-10	0	-73	-397	-560	52	-416	-595

Accelerations

LC	x [m/s^2]	y [m/s^2]	z [m/s^2]
1	0,00	0,85	-9,77
1	0,34	0,00	-9,80
1	0,00	0,00	-9,81
2	0,00	1,28	-9,73
2	0,51	0,00	-9,80
2	0,00	0,00	-9,81
3a	0,00	4,44	-8,75
3a	1,69	0,00	-9,66
3a	0,00	4,44	-8,75
3b	1,10	0,00	0,00
3b	0,00	3,28	0,00
3b	0,00	0,00	4,87
3b	0,00	0,00	3,16
3b	0,00	0,00	4,52

Wind loads	q[Pa/m^2]	q[Pa/m^2]
Height	0	8,2
Working wind	343	372
Out of service wind	1142	1241

Bibliography

Abry, J., Mittelhaeuser, C., Wolf, S., & Turlier, D. (2018). Enhanced fatigue structural stress analysis of a heavy vehicle seam welded steel chassis frame: FEA model preparation, weld model description, fatigue stress calculation and correlation with 10 year operating experience. *Procedia Engineering*, *213*, 539–548. https://doi.org/10.1016/j.proeng.2018.02.050

Alencar, G., de Jesus, A., da Silva, J. G. S., & Calçada, R. (2021). A finite element post-processor for fatigue assessment of welded structures based on the master s-n curve method. *International Journal of Fatigue*, *153*, 106482. https://doi.org/10.1016/j.ijfatigue.2021.106482

Alhajahmad, A., & Mittelstedt, C. (2021). Minimum weight design of curvilinearly grid-stiffened variable-stiffness composite fuselage panels considering buckling and manufacturing constraints. *Thin-Walled Structures*, *161*, 107526. https://doi.org/10.1016/j.tws.2021.107526

Ansys Inc. (2020). https://courses.ansys.com/index.php/courses/modeling-the-bolt-and-preload/

Ansys Inc. (2022a). https://www.ansys.com/products/structures/ansys-mechanical#tab1-2

Ansys Inc. (2022b). https://www.ansys.com/products/3d-design/ansys-spaceclaim#tab1-2

Asimow, M. (1962). *Introduction to design*. Englewood Cliffs, NJ, Prentice-Hall.

Badke-Schaub, P., & Voute, E. (2018). DESIGN METHODOLOGY: WHERE DO YOU GO? *Proceedings of the DESIGN 2018 15th International Design Conference*. https://doi.org/10.21278/idc.2018.0550

Bernd, R., Alexander, T., & Frank, R. (2007). Integrated finite element analysis (fea) in three-dimensional computer aided design programs (cad)-overview and comparison. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Bureau Veritas. (2014). Bv 595 offshore handling systems.

Bureau Veritas. (2017). Bv 526 rules for the certification of lifting appliances onboard ship and offshore units.

Bureau Veritas. (2018). Bv ni 615 buckling assessment of plated structures.

Bureau Veritas. (2019). Bv 455 rules for classification of offshore units.

Clark, K., Fujimoto, T., & Fujimoto, P. (1991). *Product development performance: Strategy, organization, and management in the world auto industry*. Harvard Business School Press.

De Norske Veritas. (2010a). Dnv-rp-c201 buckling strength of plated structures.

De Norske Veritas. (2010b). Dnv-rp-c203 fatigue design of offshore steel structures.

De Norske Veritas. (2011). Dnv-os-c201 structural design of offshore units (wsd method).

De Norske Veritas. (2019). Dnv-os-c101 structural design of offshore units (lfrd method).

De Norske Veritas. (2020). Dnv-st-n001 marine operations and marine warranty.

De Norske Veritas. (2021). Dnv-st-n001 marine operations and marine warranty.

Duffy, A., & Ferns, A. (1998). An analysis of design reuse benefits.

Duffy, A. H., & Duffy, S. M. (1996). Learning for design reuse. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *10*(2), 139–142. https://doi.org/10.1017/S0890060400001396

Ehrlenspiel, K. (2009). *Integrierte produktentwicklung*. Carl Hanser Verlag GmbH & Co. KG.

Fuh, J., & Li, W. (2005). Advances in collaborative CAD: The-state-of-the art. *Computer-Aided Design*, *37*(5), 571–581. https://doi.org/10.1016/j.cad.2004.08.005

Gericke, K., & Blessing, L. (2011). Comparisons of design methodologies and process models across disciplines: A literature review. *ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design*, *1*, 393–404.

José Legaz, M. (2015). Computer aided ship design: A brief overview. *Bol. Soc. Esp. Mat. Apl. SeMA*, *72*(1), 47–59.

Kannengiesser, U., & Gero, J. S. (2017). Can pahl and beitz' systematic approach be a predictive model of designing? *Design Science*, *3*. https://doi.org/10.1017/dsj.2017.24

Konda, S., Monarch, I., Sargent, P., & Subrahmanian, E. (1992). Shared memory in design: A unifying theme for research and practice. *Research in Engineering Design*, *4*(1), 23–42. https://doi.org/10.1007/bf02032390

Meerkamm, H. (1994). Integrierte produktentwicklung im spannungsfeld von kosten-, zeit-und qualitatsmanagement. *VDI Berichte-Verein Deutscher Ingenieure*, (1136), 1–14.

Olsson, F. (1985). Integrerad produktutveckling–arbetsmodel. *Series 21 Produktutveckling. Sveriges*.

Olsson, K. (1976). *Systematisk konstruktion: En studie med syfte att systematisera innehåll och metoder i samband med produktkonstruktion*. Institutionen för Maskinkonstruktion.

Oxman, R. (1990). Prior knowledge in design: A dynamic knowledge-based model of design and creativity. *Design Studies*, *11*(1), 17–28. https://doi.org/10.1016/0142-694x(90)90011-z

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). *Engineering design*. Springer London. https://doi.org/10.1007/978-1-84628-319-2

Rexroth. (Retrieved 2022). Luffing cylinders catalogue.

Roozenburg, N., & Cross, N. (1991). Models of the design process: Integrating across the disciplines. *Design Studies*, *12*(4), 215–220. https://doi.org/10.1016/0142-694x(91)90034-t

SDC Verifier. (2022). https://sdcverifier.com

Shojaei, A. K., & Wedgewood, A. R. (2017). An anisotropic cyclic plasticity, creep and fatigue predictive tool for unfilled polymers. *Mechanics of Materials*, *106*, 20–34. https://doi.org/10.1016/j.mechmat.2017.01.003

Sivaloganathan, S., & Shahin, T. M. M. (1999). Design reuse: An overview. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *213*(7), 641–654. https://doi.org/10.1243/0954405991517092

Smith, J. S., & Duffy, A. H. B. (2001). Product structuring for design re-use. *Design for configuration* (pp. 83–100). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-56905-0_8

THN. (Retrieved 2022). Plain bearings catalogue.

Vajna, S. (Ed.). (2020). *Integrated design engineering*. Springer International Publishing. https://doi.org/10.1007/978-3-030-19357-7

VDI. (1987). *Vdi 2221: Systematic approach to the design of technical systems and products*. Verein Deutscher Ingenieure.

VDI. (1993). *Vdi 2221: Systematic approach to the design of technical systems and products*. Beuth Verlag.

Veeke, H. P., Ottjes, J. A., & Lodewijks, G. (2008). *The delft systems approach: Analysis and design of industrial systems*. Springer Science & Business Media.

Wasserman, S. (Retrieved October 2022). *Comparison charts for structural fea simulation software*. ENGINEERING.com.