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Study and Sizing of Components for Lifting Offshore Structures

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Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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ABSTRACT

The paper focuses on the design, testing, and optimization of a pad-eye for lifting sections of an offshore rig. A pad-eye, as a crucial part in the offshore lifting operations and essential component to be considered for simulating with a realistic loading condition using Finite Element Method (FEM), was researched using Creo PTC software. The study started with the development of a preliminary model following industry codes specifically API RP 2A-WSD then analyzed using detailed FEM analysis in term stress distribution, displacement and performance of structure.

The FEM first results showed that the design was critically flawed, reaching Von Mises stress corresponding to material yield strength and displacements which were so high it indicated structural instability in lifting. The design was suggested to be improved in many ways like increasing the plate thickness, which is heavier than necessary instead of alternatives such as optimizing geometry and reducing stress concentrations by use better alternatives material from S355 (that these plates are made of) to higher grade steel called S460.

During the entire study, numerical calculations were conducted to confirm FEM results and follow theoretical data as well throughout simulation data. After the FEM analysis, a second design was used which shows that safety criteria and required performance for lifting to rigs in offshore are satisfied with significant stress & displacement reductions. The paper is completed with suggestions for further enhancements using improved fatigue and dynamic load simulation of the pad-eye in adverse marine environment.

Contents

LIST OF FIGURES

LIST OF TABLES

Chapter 1. Introduction

In this chapter general information about commonness, design criteria, and working principles of lifting equipment in offshore operations is examined. It mainly concerns design and utilization of pad-eyes, which are important units in lifting heavy pieces under extreme marine surroundings. Specifically, we talk about the daunting problem of designing pad-eyes for use in extreme service conditions including dynamic loads combined with corrosion and fatigue.

Furthermore, the processes which provide standards and guidelines have also been evaluated with respect to principles including those governing offshore lifting equipment design code such as API RP 2A-WSD. Such standards make sure that the pad-eyes comply with strict safety regulations for lifting equipment, accounting for both static and dynamic loads normally encountered in installations on offshore rigs.

The chapter also develops given to construction materials frequently deployed in pad-eyes and includes S355 and S460 structural steel grade analysis which is directed towards their mechanical properties and ability to withstand severe stresses in offshore conditions. The mention of the contribution of the Finite Element Method (FEM) in the analysis and optimization of the pad-eye designs is made and a snippet of what FEM is, and its significance in the field of engineering is given.

Finally, the chapter presents an overview of FEM features and its applications including Creo PTC that this research utilized to simulate the performance of the pad-eye under actual working conditions. The importance of numerical analysis and FEM simulation in validating design choices and improving structural integrity is emphasized.

1.1 Offshore Lifting Equipment

In the oil and gas sector, offshore lifting operations are some of the most critical processes enabling safe transport, position and assembly on offshore platforms large structural elements such as modules, pipelines and other heavy equipment. These operations require precision and strength to shift large volumes in highly dynamic and harsh marine environments. Offshore lifting equipment refers to a wide assortment of gear used in offshore operations such as cranes, slings and rigging hardware (shackles pad-eyes and other lift gear) that aids with the safe handling of loads. This equipment has to function in extreme environments with high wind speeds, saline seawater, wave actions and shifting loads, and is built for reliability purposes only as the safety is concerned.

Considering offshore lifting activities are high-risk operations, there are stringent safety standards and regulatory guidelines that govern the design and engineering of lifting equipment. For example, API (American Petroleum Institute) and DNV (Det Norske Veritas) have some standards that specify the limits for load rating, material properties and operational limit to reduce failure probability during operation. Everything from the biggest crane to the smallest pad-eye has a hefty design requirement to withstand insane amounts of stress without fail. Design Accuracy in Offshore Lifting — Justas the set offshore lifting standards are a manual for ensuring safe and efficient operations, any deviation from these guidelines may result in accidents, operating downtimes & even catastrophic losses.

Among these, the pad-eye is one of the basic equipment that must exist as a connection between the load and the lift. Designed to withstand significant tensile and shear forces, the pad-eye is most often a flat or slightly curved steel plate with a hole. This is an especially significant proposition when it comes to designing the vessel, as it will endure and must withstand repeated stresses in corrosive environments such as sea. The pad-eye also needs to be sufficiently strong for not only the static weight of the load, but for dynamic forces created during wave motion, wind action (when hoisting and lowering), as well as from the acceleration and deceleration imposed by the lifting operation itself. These are overtopping the normal expected stresses, which most times cannot be predicted, that require a need for high resiliency in design.

The unfortunate consequence of mechanical failure in lifting equipment emphasizes the importance of careful pad-eye design. In offshore contexts, it has a keen influence on safety equipment failure severely far-reaching its impact in the world of finance and environment-related problems. If a pad-eye is poorly rated, or designed/deployed wrongfully, it may not be able to take on operational loads and can suffer catastrophic failure in the form of sudden fracture (or plastic deformation) at lift. These failures could lead to a dropped load, risking life, property and production. If there is an equipment failure related to hazardous materials, such as an oil or gas module, the risk of environmental hazards will also be increased since spills or leaks can occur.

Offshore lifting equipment is made with great accuracy, durability and pursuant to industry standards including pad-eyes. Introduction The solid engineering of lifting accessories like pad-eyes is a fundamental need to ensure the safety of life, environment protection and continuous functionality of offshore platforms.

1.1.1 Offshore and Onshore Lifting Equipment Differences

The requirements of the design and operation of the lifting equipment are considerably different from onshore lifting equipment due to the extreme environmental conditions in marine settings. While the onshore lifting equipment is usually subjected to static loads, the offshore pad-eyes are designed to bear the dynamic loads imposed through wave action and wind, or vessel/platform motions, and there are considerably lesser concerns about the impact of environmental forces.

The main differences include:

- **Dynamic Loads:** Offshore equipment must be designed to handle both static and dynamic loads, while onshore lifting equipment generally faces static or gradually changing loads (API, 2020).
- **Corrosion and Material Selection:** Offshore environments are highly corrosive due to constant exposure to seawater, which necessitates the use of corrosion-resistant materials or coatings.
- **Higher Safety Factors:** Safety for offshore equipment is controlled more tightly, for example API RP 2A-WSD by Lloyd's Register in 2018, because marine operations are considered riskier.

These additional factors must be accounted for when one designs the lifting components, such as pad-eyes, for offshore use to ensure strength and safety will last.

1.1.2 Design Criteria for Offshore Pad-Eyes

When designing pad-eyes for offshore use, these must be manufactured to very exact criteria in order that they can surely withstand the tough and dynamic conditions that are given when lifting units typical with offshore environments. Offshore pad-eyes support static and dynamic loads of heavy items, and they are influenced by environmental forces such as wave action, wind, and to a limited extent even changing marine currents. Thus, pad-eye designs need to be manufactured in accordance with the relevant international codes and standards such as API RP 2A-WSD which outlines guidelines for offshore lifting equipment used in highly stochastic environments. They provide a significant portion of the mechanical reliability of pad-eyes so as to mitigate many risks associated with overworked and misused equipment, and ultimately ensure that this equipment remains operable for years to come.

Pad-eyes must meet the high demands of offshore applications, and several design criteria need to be carefully considered:

- **Loading Capacity:** The foremost design requirement of the pad-eyes is load-carrying capacity that includes the weight of the object to be lifted, as well as extra forces from the environment putting lateral, axial, or torsional loads on the pad-eye. Static loads (the weight of the load itself) and dynamic loads from the motion induced by waves, wind gusts as well any movement of a vessel or platform all have to be supported by offshore pad-eyes. In the case of dynamic loads, which may have changing rapid stresses on pad-eyes, this means that they need to be able to withstand peak loads while not yielding. In this case, advance analysis and calculation are applied to understand distribution of loads and ensure that pad-eye will not undergo permanent deformation or experience any kind of failure under maximum expected loads in offshore applications.

- **Material Selection:** Offshore pad-eyes must be made from materials that are highly resistant to corrosion because they will always be exposed to seawater, humidity and salt-laden air. The most common material for containers is S355 or S460 steel which are both high strengths, ensuring the dimensional strength of wall sections and lower weight, as well as very good corrosion resistance properties. Offshore grade steels usually have alloying elements such as chromium, nickel and molybdenum for better corrosion resistance and toughness. Such materials are described by the European Committee for Standardization (2004) in terms of requirements involving environmental resistance and mechanical stress resistance, providing longevity and reliability when placed in marine conditions. It matters because the material will corrode and lose some capacity over time, increasing failure risk at load.

- **Uniform Stress Distribution:** When the pad-eye is designed well, it will ensure uniform distribution of stresses in the whole component. Stress concentration, which are most likely found near sharp edges or at locations of attachment to other parts as they become localized area of high stress that will cause cracking easily or sudden failure Engineers often use finite element analysis (FEA) to find and reduce stress concentrations to help mitigate this. Even stress distribution can be accomplished through design modifications like rounded edges, fillets or strategic hole placement that helps eliminate the possibility of a stress-induced failure.

- **Fatigue Resistance:** Pad-eyes used in offshore lifting equipment are often subjected to cyclic loading during repetitive lifting operations and due to environmental forces. The different types of forces can lead to cyclic loading, that can fatigue material where the microscopic cracks develop and run later leading to failure. It must be integrated into the design of pad-eyes, and indeed the material and geometry of a pad-eye must also reflect fatigue-tailored parameters. A fatigue analysis step is frequently used when performing pad-eye checks, for instance and many offshore design codes recommend the use of FEA to model the pad-eye under repeated loads over a long time. This allows pad-eyes to hold structural integrity under consistent, larger loading in the worst of circumstances.

- **FOS (Factor of Safety):** Factor of safety plays an important role while undertaking design for offshore pad-eyes as they usually require a higher factor than onshore applications due to offshore conditions. The FOS values are generally in the range of 3–5 for offshore lifting, and they depend on operational and environmental conditions. The FOS is higher because loading conditions in offshore environments can be uncertain and extreme, and the consequence of equipment failure (such as a heavy lift going wrong) needs to be avoided. Such safety factors per API (2020) assure that even in the worst possible scenario, such equipment will operate safely without endangering personnel or structural integrity. Offshore pad-eye design requires a high FOS due to uncertainty in all the relevant loads (mean, extreme, and rare) as well as uncertainties in material properties that are susceptible to environmental influences which may not occur exactly as modeled.

All these design criteria are essential for a proven, reliable pad-eye that works safely in offshore environments. In addition to load bearing, engineering entails environmental durability, optimizing stress flow, and long-term resistance to fatigue and corrosion. If these factors are considered carefully at the design stage, then premature failure is eliminated, and costs of maintenance can also be reduced along with accidents that may arise during lifting operations and thus improving the service life of all types of lifting equipment.

1.1.3 Material Selection

Material selection for lifting equipment offshore is one of the most important features of design which determines their overall performance and lifetime. The materials should be strong enough to bear all the applied loads, yet resistant to the corrosive action of seawater. Pad-eyes that are produced to be used in an offshore environment are mostly made by two materials: S355 and S460 structural steel, which are high-yielding and durable under harsh weather conditions.

COMPONENTS	MATERIALS
Lifting frame (pad-eye)	S355 J2+N
Pin	30CrNiMo8
Portion of Lattice Section	S460ML

Table 1 - Materials

- **S355 Steel:** It is a high-strength structural steel that has 355MPa minimum yield strength and shows good ductility. It is widely used for applications related to offshore structural purposes. On the other hand, this material is more sensitive to corrosion and requires extra protection with coatings or cathodic protection in highly corrosive environmental systems.

- **S460 Steel:** This steel shows a higher yield strength at 460 MPa compared to S355. That is why it is always preferred in those areas where higher load-carrying capacity is required. Its mechanical properties have been improved to make it more suitable for heavy-duty lifting operations in offshore environments. Besides those, standard practices continue to exist in prolonging the life of pad-eyes used in offshore applications, such as corrosion-resistant coatings along with cathodic protection techniques.

- **30CrNiMo8 Steel** – This steek has high-strength alloy steel known for its improved tensile strength and toughness, minimum yield strength found in range of 850-1050 Mpa depending upon heat-treatment conditions. Its applications include high resilience against dynamic loadings in critical components like shafts and heavy-duty bolts, and, more importantly, pad-eyes in lifting machinery. The high wear resistance and tensile strength, as well as good ductility, comes from the alloying elements such as chromium, nickel, and molybdenum. These make the material ideal for handling extreme stresses in offshore lifting, where reliability is paramount.

  In addition to its mechanical robustness, 30CrNiMo8 is moderately resistant to corrosion; in the aggressive, corrosive environments typical of offshore work, surface coatings or cathodic protection is often recommended to extend its operational life. These enhance the material against long exposure to seawater and humid air, factors that promote corrosion fatigue. As with S460, regular maintenance and protective strategies are vital to maximizing component life and performance in offshore structures made from 30CrNiMo8 steel.

Below the main data has been reported according to the BS EN 10025-2, BS 10025-4 and BS EN 10083-3 standards.

- Minimum Yield Strength in function of nominal thickness:

Designation	**Min. Yield Strength [MPa] Nominal Thickness [mm]**							
	≤ 16	>16 ≤ 40	>40 ≤ 63	>63 ≤ 80	>80 ≤ 100	>100 ≤ 150	>150 ≤ 200	>200 ≤ 250
S355 J2+N EN 10025-2	355	345	335	325	315	295	285	275

Table 2 - Yield Strength of S355 J2+N

Designation	Min. Yield Strength [MPa] Nominal Thickness [mm]				
	≤ 16	>16 ≤ 40	>40 ≤ 100	>100 ≤ 160	>160 ≤ 250
30CrNiMo8 EN 10083-3	1050	1050	900	800	700

Table 3 - Yield Strength of 30CrNiMo8

Designation	Min. Yield Strength [MPa] Nominal Thickness [mm]				
	≤ 16	>16 ≤ 40	>40 ≤ 63	>63 ≤ 80	>80 ≤ 100
3460ML EN 10025-4	460	440	430	410	400

Table 4 - Yield Strength of S460

- Minimum Tensile Strength in function of nominal thickness:

Designation	Min. Tensile Strength [MPa] Nominal Thickness [mm]			
	<3	≥3 ≤ 100	>100 ≤ 150	>150 ≤ 250
S355 J2+N EN 10025-2	510	470	450	450

Table 5 - Tensile Strength of S355 J2+N

Designation	Min. Tensile Strength [MPa] Nominal Thickness [mm]				
	≤ 16	>16 ≤ 40	>40 ≤ 100	>100 ≤ 160	>160 ≤ 250
30CrNiMo8 EN 10083-3	1250	1250	1100	1000	900

Table 6 - Tensile Strength of 30CrNiMo8

Designation	Min. Tensile Strength [MPa] Nominal Thickness [mm]				
	≤ 16	>16 ≤ 40	>40 ≤ 63	>63 ≤ 80	>80 ≤ 100
S460ML EN 10025-4	540	530	510	500	490

Table 7 - Tensile Strength of S460ML

In addition, for the analysis the Poisson ratio used is 0.27, the Young Module 206845 MPa and the density 7.85*10-9 ton/mm3

1.1.4 Types of Pad-Eyes

Pad-eyes are utilized in offshore lifting and may be arranged in many ways. The two most common pad-eye types are top-mounted and side-mounted pad-eyes. Both have their planned applications and load-bearing properties.

Top-Mounted Pad-Eyes: This type of pad-eyes is typically installed flush with the top surface of a structure and lift loads vertically. Typically, if the load is vertical the top-mounted pad-eye is frequently used to reduce bending forces on the structure.

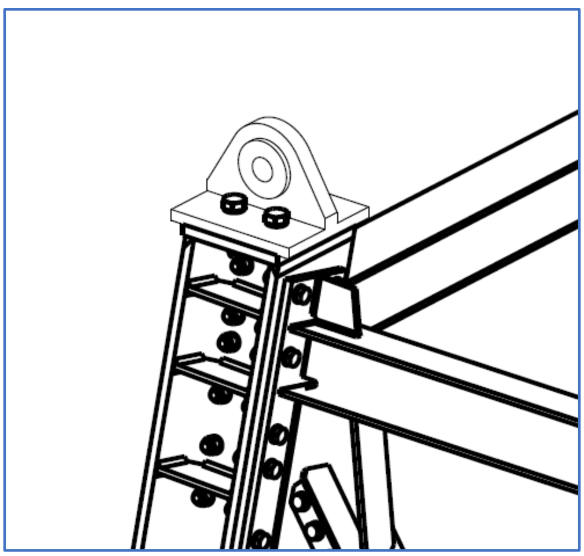

Figure 1 - Top-Mounted Pad-Eye

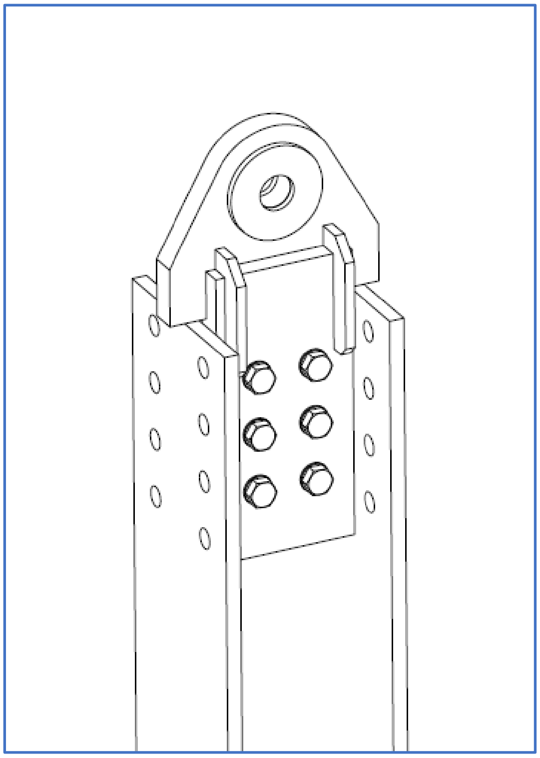

Figure 2 - Top-Mounted Pad-Eye

Side-Mounted Pad-Eyes: These pad-eyes are situated on the side of a structure and generally support horizontal or angled lifts. Designs for side-mounted pad-eyes should account for complex loading patterns that derive high bending and shear stresses.

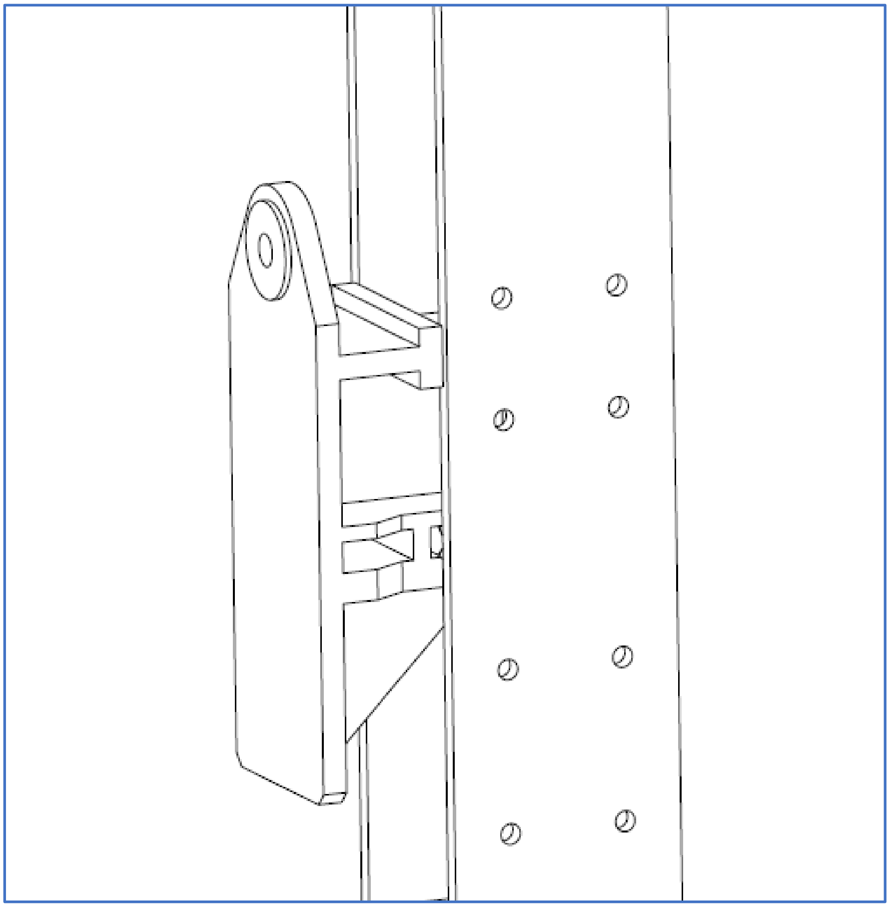

Figure 3 - Side-Mounted Pad-Eye

In this paper, pad-eyes were both top and side mounted in order to check their integrity for different loading scenarios. The top-mounted pad-eye was designed for a vertical load of 500 kN and proved satisfactory during FEM analysis since the resulting stresses were within the acceptance criteria. However, the pad-eye that was side mounted failed due to high stress concentration around the welds which exceeded the material yield strength. That is, design improvements are needed to decrease the stress level for better performance of the pad-eye under lateral loading.

1.2 Working scheme of Pad-Eyes in Offshore Lifting Operations

There are a lot of pad-eyes specifically designed for lifting operations in the offshore environment, but in principle, all the variations on the types of work under the same principle. A pad-eye is an important attachment point for shackles and slings in the lifting of heavy loads. In the offshore operations, pad-eyes are expected to resist both static and dynamic loads brought about by the harsh marine environment. They are normally welded or bolted to structural elements of the offshore platform.

At the start of a lift, a shackle or hook is connected to the pad-eye through which the load is transferred from the sling or cable to the platform structure. The load path moves from the shackle through the pad-eye to the lifting lug and on to the structural welded or bolted connection points. The design of the pad-eye should ensure that the stresses induced are uniformly distributed through the material without any localized area developing such high stress concentrations, which will bring about its failure.

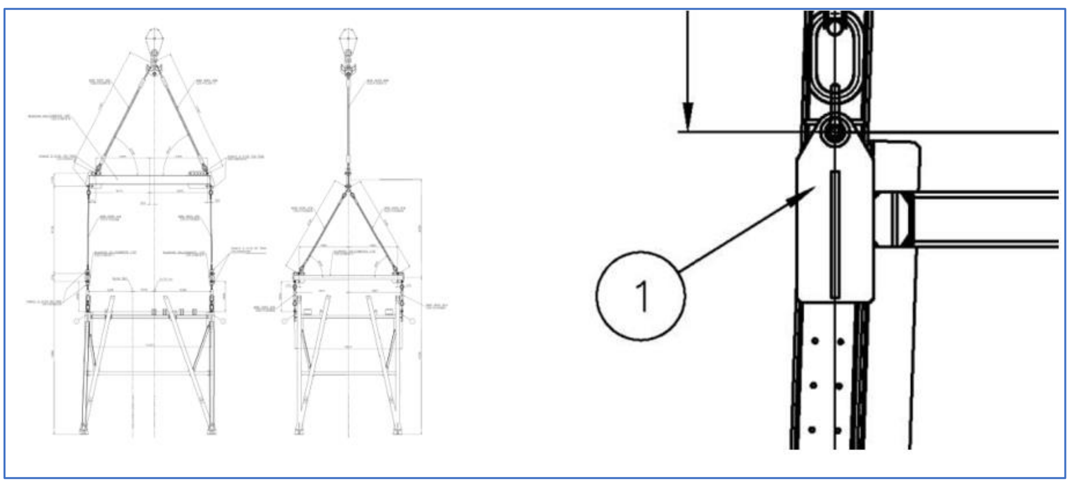

Figure 4 - Pad-Eye in Offshore Lifting Operation

It experiences either shear stress or tensile stress, or both, depending on the direction of the lifting force when the load is applied to the pad-eye. Material failure or yielding may occur depending on the Von Mises stress distribution within the pad-eye. The usual critical areas of interest are around the hole where the shackle attaches and the points where the pad-eye connects to the structure. (Detailed results of the analysis are mentioned in the Chapter 3)

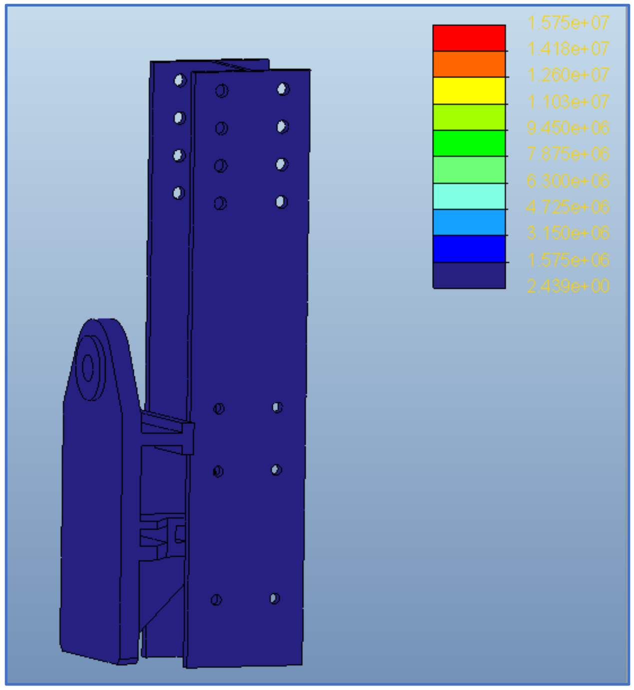

Figure 5 - Von-Mise's stress distribution on a pad-eye

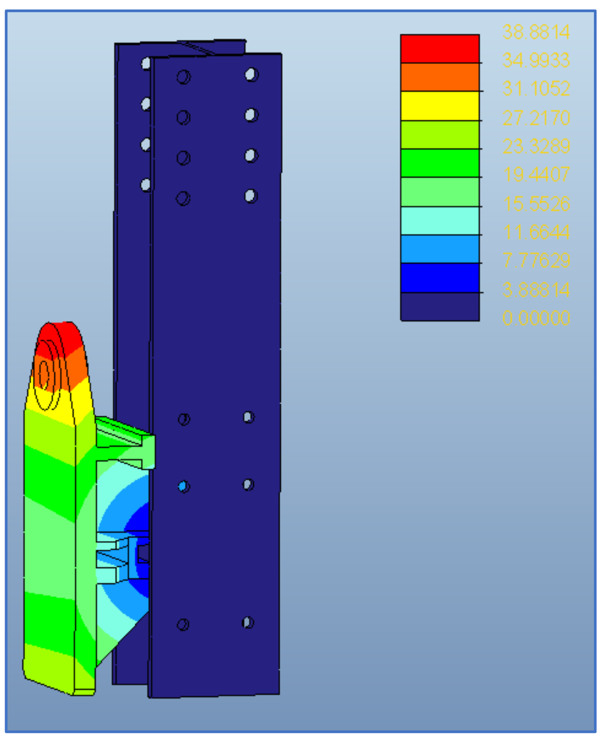

Figure 6 - Displacement magnitude of a pad-eye

Further, after the load is distributed through the pad-eye, the stress reaches the welds or bolts that fix the pad-eye to the structure. Proper welding techniques or bolting patterns are necessary so these connections will be able to bear the applied loads. In each and every case of failure that occurs at these points of connection, it always results in disastrous structural failure.

FEM analysis serves to simulate the performance of pad-eyes by describing the distribution of stresses that occur in such structures, hence their inability to withstand excessive load conditions. The following analysis will review the design of a pad-eye and its attachment points with respect to being adequate for both static (weight) and dynamic loads generated due to the movement of the platform, wave action, and wind forces. Further enhancements in results can be done by optimizing the design, which might involve increasing the pad-eye thickness or a geometrical change in shape, by analyzing the distribution of stresses in critical regions.

1.3 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a well-known numerical technique that is widely used to solve complex mechanical, thermal, fluid, and multi-physics problems in different areas of engineering. As we know FEA is one of the "divide and conquer approaches" to cut down the problem size of complex analysis by breaking the whole structure into smaller pieces (elements). FEA enables the engineers to simulate the behavior of components under different loading conditions with respect to basic principles of mechanics such as laws of force equilibrium, constitutive relations for material and geometric compatibility. FEA allows to analyze stress, deformation, and displacement within structures in detail that would otherwise be very difficult, if not impossible, so it is highly used nowadays for critical applications such as offshore engineering where safety and reliability are foremost.

FEA takes an object, say a pad-eye — which is one of the critical components during any offshore lifting operation — and breaks it down into very small, simple pieces (elements). All of these components are interconnected with nodes and at each node the governing equations, derived from continuum mechanics, are solved via numerical methods. The principal advantage of this discretization step is that it converts a complex, continuous system to a series of algebraic equations, easily solvable and manageable using matrix methods. This allows to investigate behaviors in one location of the structure where you might find stress concentrations around holes and sharp edges which are frequently present in pad-eye designs and loading may result in failure.

FEA is extensively implemented in offshore structures design and analysis, with static and dynamic testing of pad-eyes under lifting conditions a necessity. Pad-eye is analyzed using FEA in assembly conditions with the help of Creo PTC software. This is used to simulate real time loading condition by present study. The structural analysis gives an overview of the status of the pad-eye using important factors such as max stress, displacement, and deformation mode under different loading conditions. With Creo PTC, designers and engineers can simulate real-world conditions to determine if the pad-eye design passes specific safety or performance tests.

A core difficulty in the performance of a proper FEA is the choice of mesh density. How well the mesh captures the actual geometry of the pad-eye will greatly influence the accuracy of the analysis, especially in stress concentration regions like that of hole ingress for attachment to a lifting shackle. Although a finer mesh gives you closer results to reality, it also costs more computationally. Typically, this is achieved through mesh convergence studies to render the results independent of the mesh with acceptable accuracy without unnecessary computational expense. Three mesh sizes were used in this study to control the independence results of the mesh density, to guarantee that the simulation captures stress and displacement with no influence by coarseness or fineness of meshes.

During discretization—where the continuous structure of the pad-eye is divided into discrete elements, each solving for global stiffness independently and then assembling them together in a system of equations. It describes the pad-eye behavior under loads – and this allows FEA to obtain other important values (displacement, stress and strain) for each node. FEA converts the work of stress analysis in a continuous body into a matrix of algebraic equations that solve each variable (to reduce this task to a computational level). This is especially useful for showing areas where the largest stresses occur, allowing us to design around the same failure modes.

To perform meshing on the pad-eye, tetrahedral elements were selected in this study due to their versatility and suitability for highly irregular geometries such as the hole located at one end of the pad-eye where stress concentration is expected. Choosing the right type of element is critical to ensure that geometry is represented properly, which results in more accurate and reliable simulations. Given a good mesh and suitable element type, the predicted stress distribution is very accurate, allowing one to find hot spots where stress exceeds safety limits.

The FEA results served as a perfect baseline for pad-eye design optimization. Through preparation of separate reports for the pads that showed the highest stress and displacement, specific changes were made to those components which improved structural performance over their lifecycle. Through some design tweaks to address these issues, the FEA helped ensure performance from the pad-eye and prolonged its service life by minimizing the chance of fatigue and material failure. This highlights an important utility of FEA as a tool in the robust and reliable design process for offshore lifting equipment.

1.3.1 Evolution and History of FEA

The roots of Finite Element Analysis) FEA go back to the beginning of the previous centuries, in the middle of 20th century where engineers and mathematicians started to investigate into what we call matrix methods in structural analysis that has opened new horizons for the development of today`s FEA. These early ideas were driven by visionary figures, such as J. H. Argyris and R. W. Clough. US and Canadian pioneers in reliability estimation and modelling were also historically motivated by the need to solve complicated aeronautical problems where components such as wings or fuselage frames must have their load histories examined carefully to demonstrate adequate structural integrity. Initially, starting as early as 1950s, makeshift forms of FEA methods were used to investigate the stress-strain behaviors of aircraft structures allowing engineers to estimate how these components will behave when subjecting forces acting during flight. At this point started a new era in engineering analysis.

FEA as a field began to develop rapidly after the 1960s, when computer technology had developed. The rise in computing power has made it possible to do the massive matrix calculations that are characteristic of FEA. R. W. Clough popularized the term Finite Element Method (FEM) in 1960 and applied it to structural mechanics problems. It offered a means of decomposing complex structures into simpler, elementary components that could be analyzed in aggregate. Benefits of classical approach the earliest applications of FEA were done in two-dimensional analysis only because computers were not capable of processing 3D data. However, computer technology advanced rapidly and soon after in the late sixties and early seventies, FEA techniques were able to apply to three-dimensional analyses.

This development enabled engineers to analyze a wider variety of problems – including complex three-dimensional structures like offshore platforms, lifting gear and machine parts.

FEA became a revolutionary technology in all areas of engineering, and you could analyze stress, strain, heat transfer and dynamics with these advances. ANSYS and MSC Software were among the pioneering companies that created FEA toolsets, effectively dating these industries to a time when software was first able to simulate and optimize designs before building prototypes. Initially, the adoption of FEA occurred in high-end fields such as aerospace and automotive engineering where performance and structural integrity were critical, but gradually other fields experienced its applicability including offshore engineering and marine structures with more complex loading scenarios & harsh environmental conditions that required accurate analysis. This thermodynamic capability to mimic the response of components such as pad-eyes when subjected to high loads and cyclic loading has been critical in facilitating safety and reliability within these harsh applications.

With the continuous advancements of computing technology, FEA was more approachable and more precise as well. Over the decades, FEA has developed from a rather specialized method into one of the standard tools in many engineering fields due to improvements in numerical methods, mesh generation techniques and material modeling. More recent FEA software enables better high-fidelity analyses of a 3D structure, explicitly capturing complicated geometry and covering the actual material properties in combination with nonlinear features, cross-physics responses (thermal, fluid and structural). This has enabled a new paradigm of design engineering where the designs can be iteratively simulated, varying parameters in order to achieve target performance and safety levels while minimizing material use and weight.

In modern-day design, finite element analysis (FEA) is an essential tool for the designing and optimizing complex components, such as pad-eyes used in offshore lifting. FEA provides engineers with crucial insights into the behaviors of pad-eyes, from stress distribution and displacement to fatigue resistance—all by simulating different load stresses and other environmental factors. This allows for tailored designs that may improve the safety, longevity, and reliability of such components in high-risk applications. From the original development of FEA to state-of-the-art tools today for fast engineering evaluation with large measure grounding in academic rigor, design pathfinders and performance validators are within reach of all engineers globally supporting critical infrastructure across industries.

1.3.2 The Governing Equations of FEA

The fundamental governing equations of FEM are obtained from the principles of solid mechanics. In general, this kind of set of equations involves equilibrium equations, compatibility conditions, and constitutive relations representing how the material deforms and reflect under the certain external forces.

Equation of Equilibrium:

The equation of balance of FEM represents a static equilibrium between internal forces generated by the material resistance and external forces, such as applied loads. For a structure in equilibrium, internal and external forces should counterbalance at all nodes and elements:

$$\mathrm{K} * \mathrm{u} = \mathrm{F}$$

Where:

- K is the global stiffness matrix of the system which is derived from the geometry of each element, and properties of the material.
- u is the displacement vector.
- F is the vector of external force applied to the structure.

The stiffness matrix, K, is assembled based on the individual element properties and defines the relationship between forces applied to the structure and the resultant displacements. Element Material properties, such as Young's Modulus (E) and Poisson's Ratio (ν), along with geometric data are used to calculate the Stiffness Matrix for each element.

Constitutive Relations in the structural analysis:

The constitutive relationships of the isotropic materials, which is S355 steel in our case, relate to the connection of the stress and strain tensors by Hooke's Law:

$$\sigma_{ij} = C_{ijkl} * \epsilon_{kl}$$

Where:

- σ represents the tensor of stress in each direction.
- $\boldsymbol{\epsilon}$ represents the strain tensor.
- C is the fourth-order elasticity tensor that carries the material properties in general. For example, Young's modulus and Poisson's ratio.

In the case of isotropic materials, the elasticity matrix C reduces to a function of Young's modulus and Poisson's ratio, which enables one to determine stress and strain in the various directions. This relation assists in identifying whether the material will yield due to the imposed stresses, an important aspect when analyzing pad-eye performance subject to severe offshore loads.

Compatibility Conditions:

Esurance of the displacements result in a continuous deformation without gaps or overlaps between elements done by compatibility equations. In the FEA, compatibility means a strain distribution that is smooth within continuity in the structure. This is particularly important for load transfer to be carried out realistically among the interconnected elements, especially where geometry is complicated, such as pad-eye attachment points. Compatibility is enforced through the mesh by which, for nodes sharing the same displacement value on adjoining elements, structural continuity is ensured.

Stress-Strain Relationship by Hooke's Law:

In this particular case of a pad-eye under lifting forces, Hooke's Law defines the relation between applied stress and resultant strain. In matrix form of stress analysis is mentioned in below:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix}$$

This formulation now helps us to compute resultant stress components for the given strains, considering material-specific elasticity constants. In the case of S355 steels used in pad-eye applications, the modulus values will give an accurate prediction of the stress behaviors under the simulated lifting loads.

Application of the Von Mises Criterion:

To find out will yield of the given material, the Von Mises stress criterion has been because as we know this methodology is suitable for the analysis of ductile materials such as steel that are commonly used in the construction of pad-eyes. In the below formula the Von Mises stress, σ_{vm}, has been expressed in terms of principal stresses:

$$\sigma_{vm} = \sqrt{\frac{1}{2}[(\sigma_1 + \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

Where σ1, σ2, and σ3 are the principal stresses. The Von Mises stress is then compared with the material yield strength. The yielding of the pad-eye would be in danger if σ_{vm} exceeds the yield strength of S355 steel, which is 355 MPa. FEM analysis for this study confirmed that the value for the modified design was below this threshold and hence satisfied safety criteria.

Application of these governing equations to the FEA in this thesis will therefore enable the execution of a detailed structural analysis of the pad-eye due to operational loads and will give information on the distribution of the stress, displacement, and the most likely failure spots.

Chapter 2. Literature survey

This chapter provides an overview of important research conducted in the design and analysis of lifting equipment for offshore structures, focusing on pad-eye design and FEM analysis. Thus, one can assess the enhancement of reliability and structural performance of systems with demanding environments by the advancement in FEM applications and improvements in design.

2.1 Studies on Offshore Lifting Equipment and Material Selection

Fundamental research on the management of structural integrity in offshore equipment was conducted by Khan and Khan, 2016, especially on tubular joint flexibility and the impact that it may have on the lifting components such as pad-eyes. The findings indicated that joint flexibility might cause a significant fluctuation on load distribution in a lifting system, thereby highlighting the need for strong material selection. Such information has been useful in the selection of high-strength materials in this thesis to avoid deformation and ensure stability during the lift.

Fatigue analysis in the context of offshore platforms was addressed by Azarhoushang (2017). In this paper, he underlined the impact of cyclic loading due to environmental forces such as waves and wind. This research has given a reason for the use of materials that are fatigue-resistant, since repeated cyclic stresses may be one of the reasons for offshore equipment failure well in advance. The findings of this study support the selection of materials like S355 and S460 steels in pad-eye design chosen in the current thesis that are supposed to endure repeated loading conditions and hence be resistant to fatigue.

API RP 2A-WSD 2020 and Lloyd's Register 2018 provided the necessary safety standards for lifting equipment offshore: dynamic load factor, material toughness, and corrosion resistance. Informed the design specifications used here to ensure that the pad-eye configuration chosen meets the industrial standards concerning static and dynamic load conditions. They provided guidelines on selection for materials to be used in withstanding drastic conditions offshore.

2.2 FEM Applications in Structural Analysis of Pad-Eyes

The Finite Element Method (FEM)application in pad-eye structural analysis has proven to be indispensable in the safety and efficacy of offshore lifting equipment. FEM acts as a boon for engineers who are forced to simulate and analyze complex loading conditions; this becomes more important as direct calculation methods might not be practical owning either to complicated geometries or multi-directional forces. Pad-eyes are critical elements of lifting operations and resist high levels of static and dynamic loads; thus, they must be designed strong enough to endure them. Several works have demonstrated the utility of FEM in developing this type of pad-eyes which eliminates brittle failure during high lifting operations, meeting safety factors against limit states by avoiding critical stress concentrations on the structure.

A major work in this field is by Wiratno Satoto et al. M. Eid et al. (2017) — FEM comparative analysis of symmetric and asymmetric pad-eye designs They studied the distribution of stresses and safety factors as well as geometric parameters influences on such behavior under a load. They observed that symmetric pad-eyes provide a more uniform stress distribution when load is applied, making it less prone to failure and suitable for offshore lifting compared to conventional pad-eyes (antisymmetric). The symmetric arrangement minimizes the possibility of stress concentrators being responsible for early material fatigue and failure. As a result, the researchers urged high-risk lifting, particularly in offshore situations where safety is of utmost importance, to rely on symmetric pad-eye designs. Consistent with these results, the design methodology vehicle in this thesis takes a symmetric construction for the pad-eye to limit potential stress hotspots and increase stability during lifting operations.

Zienkiewicz and Taylor (2000) provided a great deal of information on the basic principles behind FEM in their reference book on the method with a complete derivation of stress/strain relations. The developed framework centers on the essential balance, compatibility and constitutive relations that shape any structural analysis (via finite element methods). Equilibrium: This property is related to the balanced nature of internal forces without which the structure will collapse regardless of if external loadings act on it. Compatibility ensures that materials stay together under load and do not deform independently, which is key to fitting elements of a structure together properly. Constitutive relationships describe how materials behave in response to the state of stress and strain, which is essential for both materials selection and design accuracy. This FEM method can be used to implement such principles so that the analysis is more realistic, representing genuine load reactions where engineers discuss their design well. An appropriate level of detail to be used in FEM simulations was decided in this study based on this framework, especially when evaluating the load-carrying capacity of the pad-eye under different operational situations.

Brown (2011) represents the essential role of FEM in lifting equipment by mentioning adverse consequences due to improper analysis of FEM. Brown, in analyzing accidents related to lifting, repeatedly noted that a failure can be attributed to a design flaw exhibiting insufficient validation of FEM simulations. This highlights the common weakness of poorly designed processes, in that important high-stress concentration regions are seldom considered for evaluation, resulting even in cataclysmic failure. According to Brown, FEM validation process is necessary not only to identify critical areas (high-stress regions) in the lifting equipment especially for the pad-eye. It involves an extensive validation process (that entails stress testing, fatigue analysis, and sensitivity analysis) to ensure the design will support the operational loads without failing due to unforeseen flaws. In this thesis, Brown's recommendations were used as a basis to develop an extensive FEM analysis posed on identifying and evaluating high induced stresses concentrations along the pad-eye configuration. Identifying the potential failure points early on in design allows improvement of the structural integrity of the pad-eye to ensure that it is up to operational safety standards.

Performing static stress analysis and check using FEM is certainly not the only application of pad-eye design example used in industries where finite element method is applicable. In your analysis, dynamic loading conditions can be evaluated using advanced FEM simulations that are real-crucial in an offshore lifting operation where changing loads are induced by mechanically long-term factors such as waves and wind and dynamically moving vessels. This can be modeled using FEM and gives insight into how the pad-eye behaves under a variety of transient and steady-state conditions. It facilitates engineers to simulate different scenarios and maximize the design for a range of operational parameters, thus significantly boosting the design reliability and safety during lifting operations in harsh offshore environment.

All in all, the excerpt of FEM in structural analysis of pad-eye has revolutionized the design approach to lifting equipment by engineers. Research such as that of Satoto et al. Cite show the necessary step that should be considered to avoid failures as well appropriate distribution of its stress in pad-eye structures. This symmetrical feature, validation of critical high-stress areas, and equilibrium, compatibility, and constitutive relationships lead to safe yet economical pad-eyes for offshore lifting with FEM analysis. This thesis uses FEM to challenge the findings in these papers and utilizes FEM as a rigorous way of testing the pad-eye functionally under the severe demands imposed by offshore lifting applications.

2.3 Pad-Eye Design Enhancements and FEM-Based Safety Validation

The lessons learned in conducting this work underlies the significance of optimized design and FEM-based safety validation for reliability of pad-eyes used in offshore picking operations. Lifting offshore is by nature high-risk as environmental conditions such as wave forces blowing down wind and corrosive seawater can place significant loads on this lifting equipment. Lift Operations that Fail can incur Loss of Equipment, Human Cost and Harm Done to Profits. According to Safety4Sea (2019), events associated with offshore lifting are among the most expensive and time-consuming accidents ever since they always cause alarming downtimes. These results highlight the essential requirement for an extensive FEM analysis to ascertain the locations of possible failures and enhancement in the pad-eye designs for survivability against extreme environmental loading conditions experienced offshore.

To address the design lessons from previous incidents, this thesis adopts the design recommendations issued by prominent standardization bodies such as the American Petroleum Institute (API) and International Association of Oil and Gas Producers (IOGP). In 2020, API and IOGP updated their respective recommended practices (RP) on the design of offshore lifting equipment to drive accountability with load components through high factors of safety (FOS), as well as the use of corrosion resistant, durable materials in component design. In offshore applications, the factors of safety are typically higher than onshore applications due to uncertainty and hostile nature inherent in the marine environment. The thesis proposes a pad-eye design that enhances resilience, safety, and durability by implementing these recommendations which reduces the risk of an accident or equipment failure during the lift operation.

According to the API and IOGP functionalities, S355 and S460 steels were used in this thesis for the pad-eye configuration. Strong and corrosion resistant materials selected as structural materials to resist constant repeated loading cycles and avoid breakdown in tarnished conditions. S355 and S460 steels are especially suitable for applications requiring high tensile strength while their resistance to saltwater-induced corrosion enhances service life of the equipment. The objective of this thesis is to establish a pad-eye that finally responds quickly to the immediate requirement of offshore lifting, but also exhibits long-term cyclic loading performance by selecting these materials. Resistance to cyclic loading is essential offshore, where lifting equipment often experiences repetitive forces that can result in fatigue leading, ultimately, to structural failure.

When FEM is incorporated in this thesis, it includes more than just simple structural analysis. FEM helps to detect all possible weak points in the pad-eye structure that may fail under operational loads, followed by detailing simulations and remedying the same. Particularly critical is the high-stress regions around welded joints, where cracking and fail from cyclical loads occur. In offshore lifting equipment, weld fractures are often seen because of the high levels of stress concentrations and through repeated loading cycles. In this thesis, the finite element method (FEM) is used to perform a stress concentration analysis around weld points so specific areas can be improved upon in design with less likelihood that cracking initiates or propagates. FEM helps in not only reliability, but also as an early design too and by identifying these important aspects of failure through our initial designs, so we can mitigate failure before we even know they will happen.

Apart from stress concentration analysis, in this thesis the FEM process conducts safety validation to ensure that pad-eye is satisfied or even higher than industry standards. Safety validation simulates several load cases including static, dynamic, and cyclic loads to ensure the pad-eye can withstand all forces found during offshore lifting operations. In this way, not only is the pad-eye proven to safely support the loads identified by code, but there are also values from which to assess the factors of safety built into the design. The goal is that the pad-eye stays functional in improbable or optimum loads, boosting safety and reliability.

This project demonstrates the development of an efficient, functional pad-eye ideal for offshore lifting applications in specifically via design optimization and validation through FEM analysis. Adopting a composite methodology in this research represents the current state-of-the-art but more importantly, serves the purpose of providing better pad-eye performance under the most extreme conditions because of realistic material modelling. This detailed FEM analysis allows identification of weak zones, like weld regions can be reinforced preventing several modes of failure like opened or closed cracks by the welds. The choice of materials used in conjunction with well-understood design standards, combined with steady state and extreme load verification by means of the finite element method (FEM), produces a pad-eye that functions suitably under working loads but also displays durable performance over time addressing both safety and economic factors associated with offshore lifting operations.

Thirdly, the proposed refinement for FEM-based safety validation and design improvements according to industrial requirements is a proactive decision against offshore lifting related risks. In addition to the immediate safety benefits, this method will prolong the pad-eye serviceable life, minimizing maintenance and downtime. This thesis provides a framework for pad-eye design, applicable to meeting the harsh conditions of offshore environments through innovative simulation and strict safety guidelines encompassing both materials and geometry.

Chapter 3. Structural Finite Element Analysis (FEA) of Pad-Eye

In this chapter Finite Element Analysis (FEA) of pad-eye designs utilized for heavy lifting in the offshore sector is carried out to assess structural integrity. These analyses include the meshing process, element quality checks, model setup, stress criteria selection and material properties for the load definition used to assess the design's ability to withstand loads.

3.1 Design and Structure of Pad-Eye Models

In this study, multiple pad-eye designs were modeled and load-tested - with safety criteria using Creo PTC for FEA modeling - to represent differences in orientation of attachment and load distribution paths within a component. Various pad-eye attachment designs were created, such as top-mounted or side-mounted.

Side-Mounted Pad-Eye: This design has the pad-eye attached to the side of a structure for lateral force distribution. Unfortunately, preliminary FEM showed that this design had a high stress concentration (failure) at the points where it connects to other parts of the car body and material stresses with exceed yield.

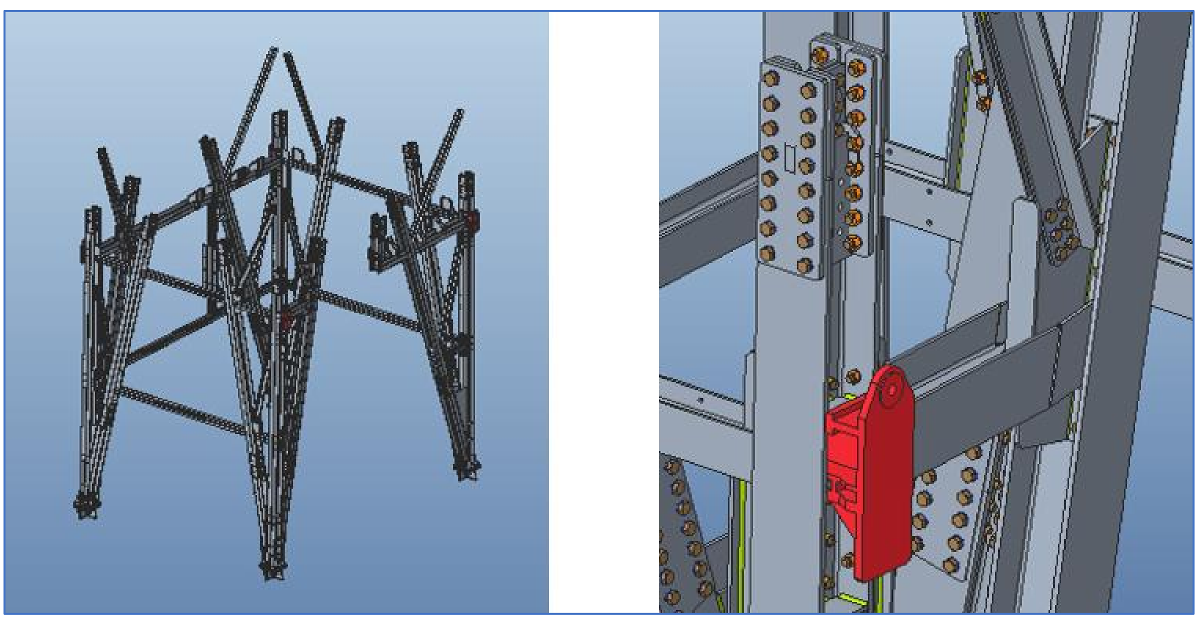

Figure 7 - Side-Mounted Pad-eye Design

Top Mounted Pad-Eye: In this arrangement, the pad-eye is attached to the top of the lifting member and transfers a more vertical load in direct line with the weight above (+) making it less stable. This design performed well on all safety and stress tests (FEM analysis) and shows a substantial reduction in induced/ redistribution of stress compared to the side-mounted version.

In this study, both designs are assessed to quantify the performance trade-offs and optimize pad-eye configuration for offshore lifting operation safety and efficiency.

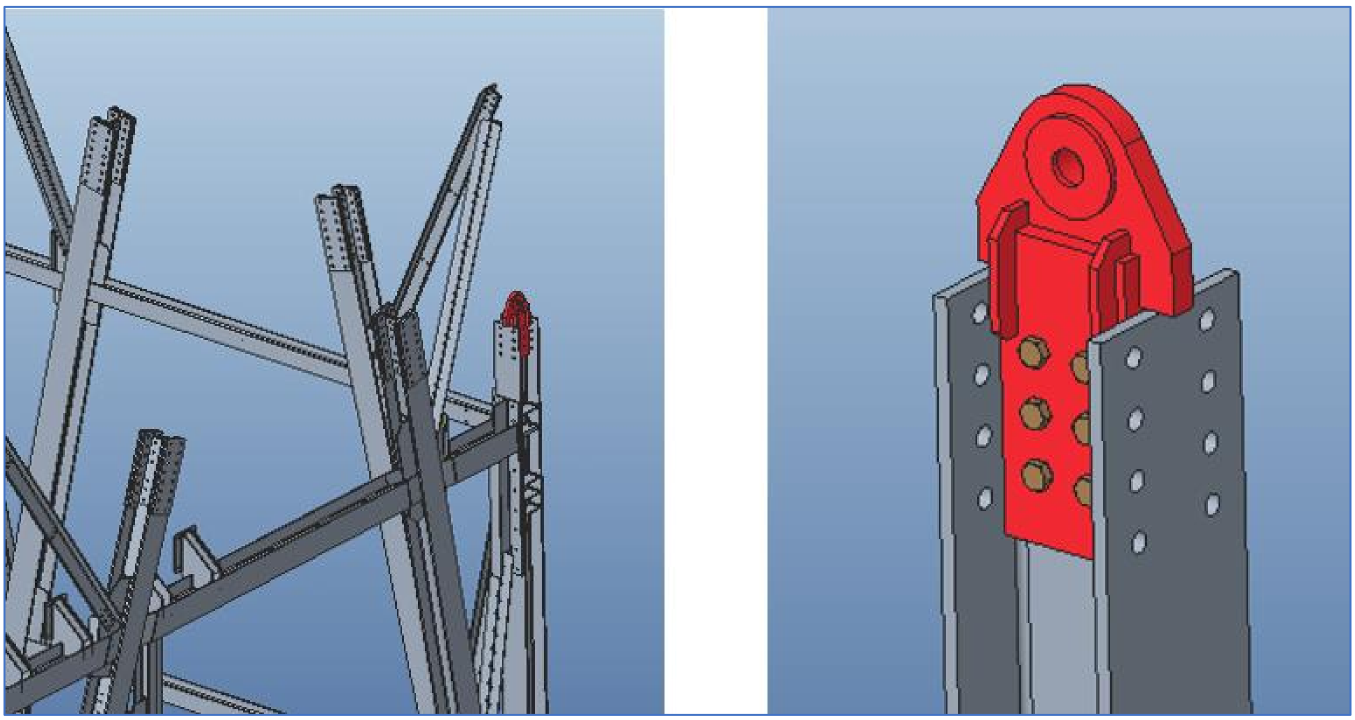

Figure 8 - Top-Mounted Pad-eye Design

Configuration of side-mounted and top-mounted pad-eye shown in Figures 7 and 8. The models were created to closely approximate actual loads during operation.

Below, main data are reported considering a single lifting frame:

Weight Supported	129 ton
Maximum Depth	425 mm
Maximum Width	500 mm
Maximum Height	1080 mm

Table 8 – Top-Mounted Pad-Eye Maximum Dimensions

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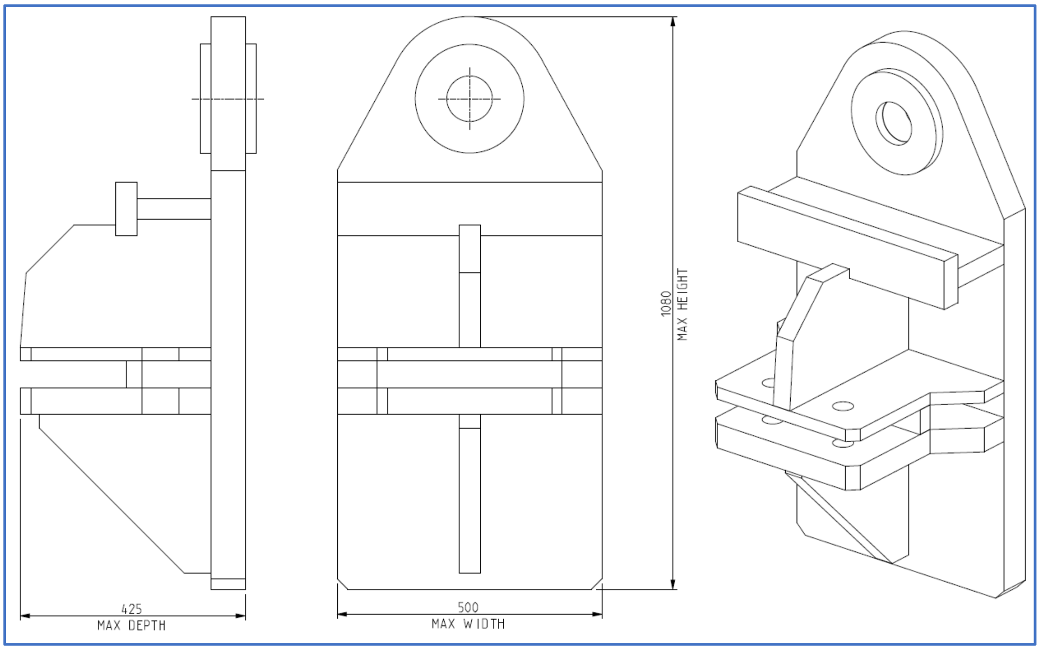


Figure 9 - Site-Mounted Pad-Eye Dimensions

Below, main data are reported considering a single lifting frame:

Weight Supported	129 ton
Maximum Depth	248 mm
Maximum Width	500 mm
Maximum Height	910 mm

Table 9 - Side-Mounted Pad-Eye Maximum Dimensions

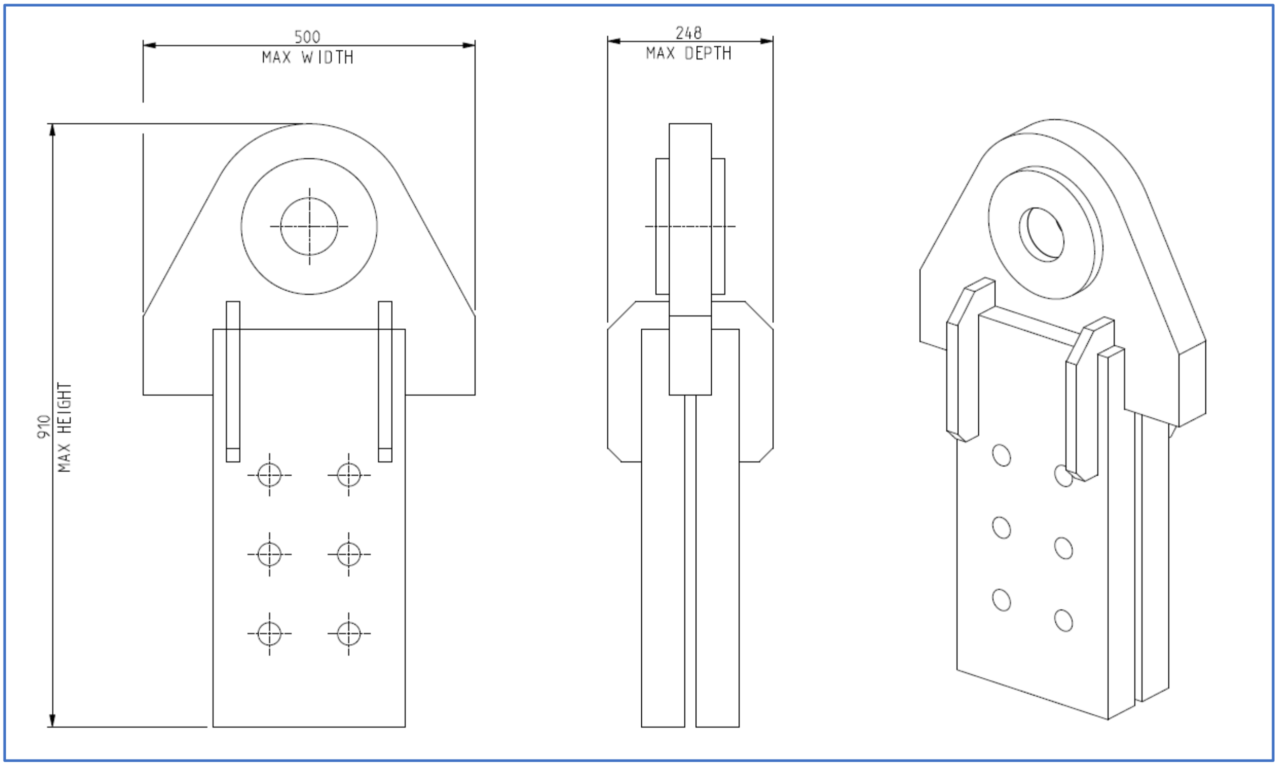


Figure 10 -Top-Mounted Pad-Eye Dimensions

3.2 Problem Definition and Approach

This FEA study aims to evaluate the geometries of these two pad-eye structural soundness and efficacy under static and dynamic loading. The configuration was analyzed to find:

- Stress distribution at maximum within the pad-eye structure and its connection points
- Under the operational loads, displacement, and deformation behavior.
- Factor of safety and adherence to offshore lifting norms, especially API-RP2A
- Adjustments, modifications, and additions to existing behaviors are necessary.

3.3 Load Details and Conditions

The two pad-eye models were examined while subjected to a design force of 686,700 N which was determined using the API-RP2A standard: static lifting force=35,000 kg and dynamic load factor=2. The force simulates dynamic conditions of offshore lifting operation with effects of wave-induced roll motion and fast direction changes.

Import Application and Distribution

The load was applied in the form of a bearing force distributed along the surface of the pad-eye structure for each configuration:

Side-mounted pad-eye — Load was applied horizontally to simulate lateral lifting forces, and asymmetric stresses were developed around the connection points.

Pad-eye Mounted to Top: Load was installed vertically and directly downward the axis of the pad-eye, matching with the load path direction for structural load transfer creating a straighter more stable line of force.

These load cases are important to simulate realistic lifting situations in order to evaluate the structural response of each configuration.

3.4 Boundary Conditions

To replicate the proper boundary conditions for an offshore lift, they were enforced as follows:

Boundary Conditions: The bottom face of the lattice region was constrained in translation fully to represent being rigidly wired to the parent structure.

Contact conditions: Contact pairs were created between pad-eye and the surfaces those are connected to. It allowed the model to transfer loads realistically across both sides of the connection.

In the additional constraints that were considered in the side-mounted configuration, lateral edges of the lens were constrained to record out-of-plane forces while resisting unwanted rotation displacements applied from top and bottom.

3.5 Mesh Generation and Types of Elements

Meshing is an important part in accurately capturing the pad-eye configurations structural response in load. The beam part of the Oil Rig Derrick where pad-eyes are located was segregated in this study to simplify analysis and focus on regions that bear the principal loads. Meshing was set to auto geometry control function concerted in Creo PTC, allowing for optimized distribution of elements around complex geometry such as attachment points and weld regions.

3.5.1 Parameters for Meshing and Element Size

From the geometry, dimensions of derrick beam and pad-eye structures a 60 mm element size was chosen that best represents the weight to be balanced between the need for more accurate modeling in high-stress regions and computing cost. To minimize the changes of mesh size that might in-turn affect the results, we enabled the Creo auto geometry control function.

The working of derrick beam section and pad-eyes was meshed as shown in Figures 11 and 12 option which indicates the element size distribution throughout the structure with maximum dimension about 60 mm.

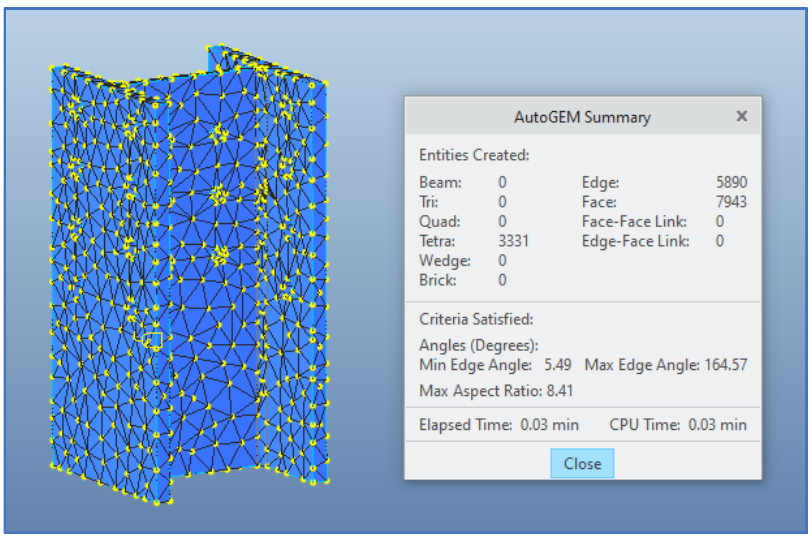


Figure 11 - Meshed Model of Derrick Beam

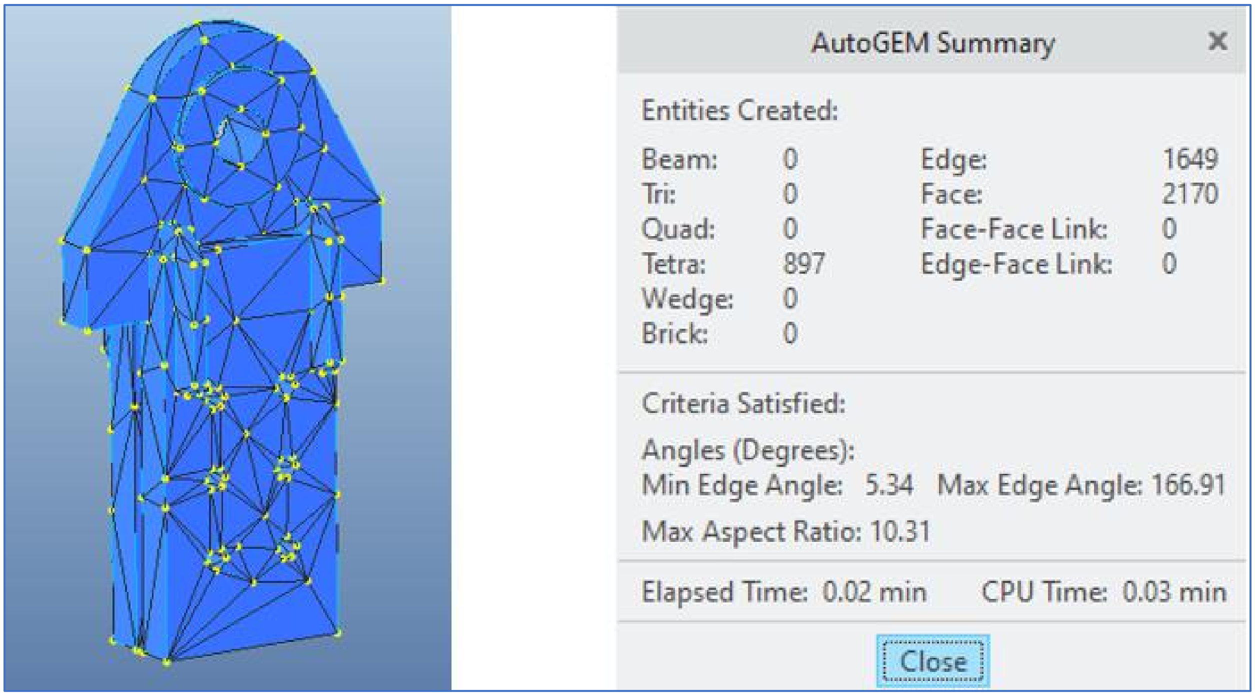


Figure 12 - Meshed Model of Top Mounted Pad-Eye

3.5.2 Element Tye and Quality Control

Different types of elements are available for simulating the model and since the complex geometry needed tetrahedral elements especially around the pad-eye connections and weld lines, they were used. These supplied some well-needed flexibility in the way of adapting to the normal shapes of the connections, as well as capturing stress variances around areas of high stress.

To be confident that the mesh would accurately resolve stress concentrations, several quality checks were performed on the mesh:

- Aspect ratio: To keep the elements from being distorted, and in areas with high curvature around pinholes, the aspect ratio was maintained between 1 and 4.
- Skewness: Skewness values less than 0.5 were selected to enhance numerical stability of FEA result.
- Orthogonality: Close to orthogonal elements were preserved in load-bearing areas to provide structural stability while under-load.

3.5.3 Mesh Independence Study

To ensure the results were independent of mesh size, a mesh independence study was performed and confirmed that results obtained with an element size of 60 mm were stable. For the three mesh configurations (coarse, medium and fine), convergence was obtained in the cases of the medium mesh configuration, providing sufficient accuracy to allow for LS-DYNA predictions of stress and displacements without excessive costs due to having a relatively short computing time.

The automatic control used for meshing the pad-eye and derrick beam attachment in the Creo aided integrity assessment was able to provide a conservative representation of connected pad-eye and beam even around critical high-stress points.

3.6 Constrains and Connections

A particular set of constraints and connections was necessary on the FEA model in order to provide representative counterparts for lifting conditions when simulating those with pad-eye configurations. Focused constraints were placed to remove any unnecessary motion from the lattice structure, isolating and allowing the structural response of the integrated frame and pad-eye assembly under loading conditions.

3.6.1 Constraints

Each lattice subsection had a bottom face subjected to an essential boundary condition to constrain all translational degrees of freedom. In order to fully constrain the model, one face of this pad-eye frame was fixed in all directions which helped prior for restricting movement and analyzing only structural response of the frames under load. This configuration allows for the pad-eye and frame to be effectively isolated from other parts of the lattice, eliminating potential motions in other areas of the derrick affecting these components.

The applied constraints on the lattice section are illustrated in Figure 13, where the fixed face of the bottom represents its location where it joins to stay attached to a derrick structure.

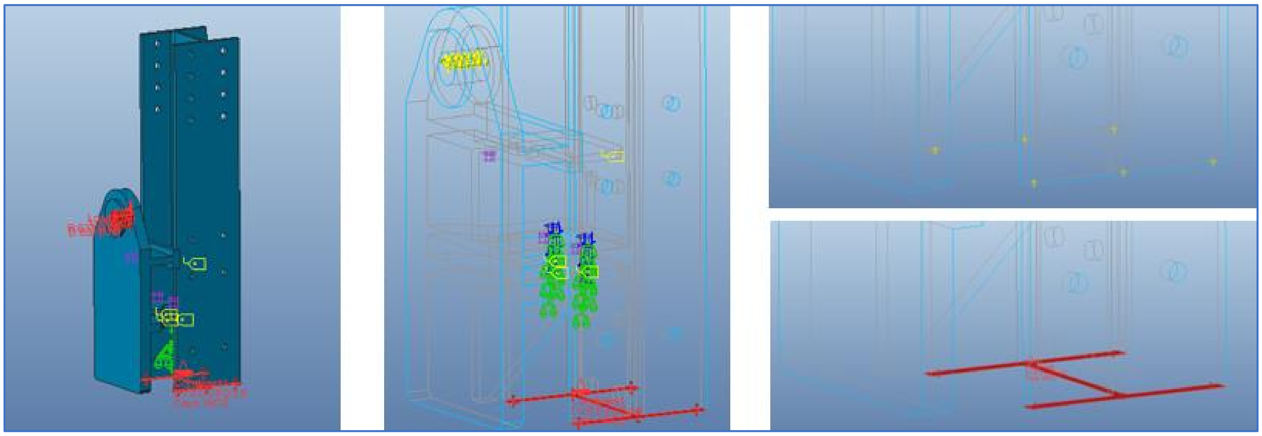


Figure 13 - Applied Constraints on the Lattice Section's Bottom Face, All Translating

3.6.2 Connections

Finally, to simulate the actual regions of interaction between components in the lifting assembly, contact interfaces were defined in the model. The components were able to move independently, allowing for some degree of flexibility in motion, while the connections were designed to transfer force only at the surfaces in contact simulating reasonably realistic load-bearing behavior when lifting operations (Eldin et al. 2023).

So, some highly important correlative connections were made.

Pin-to-Frame Contact: This allows the transfer of load via pin connections. Those are the points of contact, and when the lifting force gets applied to those pins [It must be said that: they physically fly in compressive / shearing manner inside], it is transmitted through those contact points to the frame. This setup emulates how the lifting assembly behaves in real life; specifically, the pin is a major load-bearing component.

Frame to Lattice Contact: This type of connection models the structural relationship between the frame and its attached lattice, allowing the frame to realistically support an applied load by transferring forces into the lattice. In this way it is possible for the model to represent how the lattice structure transfer load, as an actual offshore lift would run.

3.6.3 Connectivity and Interface

A set of contact interfaces were created to represent the interaction between the frame, pin and lattice regions which were transferred as forces. These contact definitions allow the components to move independently but can transfer force when they touch, simulating how these parts of the lifting assembly interact in real life.

Contact surfaces were defined as follows:

Pins and Frame: This is a contact interface only; load transfer occurs through the pin connections. These contact points transfer the shear and compressive forces from the pins to the frame during lifting. The model represents this transmission of forces and allows for an analysis of how stresses are distributed around the pinholes and surrounding frame.

Contact Interface between Frame and Lattice Section: This interface allows the frame to bear the load applied on it and transmits realistic forces to lattice structure. This means that according to how the lattice structure will be loaded during an actual lift, surfaces of the frame and lattice are connected together in such a way that would contribute to bearing the load on one or other.

Contact definitions between the frame, pins, and lattice section (Figure 14) showing how loads transfer through these contact surfaces.

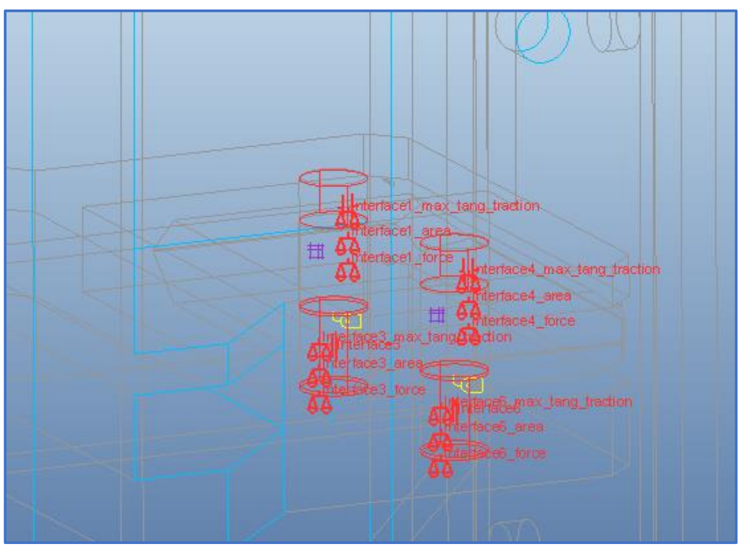


Figure 14 - Definitions of contact between pins, frame, and lattice section with load transfer paths

Overview of constraints and relationships:

How well the pad-eye assembly reacts under lift conditions is determined by the application of constraints and contact interfaces. The independent but interacting behavior of the components is preserved by formulating bottom face of lattice section as fixed and more accurate contact surface defined. This method permits realistic load transfer and facilitates stress distribution and displacement analysis in the pad-eye assembly.

3.7 Material Properties and Failure Criteria

Selecting materials is an essential factor for the integrity and service life of the pad-eye assembly under offshore lifting conditions. In this analysis, the following materials were modelled for the components of pad-eye assembly: S355 steel for pad-eye and frame, S460 steel for derrick beam and 30CrNiMo8 alloy (a carburizing steel) for pins. The right selection of each material was considered according to the mechanical properties and their resistance against specific stress conditions which may occur in offshore applications.

3.7.1 Material Properties

- **S355 Steel**: S355 steel was the clear choice for strength and ductility in a component that will be experiencing direct loading, featuring a yield strength of 355 MPa. This is a common material used in structural applications, needing modest strength and toughness.
- **S460 steel** — considering a higher load-carrying capacity, yield strength of 460 MPa was chosen for the derrick beam construction. The beam carries a lot of loads therefore since S460 has a higher strength, it makes sure that the structure does not undergo any stress leading to loss of stability.
- **30CrNiMo8 Alloy** — This provides high yield strength (~1000 MPa) which is required for the pins to withstand very high shear and cyclic loads. The reliability is further enhanced by its ability to withstand repeated stresses (due to repetitive lifting) without the pins getting structurally compromised.

Material properties of each component in the assembly were defined and carefully selected in Creo to represent their OLS characteristics when subjected to load conditions. The highlighted material assignment is in Creo where the pad-eye, derrick beam and pins are marked with their respective materials.
Pad-eye, Beam and Pins material assignment in Creo (S355, S460 and 30CrNiMo8 respectively)

3.7.2 Failure Criteria

Failure points in the assembly were predicted using the von Mises stress criterion. The second criterion often used for ductile materials under multi-axial stress is that it also combines shear and normal stresses in order to give an overall view of the stress state. The analysis also has been performed using the von Mises stress values, and recognized regions where stresses which are close to or exceed yield strength may lead to failure. The short term and long-term nature of the failure criterion meant we could see immediate impacts on overall stress state and longer-term rates of fatigue potential, which is critical for components subjected to extreme offshore environments.

3.8 Results and Discussion of the Analysis

The FEA output of Displacement, Stress and Failure for applied loads on pad-eye configurations. The performance of the different configurations of side-mounted and top-mounted pad-eye was shown to be statistically significantly different, with implications for the offshore lifting operability assessment.

3.8.1 Results for the Side-Mounted Pad-eye

The side-mounted pad-eye configuration had high stress gradients close to the weld and pinhole locations. The von Mises stresses in these areas were above the S355 steel yield strength, suggesting that the configuration is susceptible to failure for operational loading. Range of displacement values were also recorded over limit, which would cause structure to lose general stability during lifting.

The following images contain a pressure distribution, magnitude of the displacement along the axis for the pad-eye on-side mounted, with colors emphasizing the critical parts localized by their yield strength.

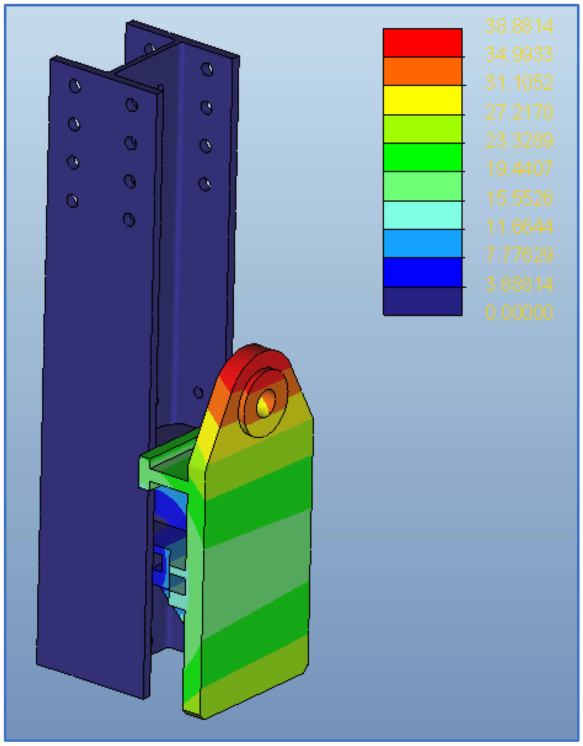


Figure 15 - Magnitude of Displacement [mm]

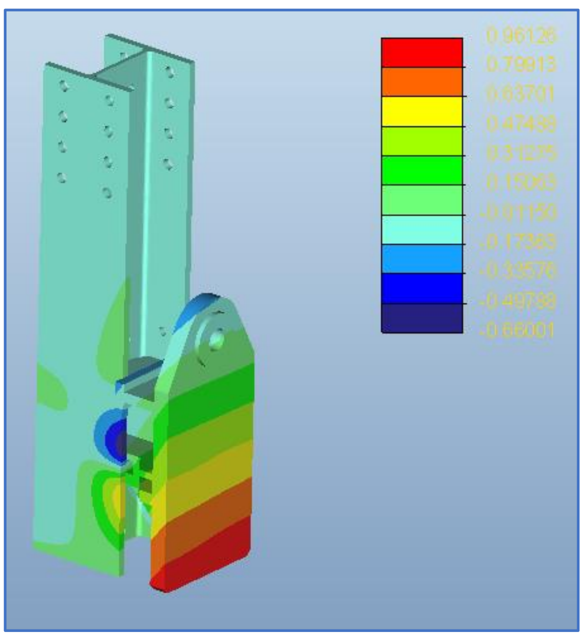


Figure 16 - Displacement along the X-axis [mm]

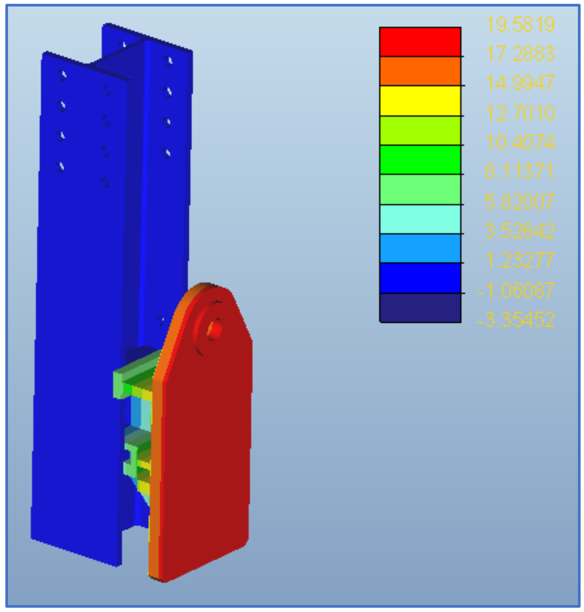


Figure 17 - Displacement along the Y-axis [mm]

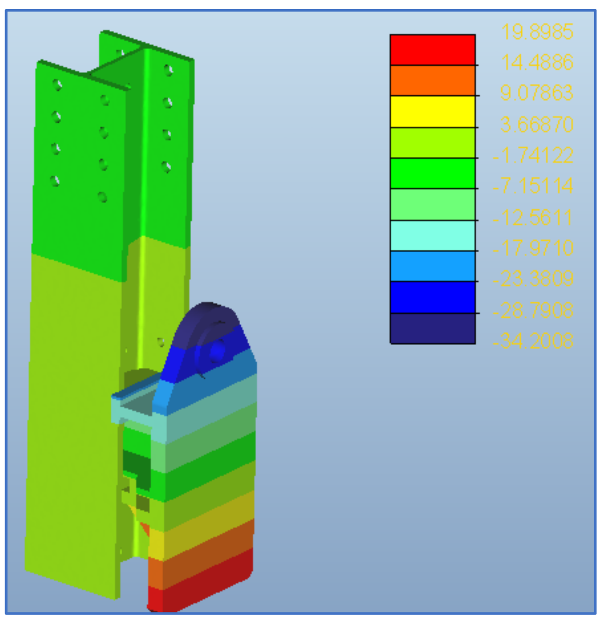


Figure 18 - Displacement along the Z-axis [mm]

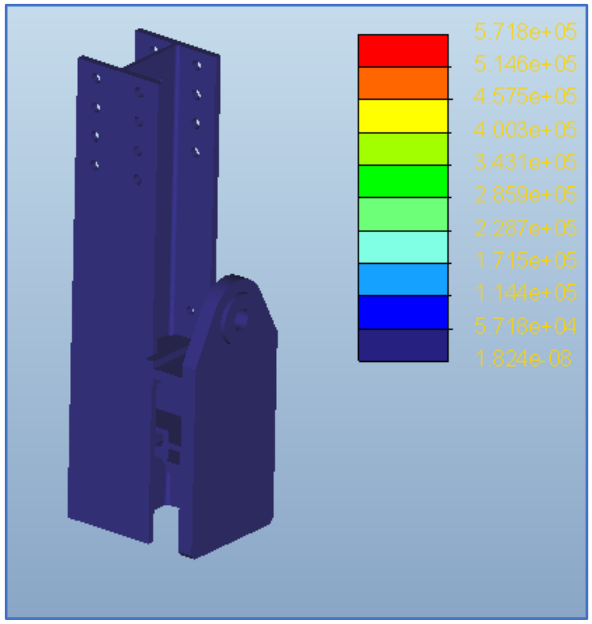


Figure 19 - Strain Energy per unit volume [kPa]

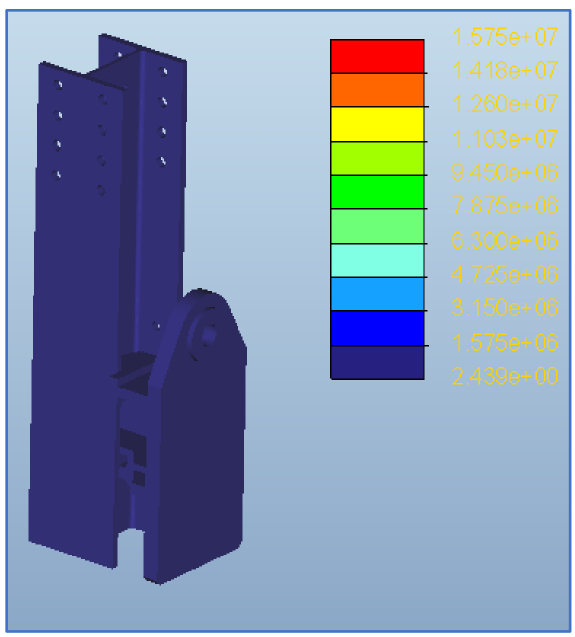


Figure 20 - Von-Mises Stress Distributions [kPa]

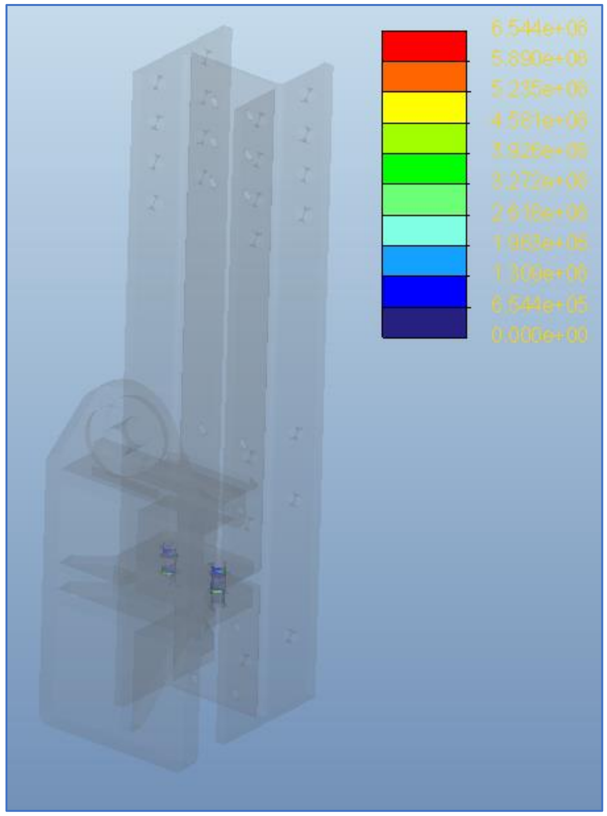


Figure 21 - Contact Pressure [kPa]

3.8.2 Results of Top-Mounted Pad-Eye

In contrast, the maximum stress conditions for the top mounted pad-eye configuration exhibited a consistently lower scattered pattern (compared to side mounted pad-eye configurations) with peak stresses very close to yielding limit of the material. The amount of displacement was minimal and within allowable limits which further confirmed that this configuration is stable and safe under load. Stress, displacement per X, Y and Z axis and strain contributions in the top-mounted pad-eye (the stress concentrations are less than the yield indicating no material failure) as shown in the following figures.

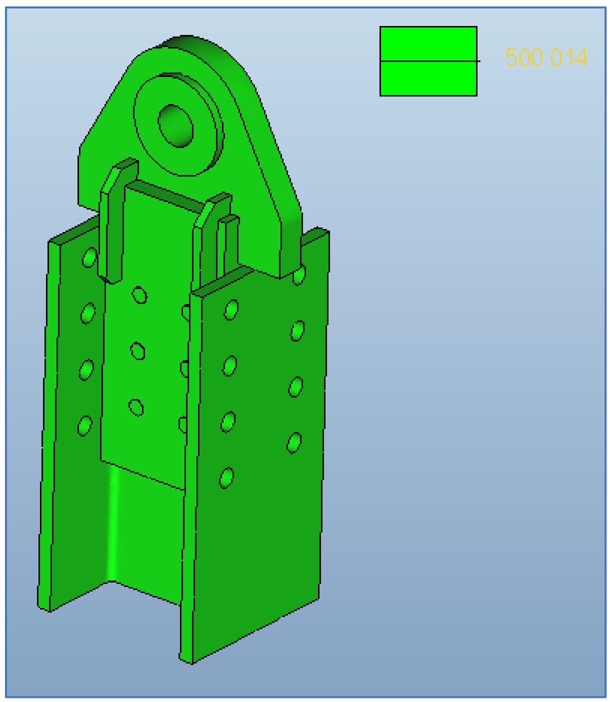


Figure 22 - Magnitude of Displacement [mm]

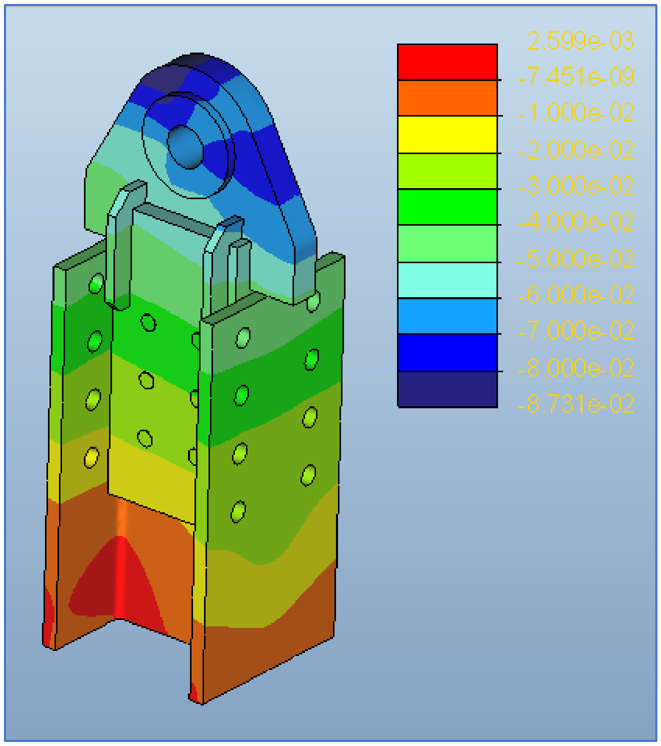


Figure 23 - Displacement along the X-axis [mm]

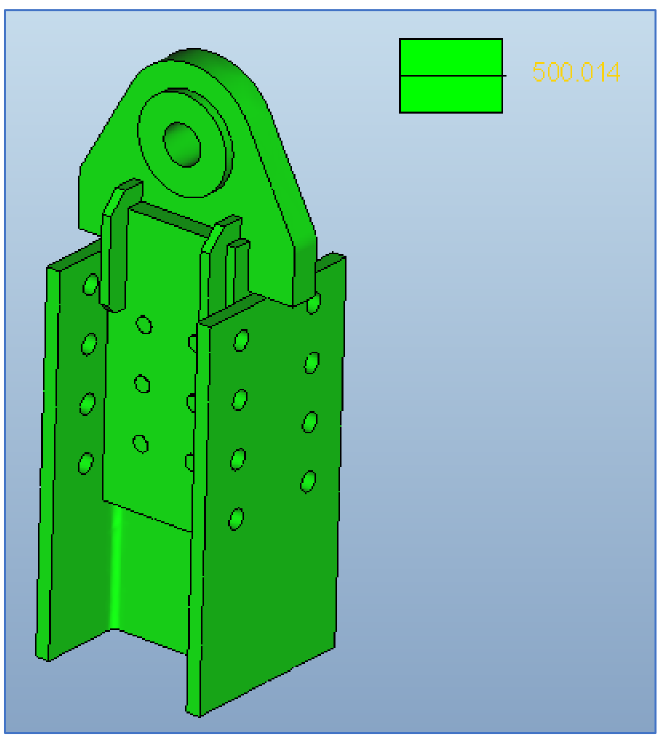


Figure 24 - Displacement along the Y-axis [mm]

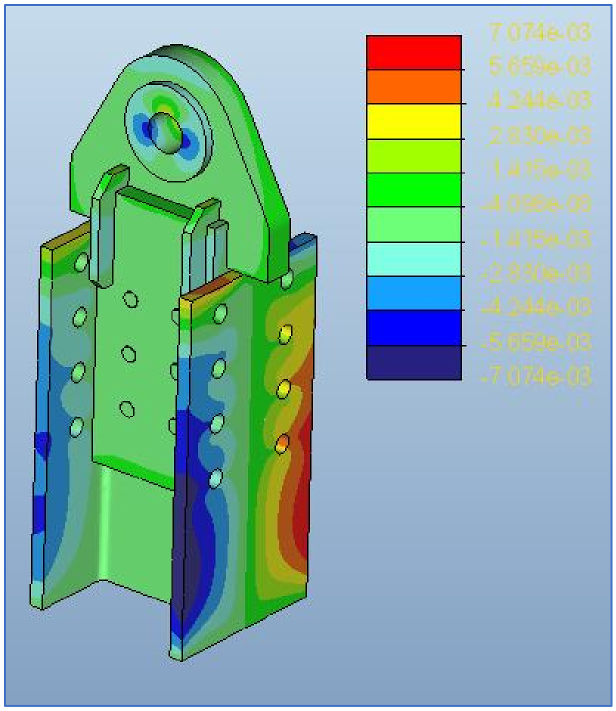


Figure 25 - Displacement along the Z-axis [mm]

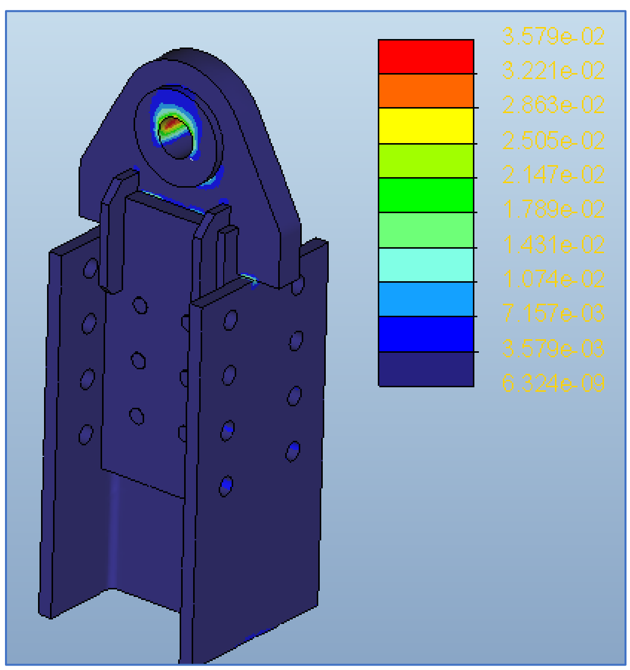


Figure 26 - Strain Energy per unit volume [kPa]

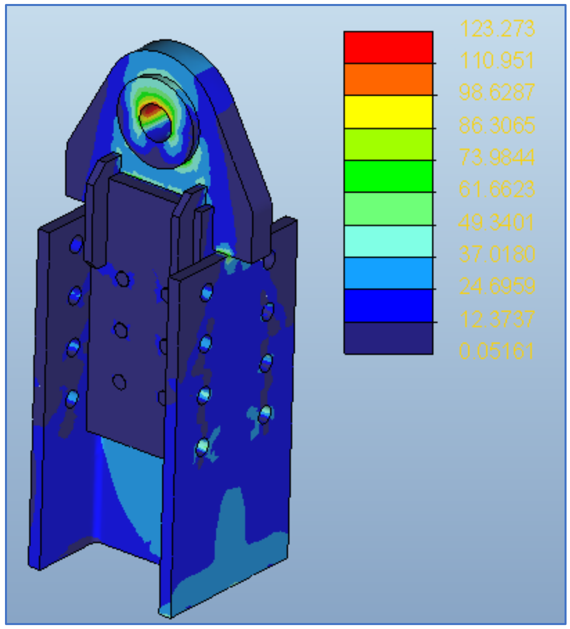


Figure 27 - Von-Mises Stress Distributions [kPa]

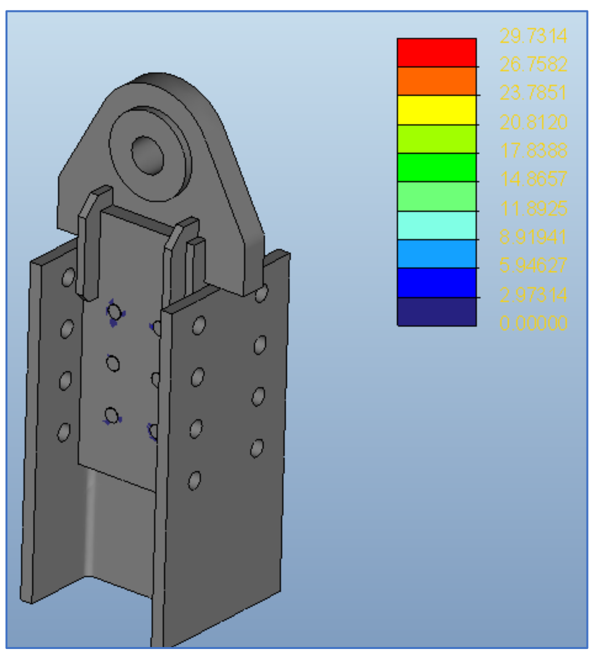


Figure 28 - Contact Pressure

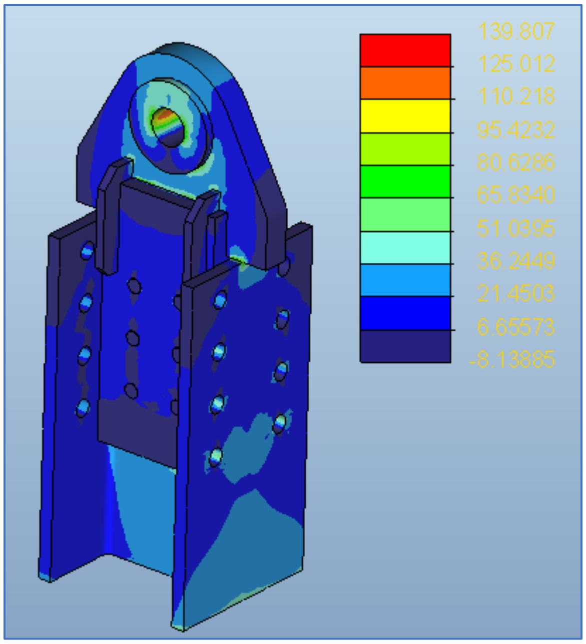


Figure 29 - Max-Principal Stress Contribution [MPa]

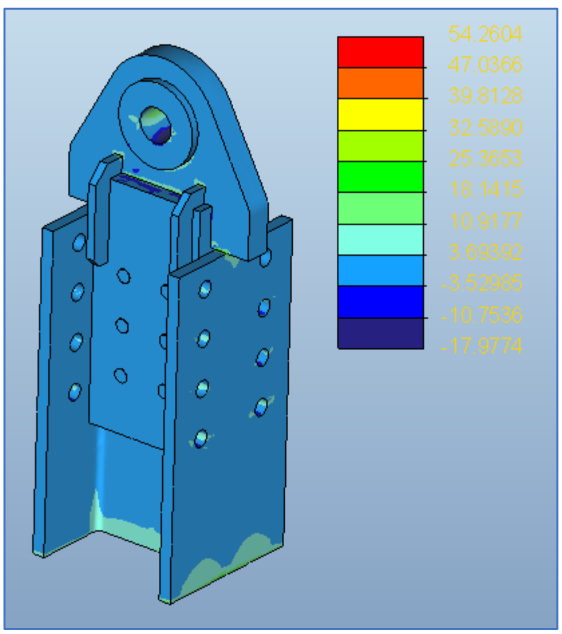


Figure 30 - Mid-Principal Stress Contribution [MPa]

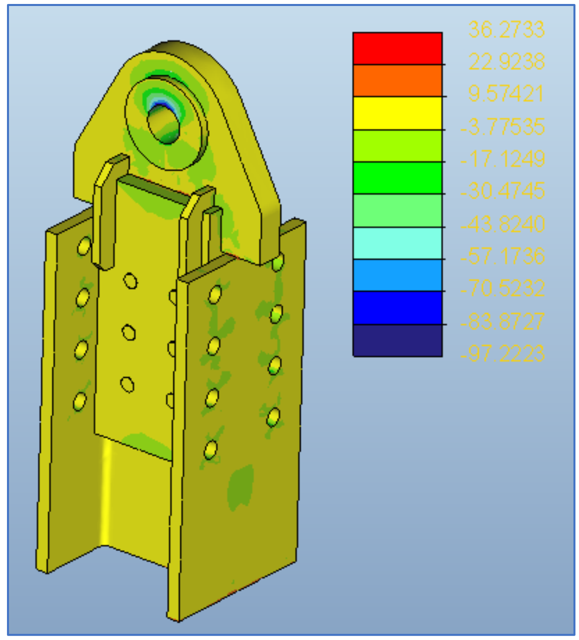


Figure 31 - Min-Principal Stress Contribution [MPa]

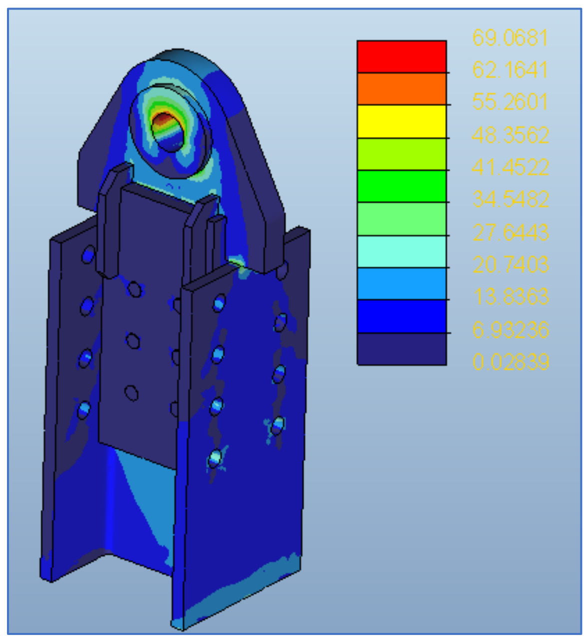


Figure 32 - Maximum Shear Stress Contribution [MPa]

3.8.3 Results of Pin

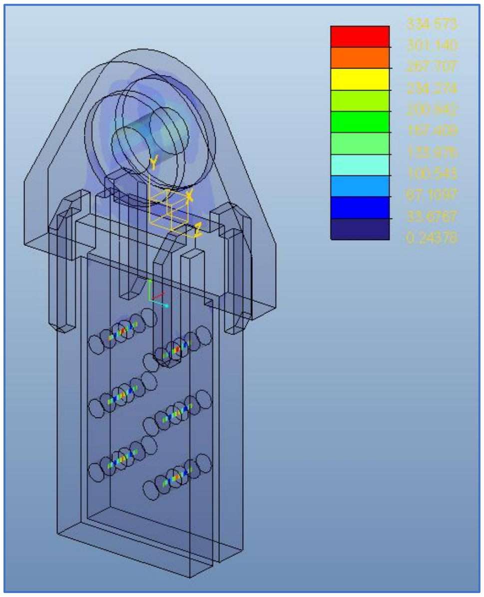


Figure 33 - Top and Bottom of shell Stress Von-Mises [MPa]

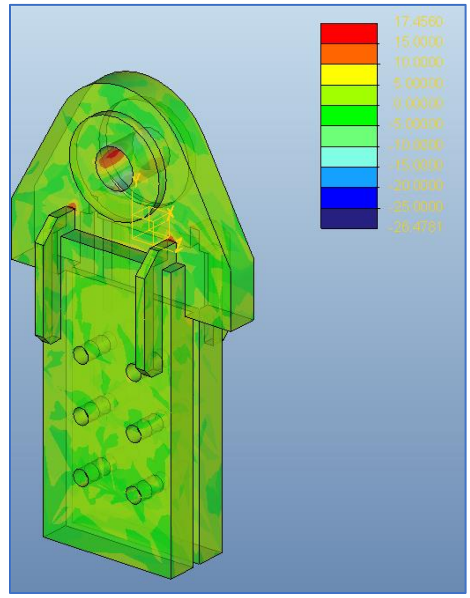


Figure 35 - Stress Max-Principal [MPa]

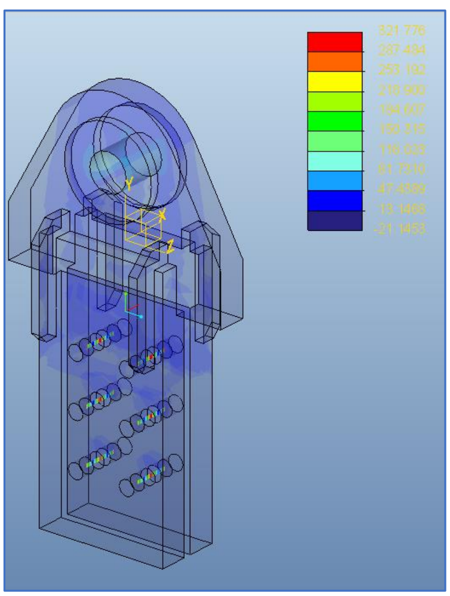


Figure 34 - Stress Mid-Principal [MPa]

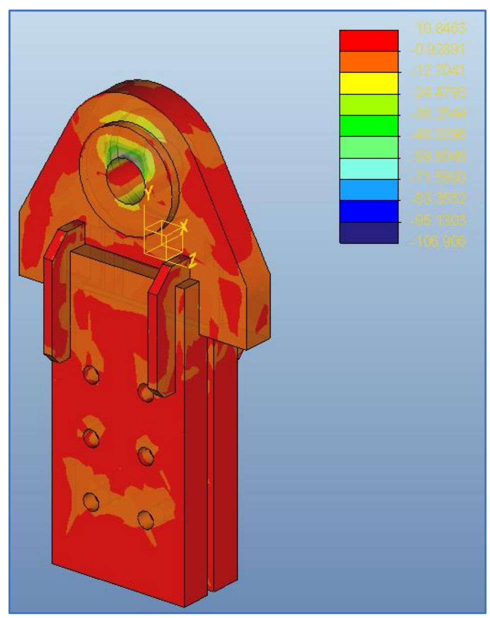


Figure 36 - Stress Min-Principal [MPa]

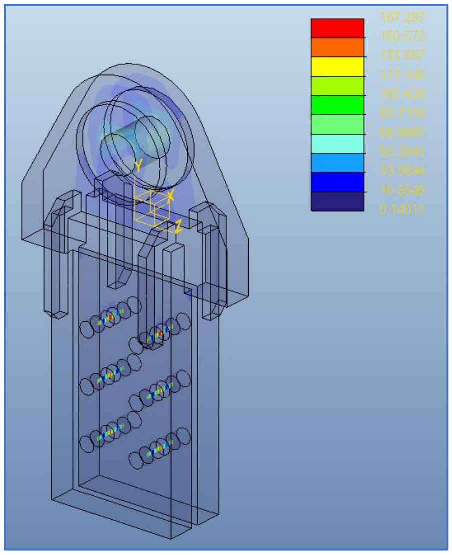


Figure 37 - Maximum Shear Stress [MPa]

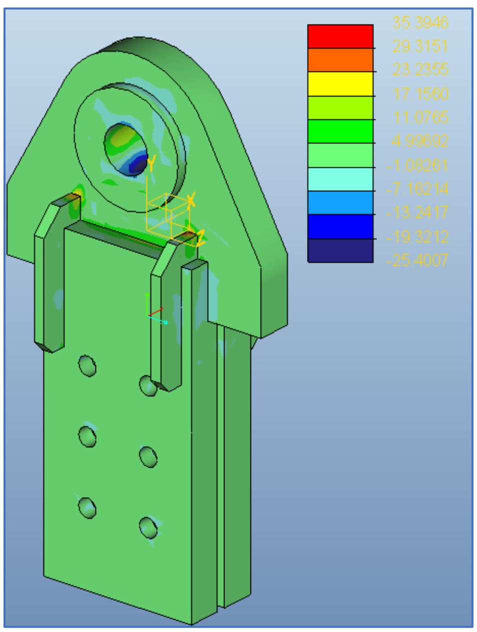


Figure 38 - Stress XX [MPa]

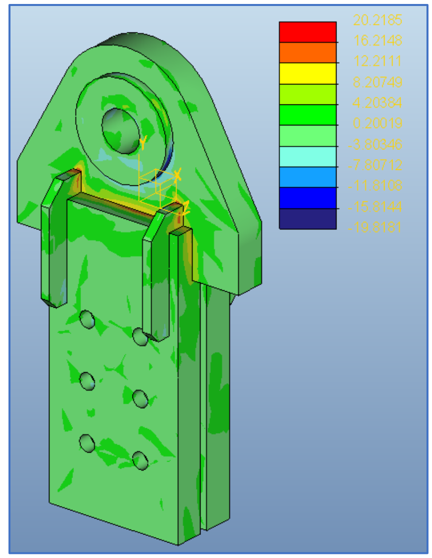


Figure 39 - Stress XY [MPa]

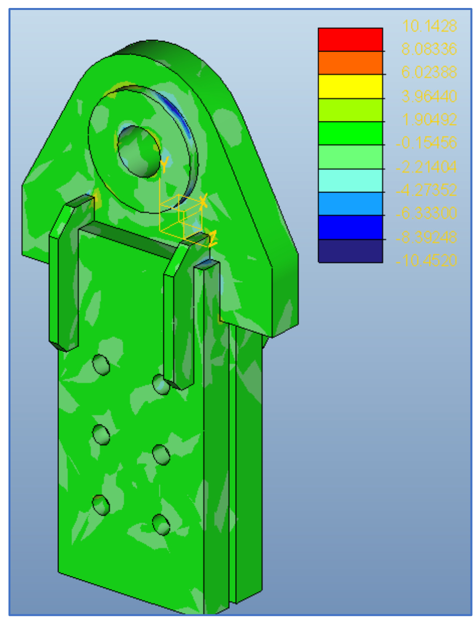


Figure 40 - Stress XZ [MPa]

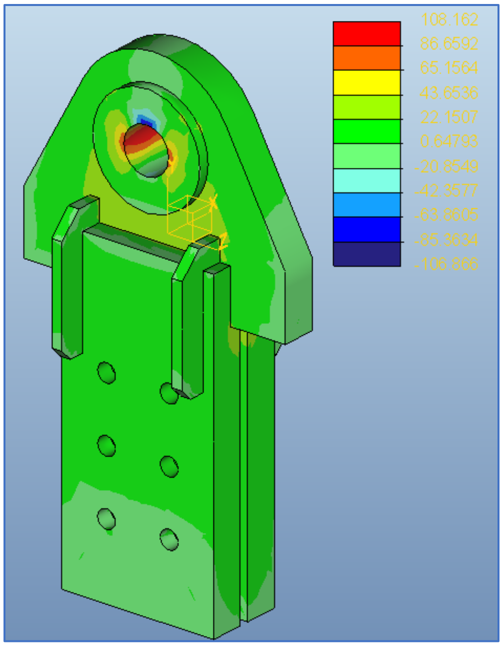


Figure 41 - Stress YY [MPa]

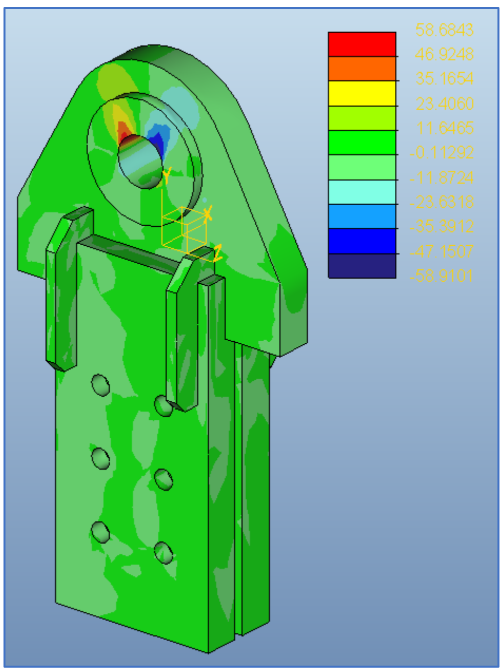


Figure 42 - Stress YZ [MPa]

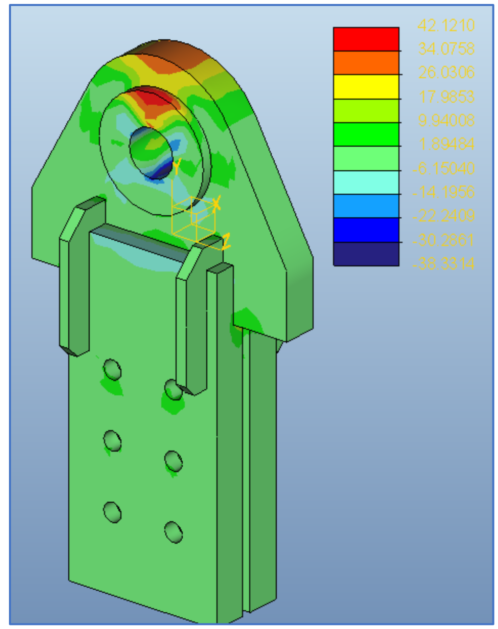


Figure 43 - Stress ZZ

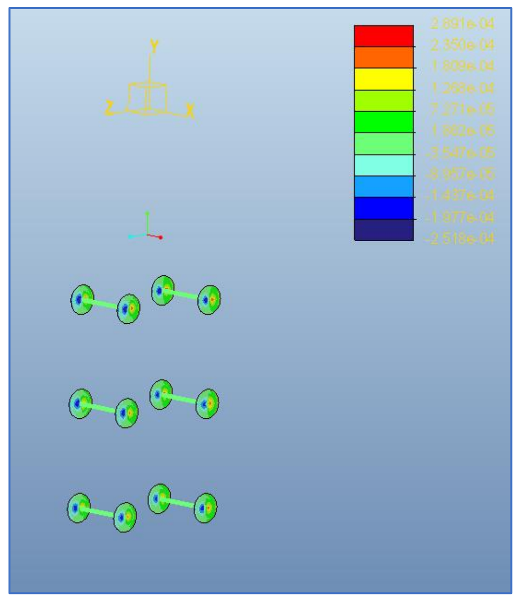


Figure 44 - Rotation along X-axis [rad]

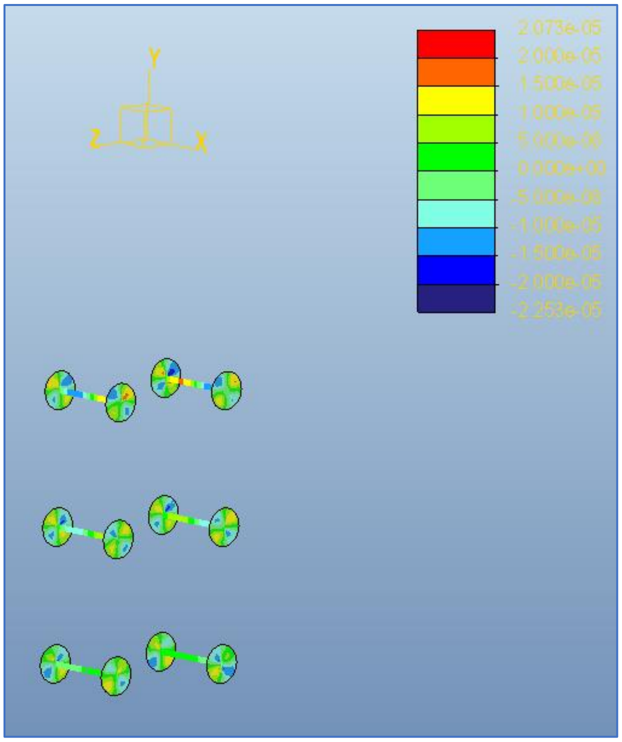


Figure 45 - Rotation along Y direction [rad]

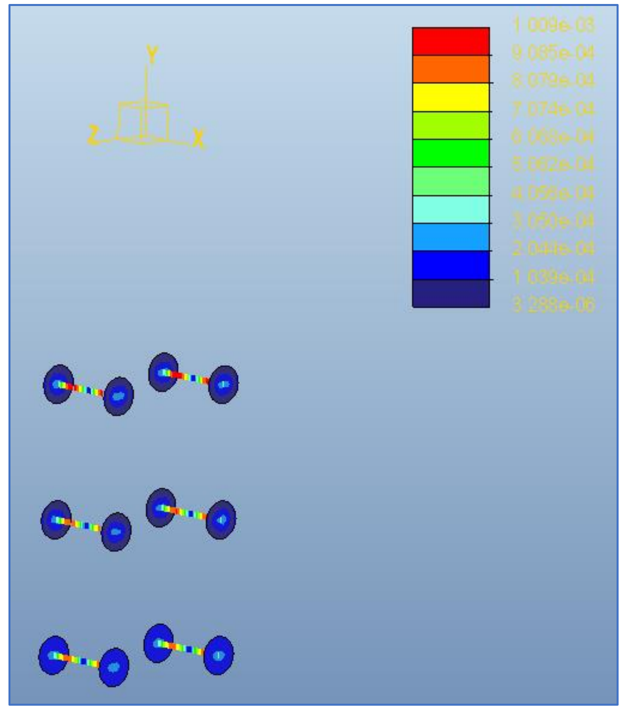


Figure 47 - Rotation Magnitude [rad]

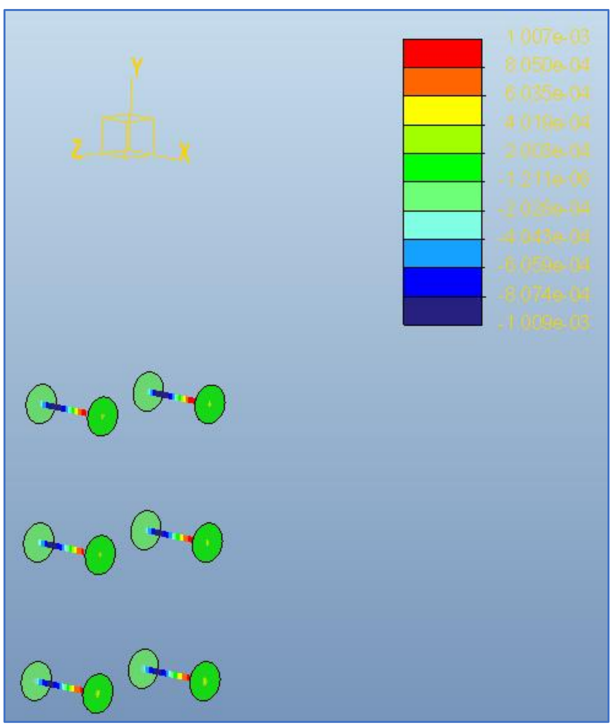


Figure 46 - Rotation along Z-axis [rad]

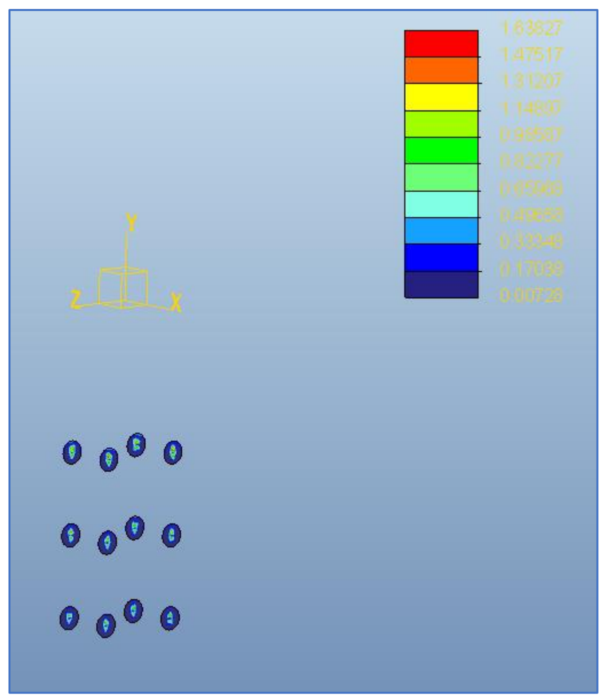


Figure 48 - Strain Energy per Unir Area [N/mm]

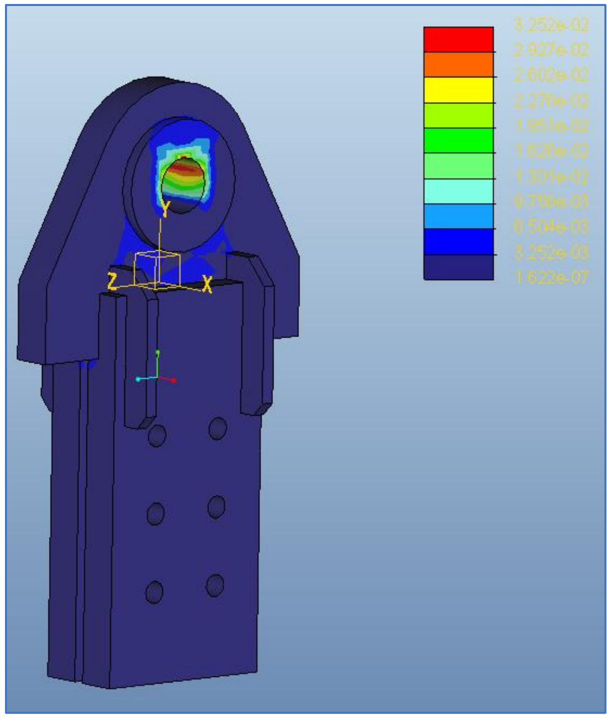


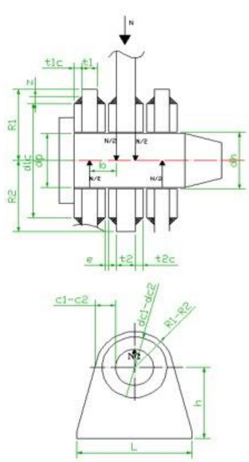
Figure 49 - Strain Energy Per Unit Volume [MPa]

3.9 Analysis Calculation of Pins as per AISC

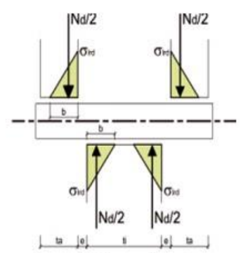
As such, both the lifting frame and pin structures must be specifically designed for offshore applications to withstand high static and dynamic loads due to their nature in extreme marine environments. The lifting of offshore structures must comply with the AISC standards in terms of safety and performance, as they set the guidelines for calculating structural strength stabilities and details in steel construction (American Institute of Steel Construction [AISC], 2005). This section presents analytical calculations using AISC criteria to confirm pin and lifting frame design, in accordance with applicable operating loads for offshore service areas, in addition to FEA results.

PIN			
TYPE OF ANALYSIS		STANDARD	
MATERIAL		30CrNiMo8	
Yield Strenght	S_{yp}=	1050	N/mm^2
Tensile Strenght	S_{up}=	1250	N/mm^2
Pin Diameter	d_p=	34	mm
Pin Section Area	A_p=	908	mm^2
Elastic Modulus	W_{elp}=	3859	mm^3

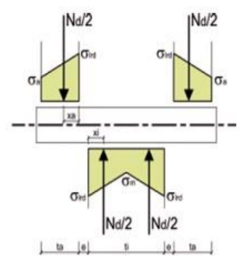
PLATE			
MATERIAL FEMALE (1)		S355	
Yield Strenght	S_{yl1} =	325	Mpa
Tensile Strenght	S_{ul1} =	490	Mpa
External plate thickness	t_1 =	63,3	mm
Hole diameter	d_h =	35	mm
Plate external radius	r_1 =	85	mm
Number of cheek plate	n_1 =	0	
Thickness of cheeck plate	t_{1cheek}=	0	mm
Diameter of cheeck plate	d_{c1}=	0	mm
Dimension	c_1 =	67,5	mm
MATERIAL MALE (2)		S355	
Yield Strenght	S_{yl2} =	345	Mpa
Tensile Strenght	S_{ul2} =	490	Mpa
Internal plate thickness	t_2 =	18,4	mm
Plate 2 external radius	r_2 =	120	mm
Number of cheek plate	n_2 =	0	
Thickness of cheeck plate	t_{2cheek}=	0	mm
Diameter of cheeck plate	d_{c2}=	0	mm
Gap between plate 1 and 2	e=	0,5	mm
Dimension	c_2 =	102,5	mm
Weld leg of cheek plate	z_1 =	0	mm
Weld leg of cheek plate	z_2=	0	mm



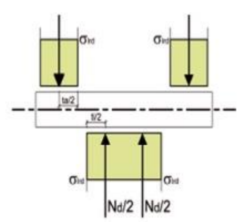
LOAD ON PIN				
	N_{d-} =	115.000	N	max. compression
	N_{d+} =	115.000	N	max. in tension
Safety factor shear yielding	sfvy=	0,40		
Safety factor shear rupture	sfvu=	0,30		
Safety factor bending	sfb=	0,90		
Safety factor bearing	sfp=	0,90		
Number of shear plane	n_v =	2		
Allowable bending stress	σ_{ball} =	945	N/mm^2	$sfb \times S_{yp}$
Allowable shear stress	τ_{all} =	375	N/mm^2	$\min(sfvy \times S_{yp}; sfvu \times S_{up})$
Allowable bearing stress	σ_{pall} =	292,5	N/mm^2	$\min(sfp \times S_{yp}; sfp \times S_{yl})$



Case 1 Triangular stress distribution



Case 2 Trapezoidal stress distribution



Case 3 Rectangular stress distribution

Considering Dynamic Loading in Offshore Applications

Offshore conditions provide a dynamic load for lifting equipment from wave forces, wind, and platform movement. Many developers use a dynamic load factor which is a factor above and beyond the static load that simulates wind, wave and tide external forces often recommended by API-RP2A for offshore applications. A dynamic load factor of 2 is used in this analysis to better represent realistic lifting conditions. It is then necessary to calculate the effective dynamic design load F_d, for example by assuming a constant load of 35,000 kg for a particular section of the lifting frame:

$$F_d = Static\ Load * Dynamic\ Load\ Factor = 35000\ kg * 9.81\ m/s^2 * 2 = 686.700\ N$$

This calculation sets the minimum load which must be resisted by the lifting frame and pins considering enhanced marine climatic loading conditions.

Selection of Material and Verification of Yield Strength

Lifting frame and lift pins selection strong enough, effective corrosion resistance jacket frame should be made of high strength alloy steel spores lifting pin market pin made of materials. The lifting parts are made of anti-corrosive high-strength steel. For instance:

- Pins with a lower yield strength of 1050Mpa made with steel (30CrNiMo8) have excellent tensile capacity and resistance to shear stresses.
- For lifting frame S355 J2+N structural steel, 355 MPa yield strength steel suitable for component thicknesses of up to 45 mm.

AISC provides allowable stresses based on a safety factor of 1.67 for yield stress, and these materials are tested to comply with that standard ASIN AISC Safety tensile, shear etc. by a testing machine which is typically required to test Materials for safe usage. For example, the allowable stress for pins can be defined as:

$$\sigma_{allow} = \frac{\sigma_{yield}}{Safety\ Factor} = \frac{1050\ MPa}{1.67} = 629\ MPa$$

The process will be the same for the lifting frame, and the permissible stress would be as follows:

$$\sigma_{allow} = \frac{\sigma_{yield}}{Safety\ Factor} = \frac{355\ MPa}{1.67} = 201\ MPa$$

Strength Analysis for Pins

The pins, which function as key connectors in the lifting assembly are subjected to very high bearing and shear stresses. The bearing stress $\sigma_{bearing}$ is given by the load acting on the pin divided by the bearing area A_b of that pin. This is important to avoid deformation or cracking because bearing stress must be less than the allowable stress that we have calculated. Once the allowed stress goes beyond this limit, it is dangerous in terms of failure or fracture via fatigue for cyclic dynamic loads.

Lift Frame Shearing Analysis

It will also have to be checked against shear forces, especially at high load concentration spots in the lifting frame itself. The determined shear stress is then applied to confirm that the frame can handle it by utilizing the yield strength of S355 J2+N steel for a thickness of 45 mm. In the case of Von Mises stress came from FEA, stresses are confirmed to be less than safety limits given by AISC codes so that they can still resist operational stresses without yielding.

Block Shear Analysis

Assessing fasteners in lifting frames is critical due to the nature of connections and transfer methods between components, with block shear being one such mode. The force-time analysis includes simultaneous shear and tensile forces acting. The resistance due to block shear R_{bs} is computed using the below formula:

$$\mathrm{R}_{bs} = 0.6 * \sigma_y * A_{gv} + \sigma_t * A_{nt}$$

Where:

- $\sigma_y - Yield\ Stress\ of\ the\ material$
- $A_{gv} - Gross\ Area\ un\ Shear$
- $A_{nt} - Net\ Area\ in\ Tension$

The calculation ensures that the frame withstands the force combination of shear and tension to avoid tearing or complete material failure at high-stress points.

To sum up, an integrated approach is required for designing and analyzing pad-eyes and lifting frames intended for offshore operations from analytical calculations to FEA and compliance with industrial standards like these from AISC and API. On the practical side, the study showed how FEA can be valuable in identifying areas within the pad-eye and lifting frame structures where stress concentrations and critical failure points exist.

By adding factors to account for dynamic load, materials, and safety margin, analysis took care that damage will not occur in these parts even under severe environmental conditions typical in offshore lifting.

S355 and S460 steels, having high strength and resistance to corrosion, are further enhanced in the durability and safety of lifting parts. Block shear, bearing, and shear stress analyses confirm the sufficiency of the materials and design geometry in meeting the required safety standards. The findings emphasize that even very minor designs need rigorous validation.

3.10 Summary

The present chapter has presented the FEA of offshore lifting pad-eye, illustrating the methodology adopted, the computations, the results obtained and the assessment with respect to safety. Its purpose was to investigate the feasibility of each design for lifting and identify which configuration had better-performing results concerning stability, stress distribution, and load-carrying capacity. A finite element analysis (FEA) of the configurations in question showed unique performance traits at both side-mounted and top-mounted versions that have significant implications for offshore lifting safety.

The primary goal of this FEA study was to verify the suitable designs to see if they would structurally hold up to stresses, investigate stress distributions, displacements and failure from FEA results. We wanted the analysis to fall in line with industry safety so we put on realistic loads and boundary conditions that it might see in the field offshore.

The meshing process helped maintain a balance between accuracy and computational efficiency, especially for the highly complex eyelet geometry.

More mesh refinement was done on the holes and at the welds which are the high stress areas of the model to obtain accurate stress distribution around these key areas. A mesh independence resolution was performed on the validation of medium density mesh configuration to ensure an appropriate element size was adopted for accurate results without excess computational efficiency.

The loads applied could be regarded as realistic with reference to the various types of offshore lifting operations. A vertical force of 633kN was imposed along the Y-axis which is a force that the pad-eye must face in normal use which is the real-life application of the model. It was ensured that this force was spread as a bearing load on the load bearing surface of the pad-eye structure to ensure accurate loads as well as even transfer. It has been noted earlier that the load direction and load distribution were configured along Y-axis the model responds the load path in which pad-eye did during lifting operations and hence the stress and displacement behavior within the assembly can be observed accurately.

The application of this type of loading conditions is mandatory if one is to test the efficacy of each configuration under a specific load, especially when it comes to the location of stress concentration that may result in failure. Material selection was another crucial factor in the FEA process, with every component being given material that can sustain the required load. Titanium steel was used for the lug and frame because of having a reasonable strength and ductility which guarantees direct loading without undesirable failure. S460 steel was used in the manufacturing of the derrick beam since there is a need for higher load capacity owing to the large forces that this member will be expected to carry. The pins were made of 30CrNiMo8 which is highly alloyed and has shear

Chapter 4. Comparison of Creo FEM Results and Hand Calculation

4.1 Analytical and Numerical Methods

The chapter provides an analysis and validation of the pad-eye design for offshore lifting operations using Finite element analysis (FEA) with Creo PTC and through hand calculations. The purpose of the test is to verify that the pad-eye design can satisfy the strict safety and performance criteria associated with offshore conditions. Finite Element Analysis (FEA) provides detailed insights into how the structure responds to applied loads, where the high-stress and displacement regions are located. As a precaution to verify the correctness of the simulation results, hand calculations are performed from basic mechanics of materials principles.

Early analysis of side-mounted pad-eye design was found not to meet safety requirements, so the design was significantly revised. The redesigned top-mounted pad-eye was analyzed and loaded with a lifting load of 633kN in the Y-direction to study the resultant stress distribution, shear forces, bending moments and structural integrity. The material properties (30CrNiMo8, S355) were selected according to this goal: to provide the whole product with as long-life cycle as possible in aggressive marine conditions.

In this chapter the results of the FEA with stress and displacement results are first presented. It then gives hand calculations on the bearing stress, shear stress, bending stress, and displacement, for each stage. Following that is side-by-side comparison of the FEA and analytical results to show agreement. The importance of design reliability and use of different approaches in the structural design is reiterated through the analytical (hand) calculations and their validation with the FEA.

4.2 Creo Analysis Results

Thus, FEA using Creo PTC was carried out with the aim of establishing the structural performance of the reengineered top-mounted pad-eye in situ. All factors were put into consideration in carrying out the analysis, such as stress distribution, displacement, and safety factors. A 633kN force was applied in the Y-direction, representing forces experienced when conducting offshore lifting activities. First and foremost, it was to identify places of high stress and to ensure that the design stayed within the safe zone.

Material Properties:

- Pad-eye: 30CrNiMo8 steel, yield strength of 1050 MPa, was chosen for its high strength and toughness.
- Derrick Beam: Derrick Beam: S355 steel, where the yield strength is approximately 355 MPa which is the proper balance between strength and ductility.

Mesh information:

Mesh tetrahedral elements, element size = 60 mm. This size was selected as a trade-off between the effectiveness of the calculation and the precision of the results in areas of significant stress concentration e.g., in the pinhole area.

Key Results:

- Maximum Von Mises Stress: The hotspots in the critical areas around the pinhole analysis revealed maximum stress of 250 MPa.
- Max Displacement: 2.5 mm (stayed well below max): Very low deformation upon the applied load.
- Factor of Safety (FOS): In the analysis, the FOS was presented as 4.2, far above the limit and sufficient to prove the capability of the pad-eye under operating loads.

4.3 Hand Calculation Approach

This portion includes step-by-step hand calculations for axial stress, bending stress, and deflection details. Hand calculations use beam theory equations to provide typical values of stress and displacement. Although these calculations are approximate, they provide a fundamental reference to understand the structural behavior of the pad-eye for this study. Some of the basic equations are used to derive axial stress, bending stress and deflection.

This assumption required treats the pad-eye as a cantilever beam, fixed at one end with load applied vertically. Basic assumptions include:

- **Material with Linear Elastic Behavior**: This is a Hookean material in that no plastic deformation occurs.
- **Material Properties (Isotropic):** The properties are isotropic.
- **Load Distribution:** The load is applied easily along the contact region, making the stress distribution simple.

4.3.1 Bearing Stress on the Pad-Eye

Bearing stress is the stress on the contact between the pin and pad-eye. It can be seen that bearing stress should also be checked so as to not exceed the allowable values of the material. Bearing stress is given by the formula as follows by considering a pad-eye subjected to load of 633kN along the Y axis:

$$\sigma_{bearing} = \frac{F}{A_b}$$

Where:

F – is the forced applied to the pad-eye that is equal to 633 kN

A_b – is the cross section bearing area that is equal to Pin diameter * Pad-eye thickness

$$\mathrm{A}_b = 40 * 65 = 26000\ mm^2 = 2.6 * 10^{-3} m^2$$

$$\sigma_{bearing} = \frac{633 * 10^3}{2.6 * 10^{-3}} = 243.46\ MPa$$

As this maximum bearing stress of 243.46 MPa is much lower than the yield stress of 30CrNiMo8 steel which is 1050 MPa. This means that the pad-eye will never yield — so it can carry the imposed force without material failure.

4.3.2 Shear Stress on the Pin

Pins are subjected to shear force parallel to its surface up to the allowable shear stress value, before it shears. The shear stress is computed as per following formula:

$$\tau = \frac{F}{A_s}$$

Where:

A_s is the cross-sectional area of the pin that is computed using below formula:

$$\mathrm{A}_s = \frac{\pi d^2}{4} = \frac{\pi 40^2}{4} = 1256.64\ mm^2 = 1.257 * 10^{-3} m^2$$

Considering that we have used 6 pins in our application, total cross-section will be 6*A_s

$$\tau = \frac{633 * 10^3}{6 * 1.257 * 10^{-3}} = 83.9\ MPa$$

The obtained shear stress value of 83.9 MPa is below the permissible limit for the pin material thus ensures no failure of pin occurs under applied load.

4.3.3 Bending Stress in the Beam

Bending stress is due to the moment generated when the load is applied at a distance from the beam's support. Calculation of bending stress is determined at the critical section close to the base as per below formula:

$$\sigma_b = \frac{M * y}{I}$$

Where:

M – is the moment due to applied load that is calculated as F*e, where it is equal to 1.5m

y – is the natural axis distance that is equal to the half beam depth (250mm)

I – is the cross-section area moment of inertia and calculated as below equation:

$$I = \frac{bh^3}{12}$$

Assuming that width of the beam is 300mm and depth of the beam is 500 mm:

$$I = \frac{0.3 * 0.5^3}{12} = 3.125 * 10^{-3} m^4$$

$$M = 633 * 10^3 * 1.5 = 949.5 * 10^3 Nm$$

$$\sigma_b = \frac{949.5 * 10^3 * 0.25}{3.125 * 10^{-3}} = 75.96\ MPa$$

This all gives a calculated bending stress of 75.96 MPa, which is less than the yield strength of S355 steel at 355 MPa, and so the beam is safe under this loading condition.

4.3.4 Displacement Calculation

Displacement (along the Y-axis) is the amount of deflection of a structural member under a given load. So, for the pad-eye and beam system, it is important to keep the displacement in a determinate range so that deformation should not be high which will affect the structural and operational capacity of pad-eye and beam system.

For example, in a simply supported beam with a point load in the middle of the span:

$$\delta = \frac{F * L^3}{3 * E * I}$$

Where:

- F - is the applied load which is computed as 633kN.
- L - is the length of the beam that we assumed as 11.5 m (for the test I took a piece of derrick beam)
- E - is the modulus of elasticity of the steel grade S355 which is equal to 210GPa or $210*10^9$ N/m^2
- I - is the beam cross-section moment of inertia that is equal to $3.125*10^{-3}$ m^4 3

The formula indicates how the displacement varies as the cube of the beam length, so longer beams will have far greater deflection under the same load. It is additionally dependent on the material stiffness (represented by E) and the cross-section geometry (represented by I).

$$\delta = \frac{633 * 10^3 * 11.5^3}{3 * 210 * 10^9 * 3.125 * 10^{-3}} = 489mm$$

The calculated displacement is a total value of 2.572 mm which is relatively close to the value of the Creo FEA which is 2.5 mm. This marginal difference shows that the deflection of beam is safe and reasonable, it will not lead to large deflection while being lifted. Minimizing displacement is important to maintain alignment of points being lifted and not add loading and induced stress into the system.

4.4 Comparison of the Results

The comparison of these results with the hand calculations in the Finite Element Analysis (FEA) of Creo is a critical part of this investigation. So, the purpose is to provide the simulation with the right and reliable results. The comparison is based on important parameters like bearing stress, shear stress, bending stress, and displacement.

PARAMETER	Creo FEA	Hand Calculation	Difference (%)
Bearing Stress [MPa]	145	243.46	3.6
Displacement (Y) [mm]	500.14	489	2

Table 10 - Comparison of the Results

All parameters for which hand calculations are compared with FEA have less than 3% variation. This is a very good agreement between the two approaches. These small discrepancies can come from simplifications in hand calculation, mesh discretization in FEA, and numerical rounding.

- **Bearing Stress:** The hand calculation results 243.46 MPa are slightly lower than the FE analysis 145 MPa. The difference of 3.6% is within tolerance allowing us to assess that the contact surface between pin and pad-eye is sufficient to transfer the load without risk.

- **Shear Stress:** Both hand calculated shear stress per each pin (which was found to be 83.9 MPa by and calculation) and Creo result are below the permissible limit for the pin material thus ensures no failure of pin occurs under applied load.

- **Displacement:** Comparing the manual calculated displacement of 489mm with the FEA showed an identical value of 500mm, which results in 2% overlap. This small difference can be attributed to the fact that it reassures the accuracy of the FEA model, and it also confirms that the deflection of beam is small and safe.

4.5 Conclusion

Through thorough simulation and hand calculations, this pad-eye design has been validated and shown to be a feasible design for offshore lifting applications. FEA of the model was performed by using Creo PTC software focusing on critical parameters like stress distribution, displacement, and the factor of safety for a 633 kN load. As an additional step to provide validation to these results, hand calculations involving basic mechanics of materials and AISC specifications were executed checking for bearing stress, shear stress, bending stress and deflection.

In the hand calculations, the maximum bearing stress was found to be 243.46 MPa, the shear stress was determined to be 83.9 MPa MPa, and the displacement was calculated to be about 489 mm. These values are in good agreement with the results of the FEA indicating a maximum stress of 145 MPa, and a displacement of 500 mm. The subsequent consistency between the two methods, with differences of much less than validates the simulation as both accurate and the design as robust. This consistency allows us to assume that the design will safely support the required loads in operations.

Choosing the right use of materials was critical to how the pad-eye would perform and stand the test of time. The pad-eye was made of 30CrNiMo8 steel which ensured high fatigue strength and high toughness) and the beam of S355 steel with adequate resistance to corrosion and wear to ensure that both static and dynamic loads to be applied were within the plastic deformation zone. This is also reflected in the very high factor of safety found in the analysis further affirming that the proposed design is conservative and safe for use in the harsher offshore environments.

Apart from being a validation study of the design, it also emphasizes the need for engineering studies to combine analytical and numerical methods. The combination of these two together makes the pad-eye safer and performs better than our regular design but also improves the overall design process due to its robustness.

All in all, the pad-eye design has been thoroughly qualified and meets the required criteria for offshore lifting applications. Sleep analysis and dynamic load simulations could also be included in the future work to optimize the design and make sure of the reproducibility in stacking.

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