University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Mechanical and Structural Engineering and Materials Science/Offshore Technology Engineering	Spring semester, 2018 Open access
Writer: Rahela Lokman Hemashrif	.... (Writer's signature)

Faculty supervisors: Ashish Aeran and Sudath C. Siriwardane

External supervisor(s):

Thesis title:

A Proposed Framework for Strengthening Mitigations of Offshore Jacket Structures and its Application

Credits (ECTS): 30

Key words: Mitigation methods Life extension Offshore jacket structures Framework Strengthening	Pages: 135 Stavanger, 15.06.2018

Abstract

The majority of offshore platforms and jacket structures are currently passing their assigned lifetime both on the Norwegian Continental Shelf (NCS), the Gulf of Mexico (GoM), the United Kingdom Continental Shelf (UKCS) and other parts of the world. The concern about ageing related issues and how to solve them is a major concern and presents a significant challenge in all sectors of the offshore oil and gas industry. The reason for mitigation and extending the lifetime of platforms is because there are still plenty of oil reserves left in existing fields. These fields are too small for stand-alone development and the construction of new platforms. Therefore, the use of existing infrastructure is a necessary and efficient solution. In addition, there are several monetary and environmental factors for extending the lifetime of platforms instead of decommissioning them. Mitigation of existing jacket platforms is especially a major concern, because the majority of offshore platforms around the world are jacket-type structures. However, the standards and codes that are available does not provide a detailed guideline for strengthening mitigation of offshore jacket structures. There is not sufficient information about the process and the necessary solutions for extending the lifetime of a jacket structure. In addition, the information is scattered among several codes, guidelines, standards and numerous published articles. To address this issue, a detailed framework is proposed that show a more precise and general guideline for the mitigation of an offshore jacket structure. A literature review is done to assess and collect the available information and present it in a clear overview. The proposed framework is more detailed and provides a list of mitigation techniques on an offshore jacket structure. It provides a better solution by addressing the issues related to the weld, the legs and braces, corrosion damage and structural integrity. At last, the significance of the proposed framework is highlighted through a case study where the proposed mitigation techniques are applied on an existing offshore jacket structure. The results from the case study are discussed and finally conclusions are drawn about the applicability and significance of the proposed framework.

Acknowledgement

This thesis finalises my Master's degree in Structural Engineering with specialisation in Offshore Constructions at the University of Stavanger. The work was done during the spring semester of 2018.

Firstly, I would like to express my sincere gratitude to my main supervisor Ashish Aeran for his continuous support and academic knowledge. His guidance and engagement made the work during this spring semester a genuine, positive experience.

I would also like to thank my co-supervisor, Associate Professor Sudath C. Siriwardane for his assistance. His advice during our countless group meetings were tremendously helpful.

During this time, I had to acquire in-depth knowledge about life extension of offshore platforms, ageing of offshore jacket structures, review several standards and codes, review numerous scientifically published articles, understand mitigation methods and learn to use SAP2000 for a case study. The guidance and advice I got kept the workload of this thesis on a steady path, and for that I am endlessly grateful.

Finally, I would like to thank my family and friends for their continuous support.

Rahela Lokman Hemashrif

Stavanger, spring of 2018

Table of Contents

Abbreviations

The most important and common abbreviations are listed below in alphabetical order.

ALS	Accidental Limit State
API	American Petroleum Institute
CHS	Circular Hollow Sections
CP	Corrosion Protection
CPC	Corrosion Protection Coating
CPS	Corrosion Protection System
DNV GL	Det Norske Veritas Germanischer Lloyd
FCAW	Flux Cored Arc Welding
FE	Finite Elements
FLS	Fatigue Limit State
FM	Fracture Mechanics
FPSO	Floating Production, Storage and Offloading
FRP	Fibre-Reinforce Polymer
GMAW	Gas Metal Arc Welding
GoM	Gulf of Mexico
GTAW	Gas Tungsten Arc Welding
HCF	High-Cycle Fatigue
HFMI	High-Frequency Mechanical Impact
HFP	High-Frequency Peening
HSE	Health and Safety Executive
HSS	Hot Spot Stress
ISO	International Organization for Standardization
IIW	International Institute of Welding
KP	Key Program
KP 4	Key Program 4
LCF	Low-Cycle Fatigue
NCS	Norwegian Continental Shelf

NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NORSOK	Norsk Sokkels Konkurranseposisjon (Norwegian Shelf Competitive Position)
OTM	Original Tubular Member
PE	Polyethylene
PP	Polypropylene
PSA	Petroleum Safety Authority
RHS	Rectangular Hollow Sections
RP	Recommended Practices
SCC	Stress Corrosion Cracking
SHS	Square Hollow Sections
SIM	Structural Integrity Management
SLS	Serviceability Limit State
SMAW	Shielded Metal Arc Welding
SMR	Strengthening, Modification, Repairs
TIG	Tungsten Inert Gas
UC	Unity Check
UIT	Ultrasonic Impact Treatment
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
ULCF	Ultra-Low-Cycle Fatigue
ULS	Ultimate Limit State
US	United States

Symbols

The most important and common symbols are listed below in alphabetical order. Symbols that are not listed here is defined in the text where they are used.

D	Yearly cumulative fatigue damage
$\frac{da}{dN}$	Crack growth rate
E	Tensile modulus, GPa
Fe	Iron
f_y	Characteristic yield strength
H	Hydrogen
k	Number of stress blocks
$log\ \bar{a}$	Intercept of $log\ N$ axis
N	Number of cycles
N_i	Number of cycles that lead to failure at a constant stress range $\Delta\sigma_i$
n_i	Number of stress cycles in stress block i
O	Oxygen
R_{corr}	Corrosion rate (in mm/year)
S	Stress ranges
SCF	Stress Concentration Factor
t	Time (in years)
t_{pt}	Corrosion protection (in years)
$W(t)$	Thickness wastage
ΔK	Range of stress intensity factor
$\Delta\sigma$	Stress range
σ	Stress
$\sigma_{nominal}$	Nominal stress
$\sigma_{hotspot}$	Hot spot stress

List of figures

1 Introduction

1.1 Background

Several of the offshore platforms around the world are now approaching or have already exceeded their design life [1-4]. The assigned lifetime for an offshore jacket structure is not exact, but approximately estimated to be from 20 to 25 years [2, 7, 10]. More than 50 % of the offshore installations on the NCS is operating beyond its intended design life, this presents a major technical and operational challenge [1-3]. Life extension and mitigation solutions are needed to overcome these difficulties. As of today, several major life extension programmes are in full-effect and more are to be initiated as we get closer to 2020. Tyra gas field, located in the Danish North Sea, is being redeveloped to extend its operational life by at least 25 years. The investment is the biggest ever made in the Danish North Sea [13]. Extending the life of a platform can have several benefits – especially in the environmental and economic sectors [3, 5]. However, safety requirements should never be compromised. It is important to mitigate an offshore jacket structure with accurate data and sufficient solutions to extend the lifetime without any failure or risk to the structural integrity. Offshore structures, especially steel jacket structures experience a wide range of stress throughout its design life. Corrosion and fatigue which causes damage and failure in the weld and structural members are the two of the most important ageing mechanisms [1, 3].

It is important to use mitigation techniques and methods in order to ensure technical, structural and operational integrity of these ageing jacket structures beyond their intended design life [6-8]. Structural integrity is one of the main concerns for ageing platforms, especially if major modifications are made which can result in higher loading, higher weight and unforeseen behaviour which the platform may have not been designed for [7, 8]. Because of this, a number of initiatives have taken place in the last 20 years with the aim to develop guidelines and framework in respect to the life extension and mitigation of ageing offshore platforms [1, 3]. The Health and Safety Executive (HSE) launched several key programmes on the UKCS related to ageing installations [3]. A structural integrity management framework for jacket structures was published in 2009, but was based on API and ISO standards [3]. In Norway, Norwegian Oil and Gas in collaboration with Petroleum Safety Authority (PSA) established necessary guidelines, and the result was a new NORSOK standard, N-006. During the 1990s several inputs were made into API RP 2A, but these inputs were based on US waters. Similar editions were added to ISO 2394, ISO 13822, ISO 19900 and ISO 19902, but contains minimal details or quantitative information [3, 9]. In 2014, the API RP 2SIM was released for the life extension of offshore facilities. In 2015, DNV GL established new guidelines for the probabilistic method for planning of inspections for fatigue crack growth in offshore structures [3]. In addition, several scientific articles and published literature provide some insight and recommendations for the mitigation of offshore jacket structures, but these are often based on older standard and codes, and do not provide a clear and detailed framework. The information across these articles is also scattered, which can lead to mix-up and confusion. There is a need to make the mitigation techniques more applicable by providing a framework to follow and not be dependent on case-by-case studies. The standards do not give a clear and detailed guideline for the mitigation of offshore jacket structures. Comprehensive mitigation recommendations are needed for different type of age-related damage to the jacket structures, presented in a straight forward manner. These can be established by adding relevant theory and models, and try them out on certain case studies. The available guidelines are not sufficient in regard to mitigation suggestions. The information is scattered across several standards and codes, with no clear framework to go by.

This paper proposes a clear framework in respect to the mitigation of offshore jacket structures (in the NCS). Furthermore, clear figures and tables are added to assess which type of mitigation technique is suited for which type of age-related damage with more precise recommendations. A literature review is done to highlight what the latest standards, codes and published articles have established so far in the mitigation techniques for offshore jacket structures. Then, a proposed framework is presented in detail. Highlighting detailed suggestions for the life extension of an offshore jacket structure. Finally, a case study is done to show the effectiveness of the framework and in the end conclusions and recommendations are drawn.

1.2 Objectives of the Thesis

Based on the clear problems presented above, the main objectives of this thesis are:

- To do a literature review/survey of the latest published data about life extension and mitigation techniques for offshore jacket structures (in the NCS).
- To organise and evaluate all existing mitigation techniques related to ageing offshore jacket structures.
- To propose a framework for strengthening mitigations of offshore jacket structures. Such a framework will make mitigation suggestions more streamlined as the available information is scattered across numerous standards, codes and published literature. This will also make the mitigations more standard across organisations rather than adopting case dependent customised mitigations.
- To apply the proposed framework on an existing jacket structure. The proposed mitigations will be applied for different damage scenarios and results will be compared to highlight the significant of the proposed framework.

1.3 Limitations of the Thesis

The life extension of offshore jacket structures and in general, offshore platforms is a very broad topic. This thesis is limited to fixed offshore jacket structures (in the NCS). With emphasis on the mitigation methods related to the jacket-legs and the tubular members.

The mitigation suggestions are mainly related to the structural integrity of the jacket platform and age-related damage. The issues that are highlighted are damages to the jacket-legs and tubular members, corrosion damage near the splash-zone and weld defects/fatigue damage around the joint connections.

Because of the broadness of the topic, not all of the published literature related to life extension and mitigation methods could be comprehensively included in this thesis. Some data were examined but were found to be of little use or not detailed enough in terms of the problems presented in this thesis and were therefore left out.

1.4 Organisation of the Thesis

An overview of the main chapters is given in the Table 1.1 with a short summary of each chapter.

Table 1.1: Overview of the thesis

Chapter 1 – Introduction Main objectives of the thesis.
Chapter 2 – Theoretical Background Background information related to life extension of jacket structures.
Chapter 3 – Mitigation Methods According to Current Standards and Guidelines Mitigation methods as per standards and guidelines (NORSOK, DNV GL, API and HSE).
Chapter 4 – Recent Research from Published Literature on Life Extension and Strengthening Mitigations Research related to life extension and mitigation methods for offshore jacket structures.
Chapter 5 – Proposed Framework for Strengthening of Offshore Jacket Structures A proposed framework that provides mitigation methods for offshore jacket structures.
Chapter 6 – Application of the Proposed Framework on a Jacket Structure – Case Study The framework is applied to a jacket structure to show the effect of the selected mitigation methods.
Chapter 7 – Discussion and Conclusions Discussion and conclusions of the thesis.

2 Theoretical Background

2.1 Overview of the Chapter

The subchapters below explain what life extension is and gives an overview of the fundamental theory related to the life extension of offshore steel jacket platforms. This is important information which needs to be understood to fully comprehend the later chapters in this thesis.

Fundamental theory is laid forward about general life extension, mitigation, ageing and the assessment process for life extension. Information related to steel jacket structures, tubular members and their main failing mechanises; corrosion and fatigue is also presented below.

2.2 Offshore Jacket Structures and Tubular Members

Offshore jacket platforms have been used in the oil and gas industry since the beginning of offshore oil exploration and production. A fixed platform is built by the use of steel and/or concrete. A steel jacket platform is mainly built by the use of steel. The jacket-legs are anchored directly onto the seabed with piles. The piles provide safe foundation for the platform. The jacket structure is then fixed and supports the deck and topside including all production units, living quarters and drilling rigs. Steel jacket platforms are made of steel tubular members and joints resulting in a very rigid and stable structure. These platforms are built for long-term production and are economically feasible for installation in water depths up to 300 meters. Usually the jacket-legs are constructed onshore and transported into place later in the sea with the use of big transport and installation vessels. After that, the topside is installed on top of the jacket-legs by the use of crane ships.

Figure 2.1: Transportation of the jacket-legs for the Bullwinkle platform in the GoM [10]

Even though jacket platforms are a proven technology and used commonly around the world, they are still accessible to damages resulting from usage, ageing and environmental loads. In the NCS, jacket platforms are designed and constructed according to NORSOK and ISO standards with the PSA providing laws and regulations to be followed. The four limit states that are important to check for, which ensures total structural integrity are [14]:

Table 2.1: Limit states

Limit states	Abbreviation	Definition
Ultimate limit state	ULS	Ultimate resistance for handling loads. Ultimate strength of the structure.
Serviceability limit state	SLS	Resistance to normal use, durability during service life.
Fatigue limit state	FLS	Resistance to fail due to cyclic loading over time.
Accidental limit state	ALS	Resistance to accidental events or operational failure.

In terms of mitigation, if major modifications are made, ULS and FLS are the most important limit states that needs to be considered in future planning. These two limit states provide significant information about the structure and whether it is structurally stable or not [14].

2.2.1 Tubular Members

Tubular members are widely used in various fields and especially in the offshore industry where they are used to construct jacket platforms. These members are under heavy stress during their service life and experience large stress concentration factors. Tubular members are either Circular Hollow Sections (CHS), Square Hollow Sections (SHS) or Rectangular Hollow Sections (RHS) which are welded together to form tubular joints. These joints are subjected to cyclic loading which causes crack propagation induced by the harsh environment in the NCS and from other sources. Near the splash-zone these tubular members/joints are also subjected to corrosion [14]. Figure 2.2 shows some common tubular welded joints used in jacket structures.

The life extension of a steel jacket platforms is dependent on the assessment of these tubular members and joints. Later in the case study the tubular parts of the jacket-legs are mitigated through the use of different mitigation techniques which are discussed in details later in the thesis.

Tubular members are used as the main load-bearing members in marine environments. Tubular members are used in drilling rigs, offshore wind structures, jacket structures and many other forms of construction [70]. The cyclic behaviour of bracing members has been the subject of investigation by several researchers. Rigid connections, as found on jacket structures provide improved stiffness to the structure, however they do cause the formation of plastic hinges at the member ends [67]. Tubular members fail mainly because of buckling or crushing due to compressive loads [15]. Buckling can be defined as a sudden failure which arises from instability of the structural member and usually happens at stress levels relatively lower than the ultimate stress level of the material [15]. Local buckling occurs when members with high d/t-ratio as in thin-walled cylinders fail by crushing or yielding. Global buckling occurs when members with low d/t-ratio as in thick-walled cylinders fail by buckling (column buckling).

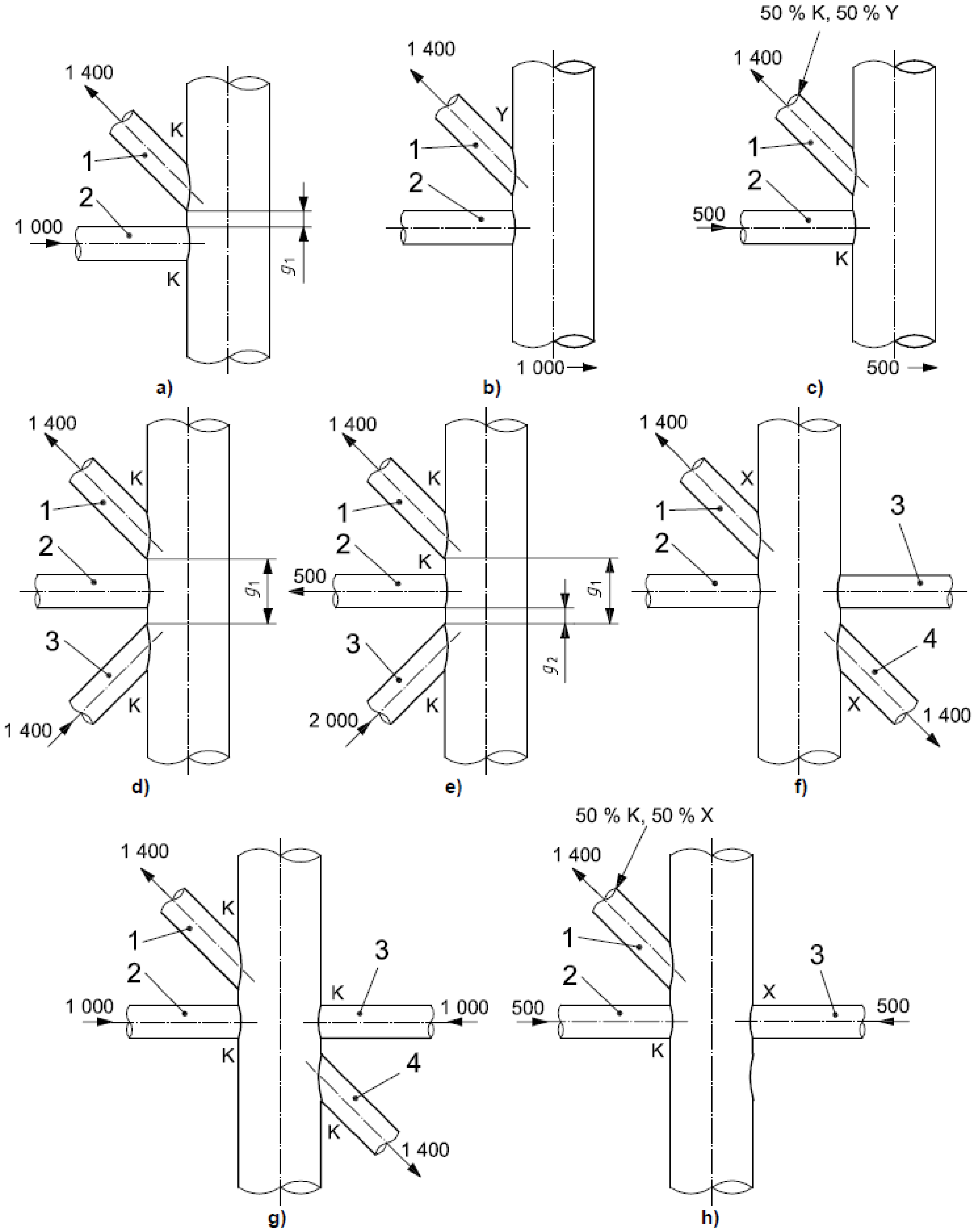


Figure 2.2: Type of joints used in jacket structures [31]

2.3 Ageing Mechanisms in Offshore Jacket Structures

This subchapter details the term ageing and the issues related to the ageing of offshore jacket platforms.

Ageing is not necessarily limited to the exact age of the structure. It can be categorised as deterioration of a platform over time because of wear and tear, external and internal corrosion, structural fatigue, obsolescence of equipment, reduction of equipment reliability, changing environments, accidental damage and marine growth [4, 11].

The ageing process is depicted by the "bathtub curve". It shows the following characteristics [4, 6]:

- Possible early life failures associated largely with fabrication defects
- Failures associated with operational wear and tear
- Accelerated failure and loss of integrity with the onset of ageing

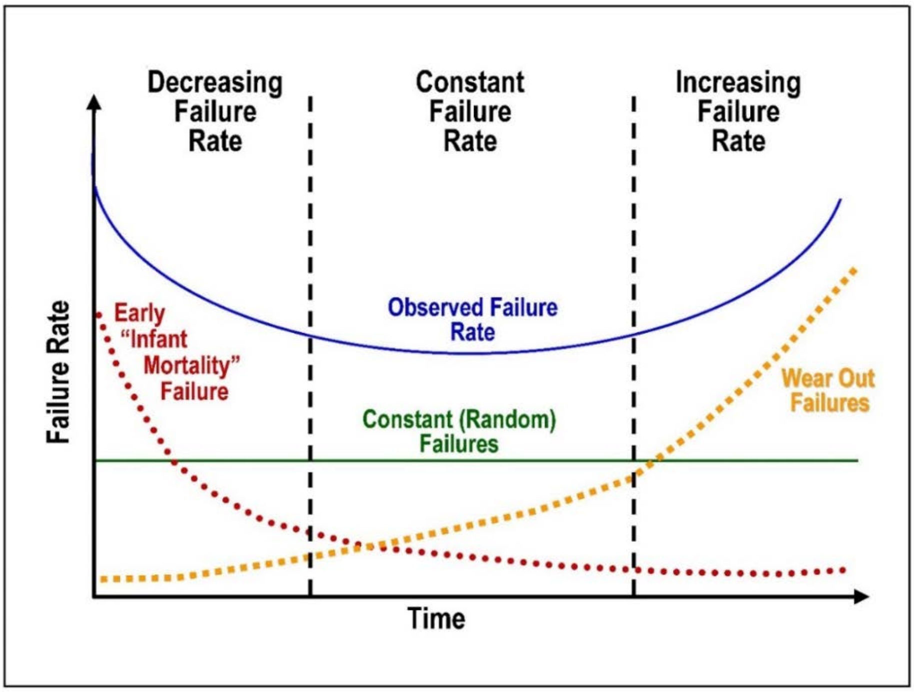


Figure 2.3: The bathtub curve [4, 6, 16]

Ageing can be essentially categorised into four systems/mechanisms [8]:

1. Functional ageing: With time, the structure or system is becoming weaker and less able to fulfil its function. The functional ability and resistance is reduced because of physical wear and tear. This can be material degradation, damages, subsidence etc.

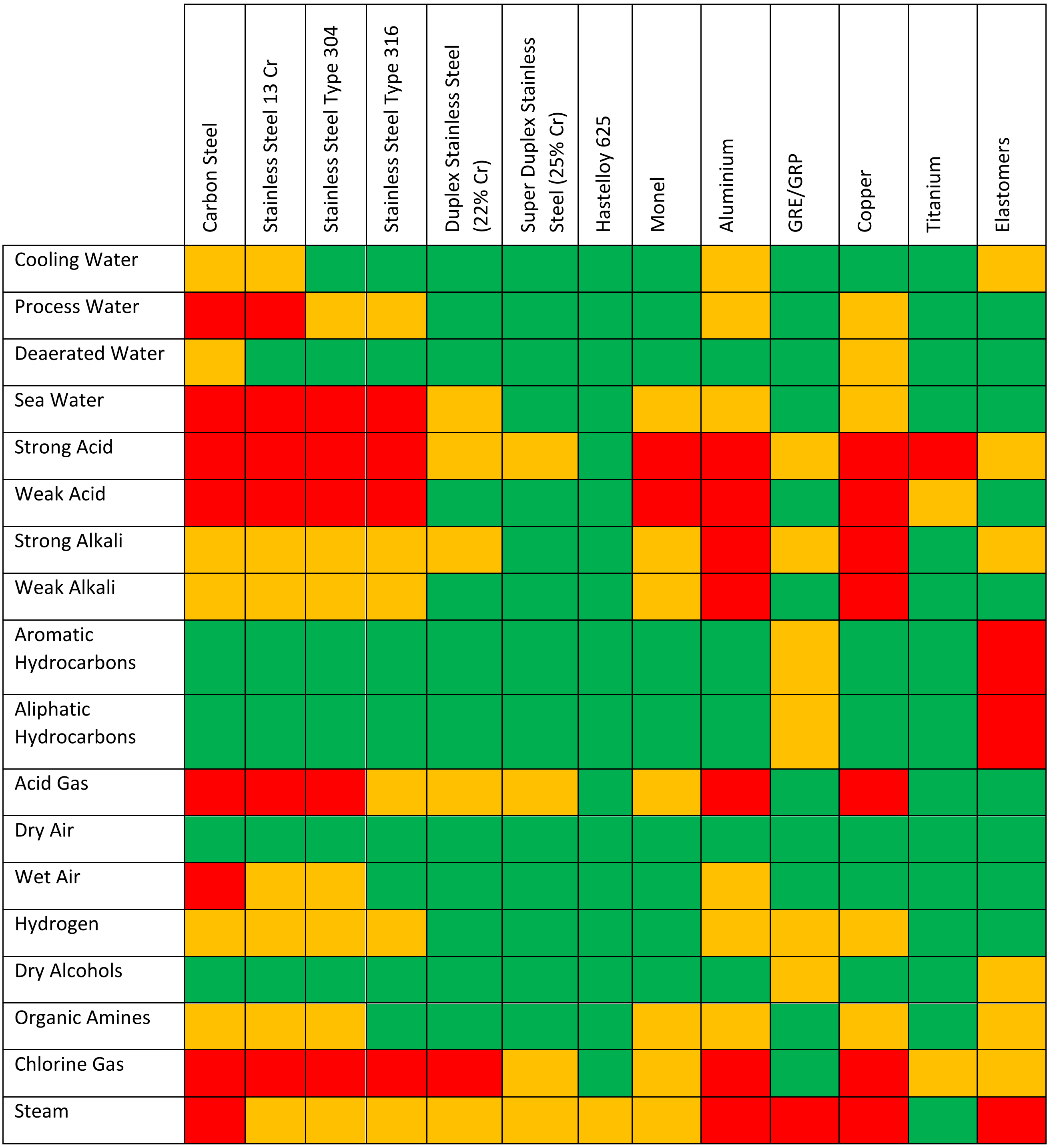
2. Technological ageing: Obsolescence, as in the present technology in the older structure or system is challenged by newer and improved technology. There can be compatibility issues between the older and newer technology and limited available spare parts due to outdated construction and installation techniques.

3. Knowledge based ageing: The structure or installation by newer standards and codes is less safe than was formerly assumed. The original design premise and outlines is outdated due to development of new knowledge.

4. Organisational ageing: The installation or system is not being taken care of, as in operated and maintained efficiently because of lack of information, change of ownership, re-organisation, retirements, lack of knowledge transfer and change of information storage systems.

An ageing accident affects a structure due to the one or more of the mechanisms given above. Table 2.3 gives some aspects of ageing on offshore installations [11, 12].

Table 2.2: Indicative guide to ageing plant degradation [12]



High likelihood of ageing degradation	
Medium likelihood of ageing degradation	
Low likelihood of ageing degradation	

In general, ageing of an offshore structure is usually characterised by deterioration which is caused primarily by fatigue and corrosion [8].

Table 2.3: Indicators of ageing and examples relevant to offshore facilities [11, 12]

Indicator of ageing	Examples relevant to offshore installations
External indicators of corrosion or deterioration.	Paint blistering, rust streaks, evidence of corrosion at joint connections, softening of passive fire protection. Surface corrosion may indicate that structural response has been adversely affected.
External indications of incomplete reinstatement.	Loose covers, ill-fitting enclosures, loose bolts, missing equipment, incomplete systems, e.g. F&G.
Variations in standards.	Modifications carried out to a higher standard while the original facility has earlier, lower standards.
Lack of commonality/incompatibility.	Replacement equipment of a later design or from an alternative supplier. Interface problems between modern and older control systems.
Deterioration in plant performance.	Difficulty in achieving a seal in isolation; Deterioration in pump performance, lower flow rates in deluge systems due to blockage, loss of sensitivity of detectors.
Deterioration in structural performance.	Initiation and propagation of fatigue cracks in structural members.
Deterioration of un-inspectable SCEs.	For example; foundations, ring-stiffened joints and single-sided joints.
Increasing congestion and lack of optimal layout.	Location of new plant such as pig traps in non-optimal locations, because of the lack of available space. Use of outer walkways for laydown and siting of new equipment. This leads to increased overpressures, new potential failures and routes to escalation.
Breakdown and need for repair.	Repeated breakdowns and need for repair suggests that the equipment has reached its intended design life. It is good practice to establish the underlying reasons for breakdowns and repairs.
Increasing backlog of maintenance actions.	An increase in the number of repairs that remain unresolved can be an indicator that ageing is taking place. As the maintenance backlog grows it can become increasingly difficult to get maintenance back on track.
Inspection results.	Inspection results can indicate the actual equipment condition and any damage. Trends can be determined from repeated inspection data.
Increasing failure to meet minimum functionality and availability performance standards.	Reduction in efficiency, in pumping capability or heat up-rates can be due to factors such as product fouling or scaling. Engines may become difficult to start.
Instrumentation performance.	Lack of consistency in the behaviour of detection and process instrumentation can suggest process instability and may indicate that the equipment has deteriorated. It could also indicate a fault with the instrumentation.
Experience of ageing of similar equipment.	Unless active measures have been used to prevent ageing of similar plant, it will be likely that the same problems can occur again.
Repairs and plant outage.	May indicate that ageing problems are already occurring. Also a risk factor, since if repairs have been needed during the life of the structure, the integrity and necessity of the repair will indicate the potential for further problems.

Many ageing mechanisms can be dependent on the circumstances around the offshore facility. Physical assets that are affected by ageing will have various degradation damage depending on the use of the asset, material strength and repairing and modification history [4]. Table 2.4 shows ageing mechanisms and their effect on primary containment, the structures and its safeguards.

Table 2.4: Ageing mechanisms that affect physical assets [12]

Ageing mechanism	Primary containment	Structures	Safeguards
Corrosion	X	X	X
Stress corrosion cracking	X	X	X
Erosion	X	X	X
Fatigue	X	X	X
Embrittlement/cracks	X	X	
Weather		X	X
Expansion/contraction due to temperature changes	X	X	X

The ageing degradation process is more widespread when there are degrees of incompatibility between materials used for the equipment and process fluids. If the reaction is unfavourable between the equipment used during operations and process fluids, the result will be a hastening of ageing degradation over time [4]. The most important ageing mechanics; corrosion and fatigue, are discussed below.

2.4 Corrosion in Offshore Jacket Structures

Corrosion can be defined as the physical degradation and destruction of a material (usually metals) due to chemical and/or electrochemical reactions when exposed to an environment which will support these reactions [2, 12, 15]. Corrosion in seawater is a destructive and unintentional attack on metal, which is called wet (aqueous) corrosion. This is driven by an electrochemical process between a cathode and an anode and usually begins at the metal surface [2, 15]. The metal that is corroding is losing a valence electron and a metal ion through an oxidation reaction. This results in the metal losing mass over time [15]. Or to be more precise, the corrosion causes a uniform loss of wall thickness. In general, the iron in a metal will exhibit oxidation when in reaction with an oxidant. The reactants are iron, oxygen and water, and the end result is hydrated iron-oxide and water, shown in chemical reaction (2.1).

$$4Fe + 3O_2 + 2H_2O \rightarrow 2Fe_2O_3 * H_2O \tag{2.1}$$

The outcome is rust which can be observed in structural elements exposed to corrosive environments [2, 4].

The corrosion process leads to a deteriorated structural integrity. Since offshore jacket structures are in the presence of seawater and oxygen, the most aggressive and exposed area for corrosion damage will be just above or just below the sea surface. This area is called the splash-zone and is highly exposed to corrosion [2, 4]. A Corrosion Protection System (CPS) is generally layered to counteract corrosion but has a typical life of only 5-15 years. The CPS is also less effective in the splash-zone due to constant waves, tides and general water movement. In addition, pitting corrosion can start long before the end life of the CPS [3].

Figure 2.4: Example of corrosion near the splash-zone [21]

There are numerous types of corrosion, the most common ones are [1-3, 12, 15]:

- **Uniform corrosion**
- **Localised corrosion**
    - Pitting corrosion
    - Crevice corrosion
    - Galvanic corrosion
- **Erosion corrosion**
- **Mechanical damage corrosion**
    - Cavitational correction
- **Carbon dioxide corrosion**
- **Hydrogen Sulphur corrosion**
- **Microbial corrosion**
- **Atmospheric corrosion**
- **Corrosion fatigue**

This thesis focuses on the mitigation methods for the most common type of corrosion which is uniform corrosion. Localised corrosion like pitting corrosion and crevice corrosion, and finally corrosion fatigue is also explained in detail because of their severity.

2.4.1 Uniform Corrosion

Uniform corrosion is the most common type of corrosion. It reduces the total member thickness due to the uniformly distributed corrosion damage on the surface. This also results in reduction of the effective cross-sectional properties of the member such as effective area, moment of inertia and torsional and warping constants. Such changes may cause change in the overall stiffness of the structure and the structural response. It is then essential to include the thickness reduction effect of uniform corrosion accurately in Finite Element (FE) models [1, 3, 15]. When the surface of a member is unprotected or the CPS has degraded in a corrosive environment, uniform corrosion is likely to happen.

Figure 2.5: Example of uniform corrosion on pipelines [87]

Several past researches have shown that uniform corrosion can be stimulated with good approximation by a nonlinear function – a nonlinear corrosion wastage model. While the protection system is active, it is assumed that there is no degradation. The formula for the wastage model is given in the following equation [1, 3]:

$$W(t) = R_{corr}\left(t - t_{pt}\right)^{\phi} \tag{2.2}$$

Where $t > t_{pt}$

$W(t)$ = Thickness wastage in mm

t = The lifetime in years

t_{pt} = The corrosion protection in years

R_{corr} = Corrosion rate in mm/year

ϕ = Value that should be precisely determined depending on on-site inspection and/or uniform/patch corrosion

2.4.2 Localised Corrosion

Localised corrosion is a form of corrosion which occurs on a specific area of the total member surface area or when the corrosion has a non-uniform intensity and concentration over an exposed area. Due to the nature of the attack, localised corrosion can pass undetected by assessment/inspection methods and therefore result in extremely damaging conditions [12, 15].

2.4.2.1 Crevice Corrosion

Crevice corrosion is a form of localised correction. This type of corrosion occurs when the exposed area has crevices which form around and under bolts, washers, connectors, corners and seals. The attack goes within these crevices and can become increasingly aggressive as the corrosion effect accelerates [12, 15].

2.4.2.2 Pitting Corrosion

Pitting corrosion is likely to occur in areas such as the splash-zone where CPS are less effective [3, 16]. In addition, pitting corrosion can start long before the CPS loses its complete effectiveness. This is a localised form of attack, the conditions within the pits on the surface can become progressively destructive and cause corrosion to advance through the wall thickness [12]. Since this is an extremely localised form of corrosion, it has minimal effect on the global stiffness of the structure. However, it can still cause local stress concentrations and reduce the fatigue life of a member [1, 3].

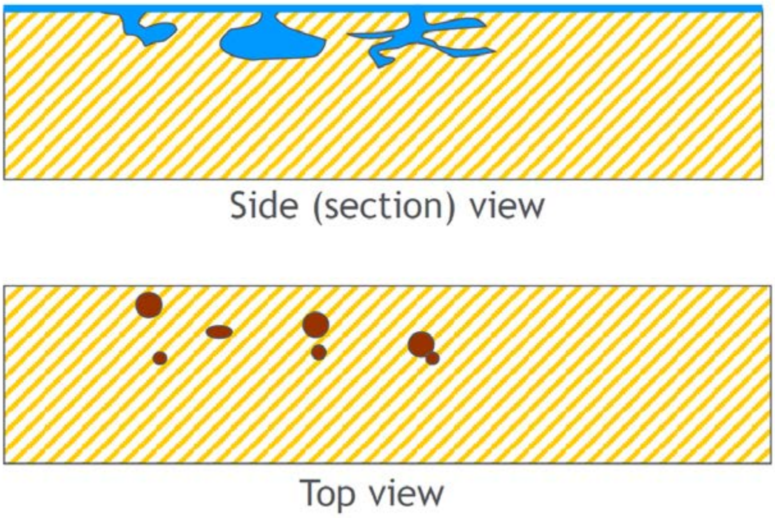


Figure 2.6: Pitting corrosion [33]

It is therefore essential to take pitting corrosion into account during the assessment for life extension. Pitting corrosion, which is one of the most hazardous types of corrosion for offshore structures requires local stress analysis to be performed to fully understand the full extent of the corrosion spread/damage [3].

2.4.3 Corrosion Fatigue

Corrosion fatigue occurs when a structure is in the presence of a corrosive environment and is subjected to repetitive cyclic loads. The combination of environmental loads and corrosion accelerates the damage of the area. The result is a hastened development of cracks. This is a mechanism that can lead to an accelerated crack growth and fatigue failure [2, 3].

2.5 Fatigue Approaches for Offshore Jacket Structures

Fatigue is a phenomenon that happens in structures when it is exposed to cyclic loads through its design life. One of the main characteristics of fatigue is that the load that is causing fatigue damage is not large enough to cause instantaneous failure, but rather through a cumulative damage process over time [17, 19]. Therefore, fatigue failure can happen at a stress levels much lower than the tensile or yield strength of a member [18].

Since offshore platforms like jacket structures are located in marine environments, fatigue damage is an important factor to consider in terms of total design life, overall structural strength and integrity, and life extension methods. Fatigue damage is particularly common in marine surroundings where environmental loads are imposed on the structure. Waves, current, ice, earthquake and wind causes cyclic loading which leads to a reduction in strength of the structure over time. In general, fatigue damage can be characterised as the concept of a material weakening over time, gradually failing as it loses its nominal strength [18].

The North Sea and the NCS in general has a relatively harsh environment throughout the year compared to other parts of the world like the GoM. Therefore, cyclic loading in these surroundings are of a higher factor.

The three main stages of fatigue damage are identified below [17, 19]:

I. **Fatigue initiation:** The material starts to accumulate microscopic plastic damage due to the cyclic loads. As the cycle of loads continue, the material accumulates defects which leads to the next phase. Normally, the initiation cycle is observed on the surface of the material.
II. **Fatigue crack growth:** As the material accumulates more and more plastic deformation on the microscopic level, cracks start to grow. Normally the crack growth is distinguished by High-Cycle Fatigue (HCF), Low-Cycle Fatigue (LCF) and Ultra-Low-Cycle Fatigue (ULCF).
III. **Failure:** As the cyclic loading and fatigue crack growth continue, the failure of the member is imminent. This will lead to the member failing by three different mechanisms; brittle fracture, ductile tearing or plastic collapse. Failure happens due to the maximum tolerable defect/crack size.

Over time, different methods have been developed to evaluate and estimate the fatigue strength of structures. A brief evaluation of these different approaches is presented below.

2.5.1 Hot Spot Stress (HSS) Method

The HSS method is an effective method developed to accurately estimate the effect of fatigue on welded structures, in cases where the nominal stress is difficult to estimate due to geometric, loading or other complexities [20].

The hot spot area is defined as the critical location at the weld toe or weld end where a fatigue crack can be projected to initiate. The geometric effect is dominant when it comes to this method since the fatigue strength of welded joints are size dependent [20]

The relationship between the nominal stress and HSS is given by the following equation [20]:

$$\sigma_{hotspot} = SCF * \sigma_{nominal} \tag{2.3}$$

SCF = Stress concentration factor

$\sigma_{nominal}$ = Nominal stress

$\sigma_{hotspot}$ = Hot spot stress

In comparison to the S-N approach, the HSS method can be classified as a "local" approach due to the inclusion of increased stress because of discontinuities in the structural geometry in the calculations [19]. Generally, hot spots can be classified as two types [98]. Type a: The weld toe is located on a plate surface, Type b: The weld toe is located on a plate edge.

The downside of this method is that it can only be applied for weld toes where cracks start from the surface of the material. In addition, mesh-sensitivity of the hot spot stress is an issue that affects this method.

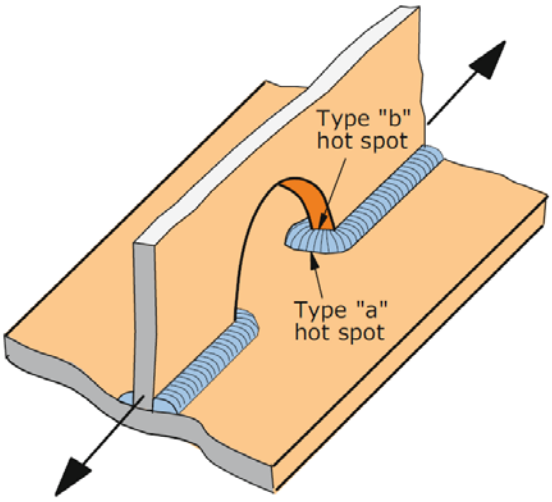


Figure 2.7: Examples of two types of hot spots in the weld [98]

2.5.2 Notch Stress Method

The notch stress method is another method that can be classified as a "local" approach [19]. Here, the stresses used in the calculations is the notch stress that can be defined as peak stress at the root of a weld or notch [19]. The approach is very flexible because both the toe and the root of all types of welded joints can be evaluated using a single S-N curve [99].

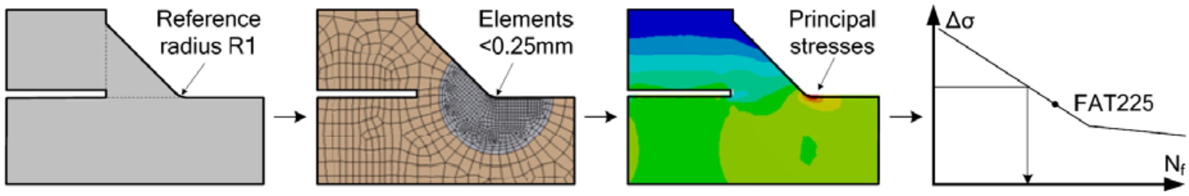


Figure 2.8: The notch stress approach [99]

The notch stress approach correlates the stress range in an "assumed" rounding in the weld toe or root to the fatigue life by means of a single S-N curve. The notch stress is typically attained using FE models [99]. For calculating the notch stresses in an accurate manner, an extremely fine mesh is needed in order to account for the weld profile [19]. Though this method is highly accurate, it can be hard to define and implement the exact geometry of the weld joint [19].

2.5.3 Fracture Mechanics Approach

The fracture mechanics approach, unlike the S-N approach, assumes that a crack or cracks exist(s) in the structure and thereby employing a deterministic crack growth model predicts the remaining useful life estimation of the structure [19, 20]. The three important variables in fracture mechanics are flaw size, applied stress and fracture toughness [20]. This method is based on fracture mechanics which covers crack growth, independently from S-N curves. The method is often used when the S-N approach or other approaches yield inappropriate results in regard to the fatigue life assessment [20]. Several different crack growth models have been developed, relating the crack growth rate to load amplitude or maximum load. The most familiar model is Paris' Law, given in the following equation [19]:

$$\frac{da}{dN} = C(\Delta K)^m \tag{2.4}$$

$\frac{da}{dN}$ = Crack growth rate

ΔK = The range of stress intensity factor

C, m = Parameters that can be fitted once two points are known

The stress intensity factor:

$$\Delta K = \Delta\sigma\, Y \sqrt{\pi a} \tag{2.5}$$

The fracture mechanics approach provides a quantitative assessment of the crack growth. However, it is relatively complex and requires initial boundary conditions in terms of the initial crack size [20].

2.5.4 Nominal Stress Method (S-N Curve Approach)

The S-N curve approach also called the nominal stress method or Wöhler curve is another way to estimate fatigue life and predict fatigue damage [20]. It is based on finding the number of cycles, N, for different stress ranges, S. Hence the name S-N curve.

The fatigue strength is described by the S-N curve which has been obtained by laboratory experiments on smaller-scale test specimens. These specimens have similar characteristics to the real member at a given stress ratio. The fatigue strength is then presented in the form of a table or curve by using a log-log or semi-log scale.

Equation (2.6) gives the relationship between S (applied nominal stress range) and N (number of load cycles to failure) [19]:

$$S^m * N = C \tag{2.6}$$

C, m = Constants depending on material type, geometrical configuration and environmental settings

In reference to DNV GL-RP-C203, the basic design S-N curve is [31]:

$$\log N = \log \bar{a} - m \log \Delta\sigma \tag{2.7}$$

$\Delta\sigma$ = The stress range in MPa

N = The predicted number of cycles until failure for stress range $\Delta\sigma$

m = The negative inverse slope of S-N curve

$log\ \bar{a}$ = The intercept of $log\ N$ axis

The S-N curve approach is categorised as a “global” approach [19]. This is because the local geometries of the weld are included in the corresponding S-N curves. The stress concentrations due to discontinuities in the structural geometry and the effects caused by the presence of the weld are disregarded in the fatigue stress calculation but they are entrenched in the S-N curves [19].

When dealing with complex structures with intricate details, the choice of an appropriate S-N curve becomes challenging. The test specimens are often less complex than the real structural members, in terms of applied loads, geometry and behaviour. “Local” approaches should be employed in order to account for local changes. The S-N approach is suited for predicting fatigue damage on members subjected to fluctuating stress below the yield, i.e. HCF [20].

2.5.5 Miner’s Rule

Miner’s rule (1945) is one the most popular damage accumulation models to assess fatigue damage due to its ease of implementation. Using Miner’s rule, the yearly fatigue damage can be calculated and is given in the following equation [3, 19, 31]:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{2.8}$$

D = The yearly cumulative fatigue damage

n_i = The number of stress cycles in stress block i

N_i = The number of cycles that lead to failure at a constant stress range $\Delta\sigma_i$

k = The number of stress blocks

The final life is considered to be reached once the overall damage D equalises the value of 1 [19]. However, under Miner’s rule, amplitude loading is not taken into account and can lead to unreliable predictions of remaining life. In addition, experimental results have shown that the damage threshold of 1 is not accurate enough [3, 19].

2.6 Structural Integrity Management (SIM)

SIM can be defined as ensuring the people, systems, processes and resources that safeguard and manage the integrity of a structure is in place, and will perform when required during the lifecycle [6, 22].

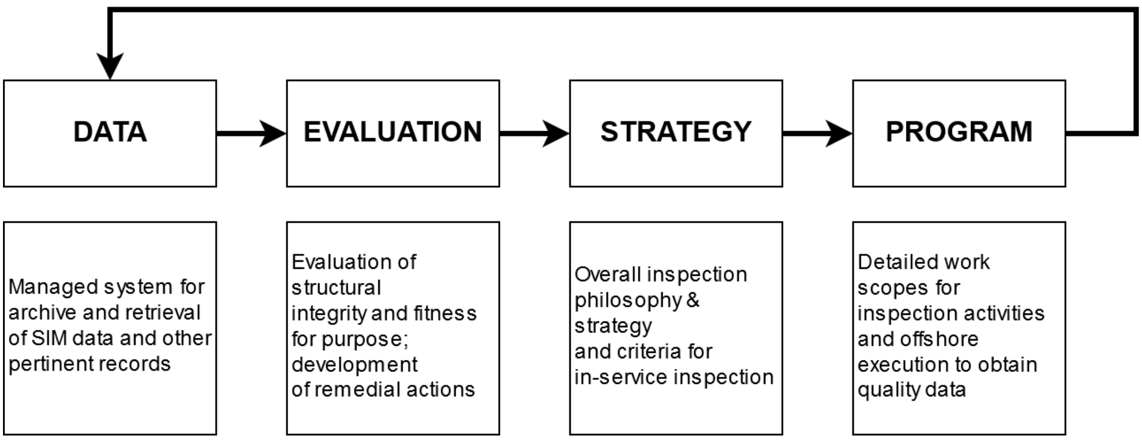


Figure 2.9: The SIM process according to API RP 2SIM and ISO 199902 [29]

The loss of structural integrity can have severe consequences. As the facility ages, the probably of failure increases with time without proper management [6].

The SIM of an ageing offshore structure requires accurate data about [6]:

- The design and layout of the facility
- Fabrication process
- Installation - including any deviations from procedures
- Operational history of the facility
- Environmental conditions and any variations against the design assumptions
- Effects of fatigue on the structure
- Effects of corrosion on the structure

Therefore, appropriate inspection techniques, structural assessments and maintenance procedures of the facility are major focal points of SIM for ageing offshore structures [22, 23]. SIM is an ongoing process for the continued operation of offshore structures. It is of the outmost importance that deterioration and degradation are incorporated into a well-rounded SIM plan. The SIM of an ageing offshore facility can be a complex process. As time goes on, the performance of the installations become more variable. Usually deterioration happens at different rate to the members, depending on the fabrication quality, the in-service quality, the repair quality and the frequency of use [11].

Table 2.5: The SIM process and the associated issues affecting the life extension and mitigation methods [11]

SIM Process	**Description**	**Main issues affecting life extension**
Structural integrity strategy.	Development of an overall inspection philosophy and strategy and criteria for in-service inspection.	The strategy should include managing the approach to assessing ageing processes and the need to link inspection requirements to these.
Inspection programme.	Development of detailed work scopes for inspection activities and offshore execution to obtain quality data.	A more detailed inspection may be required if a period of life extension is to be justified.
Structural integrity evaluation.	Evaluation of structural integrity and fitness for purpose, development of any remedial actions required.	The evaluation should include assessment taking account of the original design requirement (which may have been less onerous than modern standards) as well as the consequences of ageing processes (e.g. fatigue, corrosion).
Managed system of data.	Setting up and managing a system for archiving and retrieval of SIM data and other relevant records.	Loss of key data from original design, construction and installation and early operational inspections.

2.6.1 Assessment for Life Extension of Offshore Structures

Life extension is the practice of extending the life of a structure beyond its intended design life. This is not necessarily characterised by physical age. It refers to continued operation of an installation beyond its intended design life by using different mitigation techniques [6]. The process of life extension should be performed without compromising safety measures. Structural integrity needs to be evaluated during every course of action to ensure future safety of the facility, equipment, environment and personnel [4, 10].

A general life extension process can essentially be summarised into six steps [6]:

1. Data and information. Collecting relevant data and information to carry out the life extension process. This can be information about the initial plan and design of the structure, loading history, damage and accident rapports, operational rapports, maintenance programmes, performed modifications and repairs prior to the life extension process, operation and environmental parameters, planned modifications and operational changes etc.

2. Critical primary screening of the structure. Identify critical units and barriers in terms of failure consequence and probability. Since life extension can be very time consuming and requires a great deal of resources, it is necessary to concentrate on systems, structures and components that directly or indirectly have an impact on safety.

3. Analysis of failures and challenges. Perform secondary screening with respect to material degradation considering the availably of inspection and monitoring, and the current state of the facility. With respect to obsolescence and administrative problems it is necessary to identify challenges and gaps in relation to current standards and requirements.

4. Risk reducing measures should be identified and evaluated.

5. Total assessment of the overall risk scenario based on all aspects of ageing, given the risk reducing measures.

6. Life extension management plan can be initiated if the overall risk picture is acceptable. The plan should ensure structural integrity throughout the life extension period and is to be adjusted to meet todays and future operational, organisational and personnel requirements.

The assessment, life extension process, and required measures taken need to be in compliance with current regulations and standards throughout each step.

A key concern in the case of assessment for life extension is whether the facility is sufficiently safe and structurally stable after the planned mitigations and maintenance efforts have taken place [4]. Original design guidelines and codes are often used to document the safety of a structure for life extension. If the structure fulfils the original design regulations and parameters, and meets all the demands for safe and continued operation, it may be sufficient [4]. However, extended knowledge still needs to be in place in the assessment process. Accidents and special incidents could have major effect on the structure, which is not part of the original documents. Design codes and standards do not include operational history, damages and degradations [4]. Guidance on life extension is limited but is developing [11].

The main technical concerns are local and global fatigue damage, corrosion damage, pile integrity and accumulated accidental damage [11].

There is uncertainty associated with the structural integrity of ageing offshore structures. Effective management of ageing offshore installations entails effective application of inspection methods and maintenance policies and solid structural analysis techniques [11].

A following conclusion is likely to be drawn after an assessment of a structure [44]:

1. Specific inspection and monitoring requirements are put forward to monitor defects and potential defects.
2. A load reduction programme is instigated. Here, several components might be removed depending on the severity of the situation.
3. Mitigation methods are required.
4. Operation procedures are changed, e.g. demanning or limiting operation time of the platform.

In the assessment process for life extension, new technology needs to be taken into account to ensure up-to-date technology and methods have been assessed for usage and are compatible with the structure. It should be apparent that during the life extension phase total structural integrity must be maintained at all times.

2.6.2 Mitigations for Extending the Life of Offshore Jacket Structures

Mitigation in terms of offshore structures can be defined as the act of lessening or removing the force or intensity of something undesirable that affects the structural integrity and the safety of the personnel in a negative manner. It can be defined as the act of making a condition or consequence less severe by implementing certain strategies and/or methods. Mitigation methods are also used as a definition for “prevention strategies”. As in implementing certain mitigation methods to prevent the occurrence of certain conditions that may have an unfavourable effect on the structure.

Some mitigation examples are mentioned below, these are discussed more in detail in the later chapters:

- Corrosion damage can be mitigated by recoating of CPS or additional anodes.
- Tubular members can be mitigated with grouting to handle more loading.
- Weld defects can be mitigated with post-weld improvement methods like hammer or needle peening.

3 Mitigation Methods According to Current Standards and Guidelines

3.1 Mitigation Methods According to NORSOK Standards

Developed by the Norwegian petroleum industry, the NORSOK standards ensure adequate safety, cost effectiveness, solutions and guides for petroleum industry developments and operations. The standards serve as references for authority regulations [88].

The supervision of NORSOK standards is done by multiple parties. Standards Norway signed an agreement where the Federation of Norwegian Industries, the Norwegian Oil and Gas Association and Norwegian Ship-owners' Association contribute to the management of the NORSOK standards. NORSOK standards have over 40 years of petroleum experience from the NCS behind them. As of 2018, there are currently 79 national NORSOK standards in active use [88].

3.1.1 NORSOK N-001: Integrity of offshore structures [24]

This NORSOK standard is the principle standard for offshore structures. It mainly refers to ISO 19900 – Petroleum and natural gas industries – General requirements for offshore structures. This standard specifies general principles and guidelines for the design and assessment of offshore facilities. It is applicable for all types of offshore structures used in the petroleum activities. It is also applicable to all structural parts including substructures, topside, foundation and subsea facilities [24].

In addition, it also specifies principles applicable to the assessment of existing structures, which is required when [24]:

- The structure and related maritime systems has experienced damage or deterioration
- Changes deviate from the original design basis. Such changes would include:
  - Changes in manning
  - Changes to facilities
  - Modifications of existing facility
  - More onerous environmental criteria
  - More onerous component or foundation resistance criteria
  - Physical changes to the design basis such as scour and subsidence
  - Inadequate freeboard
- extension of intended design service life

The assessment and design process of offshore structures is the main part of this guideline, there is no mention of mitigation recommendations for the extension of intended design life.

The standard does include "planned modifications and mitigations to the structure and facility" as part of elements that should be considered during the assessment process for existing facilities. It also includes a sub-chapter; *5.2.4 – Verification of assessment of existing facilities*, which is a guideline to assess the facility for service life extension [24].

However, there is no guideline for the step-by-step process to implement the necessary arrangements for life extension and mitigation methods. The standard is a general assessment and design guide, with the core focus on checking and verifying the structural integrity of an offshore facility.

3.1.2 NORSOK N-003: Actions and action effects [25]

This standard specifies general principles and guidelines for determination of action and action effects for the structural design and the design verification of structures. It is applicable for all types of offshore facilities used in the petroleum activities and is applicable for the different stages of construction as in fabrication, transportation and installation and finally abandonment. Since this is a standard focused on the effect of actions, there is no mention of life extension and mitigation methods [25].

It does include detailed information about permanent actions, variable actions, weight, hydrostatic pressure, environmental conditions such as waves, wind and sea states, impacts, accidents, air gap analysis and other forms of actions that may affect a structures stability. These are all important parameters to consider during the life extension of a structure. Altering the original structure by adding or removing certain elements might drastically change how the structure handles all the given parameters above.

This standard has no important information regarding mitigation methods and if necessary should be referred to during and/or after the mitigation methods have been decided.

3.1.3 NORSOK N-004: Design of steel structures [26]

This standard is a detailed guideline intended to fulfil the PSA regulations relating to the design and outfitting of facilities in offshore petroleum activities. The design principles follow the requirements in ISO 19900. It specifies guidelines and requirements for design of offshore steel structures. It is applicable for all types of steel offshore structures with a specified minimum yield strength less or equal to 500 MPa. This is a detailed standard about the design and construction of steel structures in an offshore environment [26].

In the standard, section *5.1 – Design steel* and *5.2 – Steel quality level*; are two important sections in regard to which type of steel and structural joints should be chosen. Section *5.3 – Welding and Non-Destructive Testing (NDT)* mentions that welds in joints below 150 m water depth should be assumed inaccessible for in-service inspection [26]. For the tubular members, Section *6.3 – Tubular members* defines detailed strength and stability requirements such as axial tension, axial compression, bending, shear, hydrostatic pressure and material factor [26]. Section *6.4 Tubular joints* detail necessary data to the design of tubular joints formed by connection of two or more members. Section *6.8 – Design against brittle fracture* is a chapter which is important in regard to correct welding principles. Fracture in steel offshore structures may occur under unfavourable combinations of geometry, fracture toughness, welding defects and stress levels [26].

This is a detailed standard about the design of steel structures. It includes specified criterions that should be satisfied for the structural stability and integrity of an offshore steel structure. Several of the chapters in this standard are important for the mitigation method suggestions and their applications, to make sure they follow the correct guidelines and do not deviate from the core design principles. However, as the main emphasis of this standard is related to regulations and design criteria for the structural integrity of an offshore steel structure, there is no specified mitigation chapter.

3.1.4 NORSOK N-005: Condition monitoring of loadbearing structures [27]

This standard describes principles and guidelines on the safety and cost related issues throughout the design, construction, operation and final disposal of offshore structures [27]. It describes principles of how condition monitoring of loadbearing structures should be planned, applied and documented to uphold a safe installation to comply with specific regulations and relevant standards.

This standard, similar to the other NORSOK standards mentioned is applicable for all offshore structures used in petroleum activities. It covers all aspects related to condition monitoring; from installation, operation and final decommissioning. The main objective of condition monitoring for loadbearing structures is to ensure that adequate level of structural integrity is maintained at all times [27].

In order to achieve this, the monitoring shall determine and include:

- Degradation or deterioration due to fatigue or other time dependent structural damage
- Corrosion damage
- Fabrication or installation damage
- Damage or component weakening due to strength overloading
- Damage due to man-made hazards
- Excessive deformations

The main concern is the injury and loss of personnel, pollution to the environment, property damage and economic losses.

In section *5.1 – Condition Monitoring Philosophy*, the major and main objectives of condition monitoring of loadbearing structures is described in detail. One of the points mentioned is*: Consideration and conception of prevention and mitigation measures*.

This standard describes the necessity and usefulness of condition monitoring, especially regarding areas like the splash-zone and submerged zone which are typically more open for degradation due to corrosion and fatigue damage. Though the standard never mentions any mitigation methods, the annex that is attached to it, has dedicated a small section to remedial measures. The sub-chapter *C.6 – Remedial Measures* in *ANNEX C – Jacket structures*, mentions that prevention measures and mitigation measures should be considered at all stages of an assessment process for a structure that deviates from the original code or standard [27].

The remedial measures are as follows [27]:

- Load reductions
- Strengthening
- Change to operational mode and procedures
- Intensification of and change to condition monitoring
- Removal of facilities exposed to the environmental pollution and damage

The sub-chapter *D.6 – Remedial Measures* in *ANNEX D – Column Stabilized Units*, mentions both temporary and permanent solutions for structural stability [27]. Temporary measures are drilling of crack stoppers, temporary strengthening, operational limitations and changes, increase inspection activity and use of specific monitoring equipment [27]. Permanent solutions such as strengthening and increased inspection activities should be taken as soon as possible.

The sub-chapter *E.5 – Remedial Measures* in *ANNEX E – Ship-shaped Units*, mentions remedial measures such as [27]:

- Load reductions
- Strengthening
- Change in operational and procedures
- Intensification of and change in condition monitoring

These are related to floating units and not jacket structures, but the suggestions are very similar.

The suggestions above are not sufficient, comprehensive information about the remedial measures and mitigation techniques needed to secure an offshore structure for life extension. The information mentioned is extremely broad and too general. A simple suggesting such as "strengthening" has numerous ways to be achieved which are described more in the proposed framework chapter and applied in the case study.

In addition, as of 2017 this standard is no longer in use. It has been substituted by the new standard, NORSOK N-005: In-service integrity management of structures and maritime systems.

3.1.5 NORSOK N-006: Assessment of structural integrity for existing offshore load-bearing structures [28]

This standard gives additional requirements for assessment of the structural integrity of offshore structures in-service and for life extension. This standard serves as an alternative to NORSOK N-001: Integrity of offshore structures, for cases where structures are to be operated beyond their intended design life and structural resistance is not easily verified through ordinary design calculations [28]. As usual, this standard is applicable for all offshore structures involved in petroleum activities. Since the majority of ageing offshore facilities are fixed structures, the main focus is on jacket structures [28].

In *chapter 4 – Assessment process*, the assessment for life extension is described. The main theme is to conclude on a safe life extension period with respect to technical and operational integrity of the structure [28].

Figure 3.1 shows an assessment process flowchart and the lack of detailed mitigation planning is highlighted. The flowchart mentions mitigation in a very broad manner and no further details are given for the planning part or implementation part.

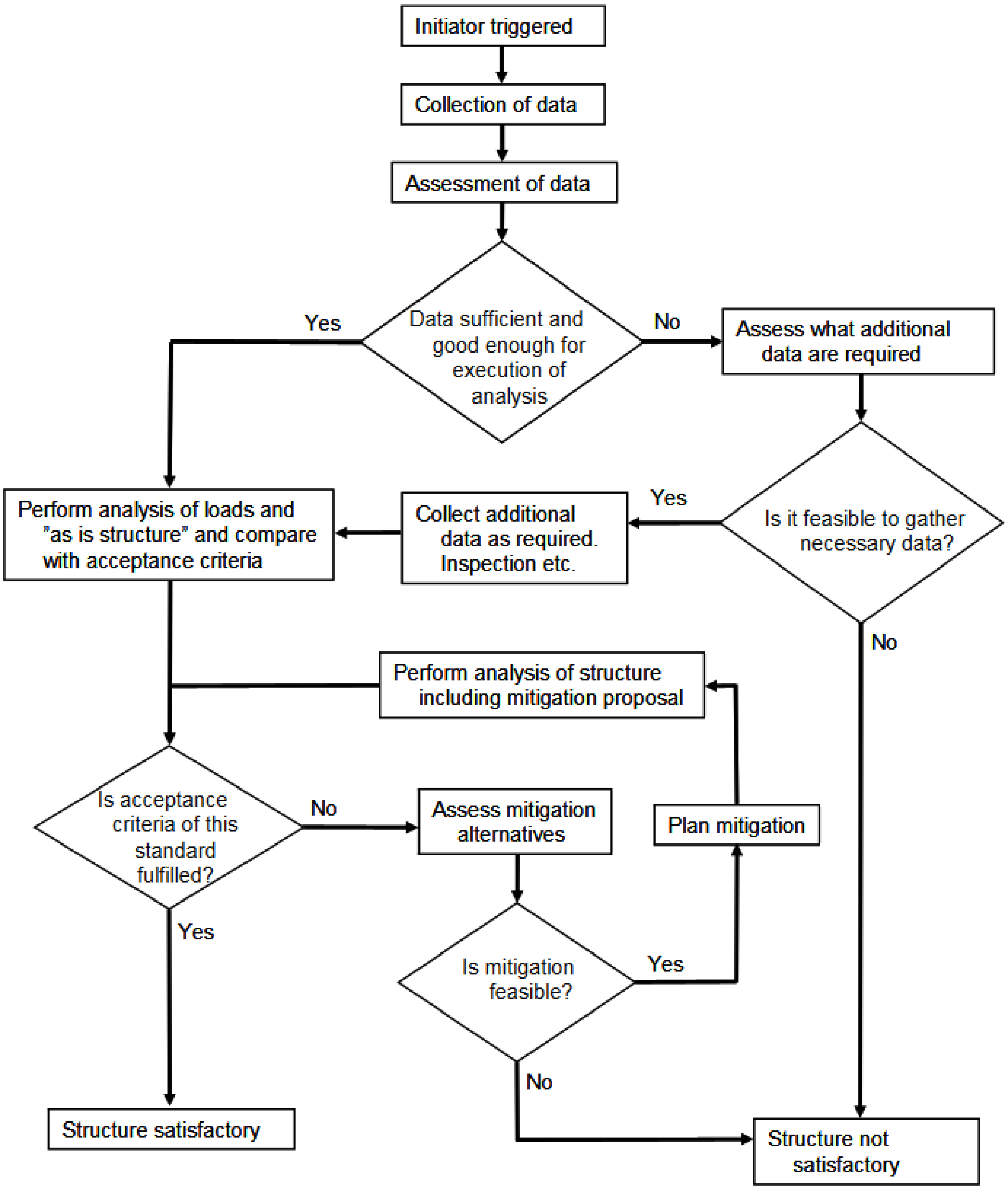


Figure 3.1: The assessment process flowchart [28]

According to NORSOK N-006, corrosion mitigation shall be implemented if the CPS is no longer satisfactory. The suggested methods are [28]:

- Addition of anodes that are clamped or otherwise attached to the structure and electrically connected
- Installation of a separate structure with anodes that is placed near the facility and is electrically connected to the structure
- Installation of system for impressed current
- Maintenance or recoating of coated surfaces

Improvement methods for fatigue life are mentioned in sub-chapter *7.6 – Improvement methods*. It is mentioned that the potential for fatigue improvement is the largest where fatigue cracks are growing from a weld toe into the base material [28]. For the butt welds, significant improvement can be hard to achieve and document due to limitations in detecting defects in the weld by NDT. Different type of connections has potential for significant fatigue life improvement by use of different improvement methods. In general, improvements are dependent on geometry of the member or members and the improvement method. For example, the fatigue damage at a welded hot spot can be drastically reduced by grinding or hammer peening. Though this does not solve the problem for internal defects and only improves the surface. In addition, grinding is recommended to be used to remove cracks that are up to 60 % of the plate thickness, if it is performed within a limited area and entirely removes the crack [28].

Mitigations for fatigue cracks are detailed below from sub-chapter *7.7 – Mitigations for fatigue* [28]:

- Reduce loading, e.g. remove members, remove inactive conductors, appurtenances and marine growth
- Reduce stress level by strengthening, e.g. install new members or clamps
- Reduce stress concentrations, e.g. by internal grouting of a tubular joint
- Improve fatigue capacity by improvement methods
- Perform controlled in-service inspections such that cracks are detected before they are through the wall thickness such that they can be removed by grind repair methodology

If cracks that are through the wall thickness are detected, other mitigations should be considered such as bolted and grouted clamps. As mentioned, fatigue life can be improved by different methods such as grinding and peening of the weld toes [28]. The different peening methods mentioned in the standard are: Hammer peening, needle peening and ultrasonic peening. The effect of fatigue improvement can be significant. However, it also depends on the quality of the weld. In general, the most consistent enhancement can be obtained for full penetration welds. It has also been shown that a significant amount of fatigue life improvement of tubular joints can be made even if significant amount of material is removed by grinding, as stated by the standard [28].

In the case of ULS and FLS, *8.10 – Suggested mitigation possibilities*, suggests certain mitigation methods if the ULS and FLS assessment has failed. The mitigations may be in the form of reinforcement of the structure, reduction of actions, and operational limitations and changes.

For jacket type structures, the following mitigation methods may be selected [28]:

- Reinforcement of the structure in the form of grouting of members to increase buckling capacity
- Grouting of joints to increase joint capacity
- Installation of additional braces
- Reinforcement of steel structure by stiffeners, brackets etc.
- Reduction of wave actions by regular removal of marine growth or anti-fouling protection

- Implement storm unmanning preparedness for the facility

In the case of in-service inspection in extended service life, the inspection shall take into account parts of the structures that has passed or will pass the design service life. This standard describes the assessment, data collection, requirements, analysis and determination of acceptance criteria for service life extension of offshore structures. Mitigation methods are mentioned throughout this standard in case of assessment failure. The methods are recognised approaches, yet not adequately described. This standard has several flowcharts and frameworks for the assessment process but no general framework to follow for the application of mentioned mitigation methods.

3.1.6 Comments on Mitigation Methods According to NORSOK Standards

In general, the NOROSK standards are extremely important for the design and assessment of offshore structures and steel structures used in the petroleum industry. There is comprehensive information in all of them with significant and necessary suggestions, guidelines, tables, figures and frameworks. This ensures the safety of the personnel, minimises economical costs and minimises pollution to the environment. The standards ensure that the facilities have adequate integrity from fabrication to decommissioning and everything in-between in terms of design, construction, assessment and usage.

The area that is most lacking in these standards is detailed and useful suggestions, guidelines and framework for the mitigation of offshore structures. The few mentioned methods are very broad and inadequate. There is a clear need for a general framework for mitigation methods or a complete new standard with the main emphasis on mitigating offshore structures like a typical jacket structure with a step-by-step implementation system.

3.2 Mitigation Methods According to API Standards

For more than 90 years, the American Petroleum Institute (API) has led the development of petroleum, natural gas and petrochemical equipment and operating standards in the US. API maintains nearly 700 standards and recommended practices as of today. Even though API is mainly focused on the US, in recent years they have expanded their work and is recognised around the world for their wide range of standards and guidelines.

3.2.1 API RP 2SIM: Structural Integrity Management of Fixed Offshore Structures [29]

API RP 2SIM: Structural Integrity Management of Fixed Offshore Structures provides guidance for the structural integrity management of existing fixed offshore structures. A detailed SIM process is provided, applicable for existing platforms, though the data and recommended criteria are based on locations in the US - GoM and US West Coast [29]. Risk assessment and risk reduction is provided in this guideline.

In section *5.4.3.2. – Exposure mitigation*, exposure mitigation is defined as actions that reduce the consequence of platform failure through hydrocarbon inventory reduction and reducing the personnel levels, either during a forecast event or permanently. In section *5.4.3.3 – Likelihood reduction* is defined as modifications that reduce the likelihood of structural failure. These can be load reduction, increased strengthening and repairing. In chapter *13. Risk reduction,* Risk reduction methods are recommended if the structure does not meet fitness-for-purpose performance criteria. The main reduction methods are exposure reduction which includes demanning the platform temporarily or permanently. The other method is likelihood reduction as discussed above. This involves load reduction to minimise the chance of failure, removal of known damaged components and repairing of members. Strengthening in general for jacket structures can be an effective technique to reduce the likelihood of failure.

3.2.2 Strengthening, Modification, Repairs (SMR) According to API RP 2SIM

There are a number of SMR techniques mentioned in the standard, Figure 3.2 shows the different suggestions.

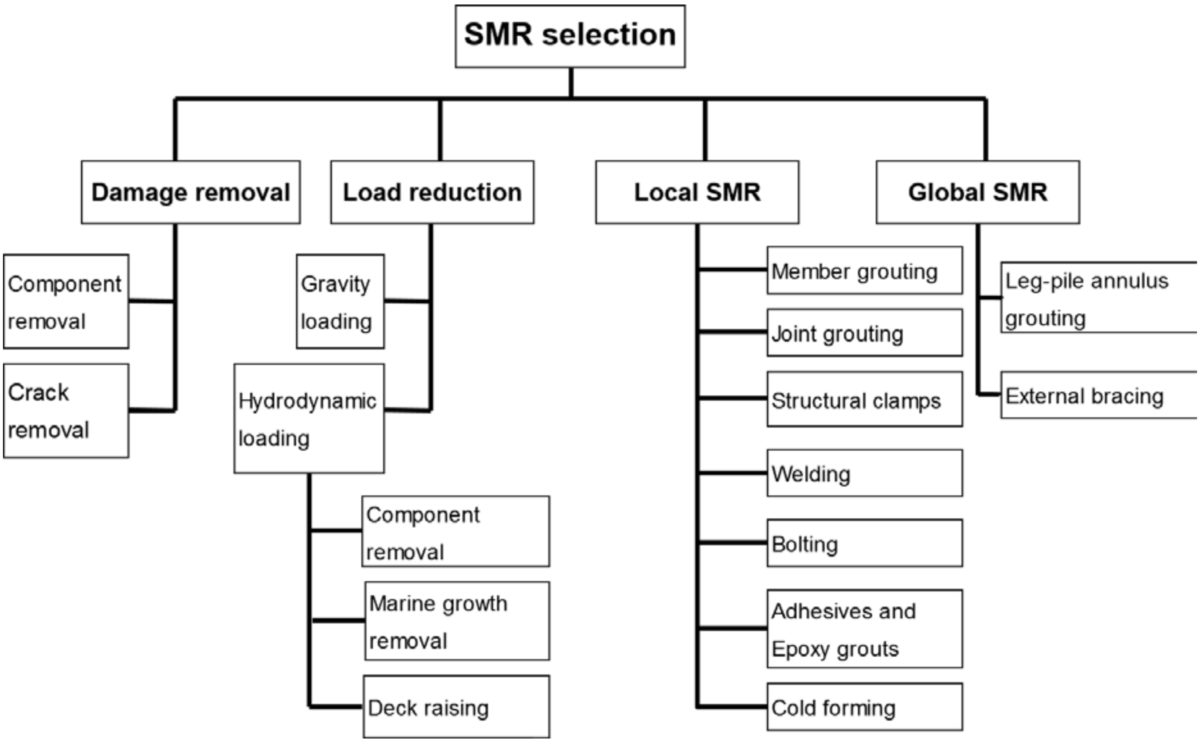


Figure 3.2: SMR techniques [29]

If it is decided that SMR is needed; local and global SMR systems should be considered in terms of their effect on the structure [29].

The standard describes them with short-summary paragraphs to explain the main purpose.

3.2.2.1 Damage removal

- Component/Member removal – The removal of damage by cutting out the affected member or area.
- Crack removal – Removal by remedial grinding. Other SMR techniques are needed for cracks caused solely by fatigue loads.

3.2.2.2 Load Reduction

- Gravity loading – Operational procedures can be implemented to reduce and control topside loads, for example by removal of unnecessary equipment, effective weight management, use of lightweight equipment and use of cantilever jack-up drilling operations.

- Hydrodynamic loads
  - Component removal – Removal of items that attract metocean loading such as barge bumpers, boat landings, risers etc.
  - Marine growth removal – Removal of areas with excessive marine growth
  - Raise deck – Raising the deck out of the wave crest will significantly reduce global hydrodynamic loads.

3.2.2.3 Localised SMR

- Member grouting – Filling tubular members with grout can be an effective way to enhance axial performance.
- Joint grouting – Grout filling of tubular chord elements can be used to increase the strength of joints.
- Structural clamps – Clamps can be used to repair brace members or joints of jacket structures. In addition, they can also be used to add new members, increase the capacity of existing members and to reinstate the capacity of damaged members of joints.
- Underwater welding – Welding is regarded as one of the best strengthening techniques, but is not used too often due to operational limitations in its execution. Different techniques include dry welding, hyperbaric welding and underwater wet welding.
- Bolting – Bolts can be used to minimise the loss of bolt tension. Additional bolting can be used for topside repair of jacket structures.
- Adhesives and Epoxy grouts – For joining metals, plastics and cement/concrete.
- Cold forming – Mechanical connections and/or swaging.

3.2.3.4 Global SMR

Leg-pile annulus grouting – Grouting of the annulus between the jacket legs and piles is an effective method of increasing the global capacity of the jacket structure. In addition, it has the added benefit of locally strengthening the jacket joints for bracing loads.

External bracing – A method used to increase the global strength of a structure by the addition of external bracing to additional piles. However, this method is limited to smaller platforms.

3.2.3 Comments on API Standard

Many of these suggestions mentioned are great options for life extension. There are several flowcharts related to life assessment topics. However, similar to the other standards, it does not provide the clear pathway or a framework to implement these suggestions in an orderly manner. There is also minimal mention of weld-mitigation solutions which is a huge part of the key-performance for life extension. The assessment process for a structure is described in detail in this standard. There are guidelines provided for risk assessment and risk reduction of structural failure. In addition, several survey methods are mentioned.

3.3 Mitigation Methods According to DNV GL Guidelines

DNV GL is an international quality assurance and risk management company. They provide classification, technical assurance, software and independent advice for several industries including maritime, renewable energy and oil/gas. Det Norske Veritas (Norway) and Germanischer Lloyd (Germany) merged together in 2013 to create DNV GL.

3.3.1 DNV GL-RP-C210: Probabilistic methods for planning of inspection for fatigue cracks in offshore structures [30]

This DNV GL document is a Recommended Practice (RP) intended to provide guidelines for the use of probabilistic methods for inspection planning of fatigue crack in jacket structures and floating vessels in offshore environment. This document is assumed to be used with other DNV GL standards or NORSOK standards. The inspection methods recommended in this document can be used for fatigue cracks in new or existing structures or for lifetime extension of platforms [30].

The main focal points of this document are inspection planning for fatigue cracks, S-N approach, probability of failure, residual and mean stress, and assessment guides for different facilities such as jacket structures, Floating Production, Storage and Offloading (FPSO) and other floating units. Therefore, there are no mention of mitigation methods after the finished assessment process for fatigue crack growth. Neither are there recommended suggestions for the mitigation of fatigue crack growth if it reaches critical factors. This is understandable as the emphasis of this standard is the analysis of the structures and not the after-care or life extension.

3.3.2 DNV GL-RP-C203: Fatigue design of offshore steel structures [31]

This document recommends practices in relation to fatigue analysis based on S-N data and fracture mechanics for steel structures [31]. The aim of a fatigue analysis is to ensure that the structure has adequate fatigue life, during fabrication, installation and the operational life of the structure.

Section *7 Improvement of fatigue life by fabrication* recommends different methods for improving the fatigue life. Weld toe profiling by machining and grinding is suggested as methods to improve the fatigue life, as shown in Figure 3.3 [31].

Weld toe grinding of weld toes can be used to increase the fatigue life by certain factors given in Table 3.1. Grinding has been used as an effective method for consistent fatigue life improvement after fabrication. Grinding also improves the consistency of inspection after fabrication and during service life. In Figure 3.4, there are two practices shown; A and B. Grinding a weld toe tangentially to the plate surface, as at A, will produce small improvement in the fatigue strength. Grinding the weld toe below the surface, as at B, will produce efficient and higher improvement to the fatigue strength. Another mentioned improvement technique for fatigue life is TIG dressing. However, there are no details provided for the use of this method. The last weld improvement technique mentioned is hammer peening [31].

This standard provides detailed information about fatigue analysis methods, S-N data, fracture mechanics, stress concentration factors, analysis of weld connections and finite element analysis. Though some mitigation methods are mentioned to improve the fatigue life of welds, they are not presented fully in-detail and are very surface-level. This standard has no flow charts in relation to using these methods for mitigation.

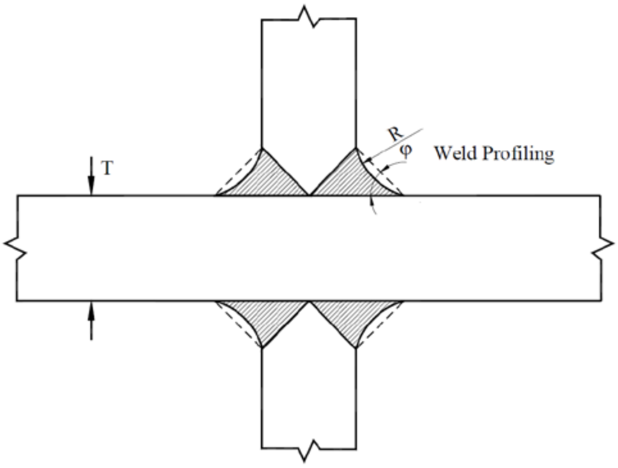


Figure 3.3: Weld profiling of cruciform joint [31]

Table 3.1: Improvement on fatigue life by different methods [31]

Improvement method	Minimum specified yield strength	Increase in fatigue life (factor) 1)
Grinding	Less than 350 MPa	$0.01f_y$ 2)
	Higher than 350 MPa	3.5
TIG dressing	Less than 350 MPa	$0.01f_y$
	Higher than 350 MPa	3.5
Hammer peening 3)	Less than 350 MPa	$0.011f_y$
	Higher than 350 MPa	4.0
1) The maximum S-N class that can be claimed by weld improvement is C1 or C depending on NDE and quality assurance for execution. 2) f_y = characteristic yield strength for the actual material. 3) The improvement effect is dependent on the tool used and workmanship. Therefore, if the fabricator is without experience with respect to hammer peening, it is recommended to perform fatigue testing of relevant detail (with and without hammer peening) before deciding a factor.		

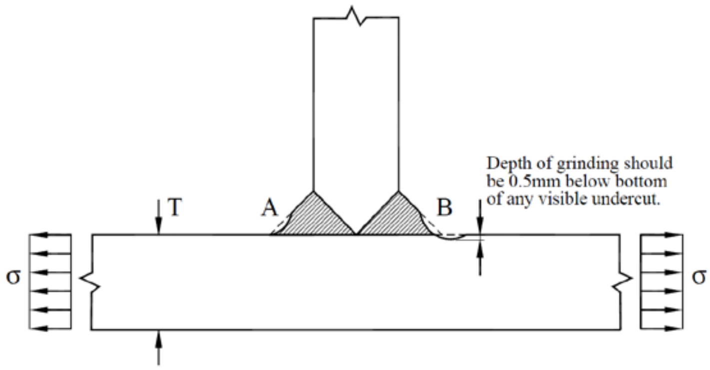


Figure 3.4: Grinding of welds [31]

3.4 Mitigation Methods According to HSE Guidelines in UK

The HSE is responsible for the regulation and enforcement of workplace health, safety and welfare in UK. Since the facilities in the UKCS faces many of the similar difficulties the facilities in the NCS face, they've launched and published several guidelines and Key Programmes (KP) related to the safety, structural integrity, life assessment and life extension of ageing offshore structures. KP 4 is the programme related to ageing and life extension of hydrocarbon exploration and production facilities in the UKCS. It was carried out between 2011 and 2013 [32]. The programme found a range of areas where focus was needed. Some of the key recommendations are listed below [32]:

- Improve structural analysis methods by using up-to-date models and analytical tools to get accurate data about the structure
- There are integrity and safety benefits to be gained by addressing the potential fatigue risks of equipment operating beyond the initially expected service life
- Greater attention should be given to equipment obsolescence
- Expanding the identification and early resolution of corrosion damage on jack-up structures will significantly improve the service life
- Early preparation for life extension will allow the identification of key issues to be managed to assure continued safe operation

KP 4 identified several areas where improvements where needed. However, the main focus was on “prevention” methods, and not “extension” methods. As in the majority of the recommendations for improvement was about ensuring safe operation of the offshore facilities during their service life, and not mitigation recommendations of said facilities after the necessity for life extension. The summary for *Managing ageing plant* provides several mitigation actions on how to resolve age related issues on offshore facilities.

On the topic of corrosion [12]:

- Monitor and control corrosion susceptible areas
- Use coating and cathodic protection to extend the life of prone areas

On the topic of Stress Corrosion Cracking (SSC) [12]:

- Use appropriate material that can resist SSC
- Since SSC is difficult to monitor, control of stress levels is crucial

On the topic of erosion [12]:

- Options for erosion are the same for corrosion, stated by the document.

RR 684 (2009) which is a research report published in 2009 include a small section on splash-zone maintenance. Here it is recommended that coating repair should be part of the mitigation method [33].

The above recommendations from the HSE guidelines are not sufficiently detailed for life extension. Similar to a lot of the standards and codes mentioned in this thesis, the mitigation options for the life extension of offshore facilities are uncomprehensive. The need for a clear-cut framework to be referred to is missing here and in the other standards that have been mentioned.

4 Recent Research from Published Literature on Life Extension and Strengthening Mitigations

4.1 Introduction to Literature Review

In recent years there have been numerous published scientific articles on the topic of life extension of offshore structures and mitigation options to extend the service life. This thesis will review and summarise the latest relevant published data related to life extension and mitigation options. Due to the public nature of the articles and their content, not all of them have been summarised and included in this thesis. Many papers were examined, but not all of them were included in this thesis due to unsatisfactory information, unrelated data and substandard cases studies. The purpose of this examination is to make sure the most relevant information in terms of mitigation methods related to the proposed framework are examined and put forward.

4.2 Mitigations on Life Extension of Offshore Structures and Available Mitigation Methods

J.W. Turner et al. (1994) mentioned mitigation methods categorised into three areas; reduction of loading, increasing of strength and/or reduction of consequences [42].

- For reduction of loading: Reduce total deck weight by removal of unused deck structure which will lead to less loading on the piles and member legs.
- For reduction of hydrodynamic loading: Increase deck height or remove non-essential items such as barge bumpers, boat-landings, stairs on lower deck area, walkways and so on. Removal and prevention of marine growth.
- For strengthening: Grouting, bracing, mechanical clamps and addition of extra piles close to existing piles.
- For fatigue performance: joint flexibility, weld toe grinding and hammer peening.
- For reduction of consequences: Modify or eliminate certain operations to minimise potential consequences such as demanning, reduced production time and relocation of stored hydrocarbons.

Dr. A. F. Dier presented a paper on the assessment of repair techniques for ageing or damaged structures and the selection of the optimal SMR technique for ageing offshore structures in 2004 [44]. Here different SMR methods are put forward and the correct approach is selected by using several factors such as equipment requirements, and the techniques' ability to mitigate several damages at the same time. Summarised, different SMR techniques are categorised into five main sections as it is shown in Figure 4.1.

In addition, it is mentioned that there are four basic approaches to SMR [44]:

1. Remove damage
2. Reduce loadings
3. Local SMR
4. Global SMR by providing new members

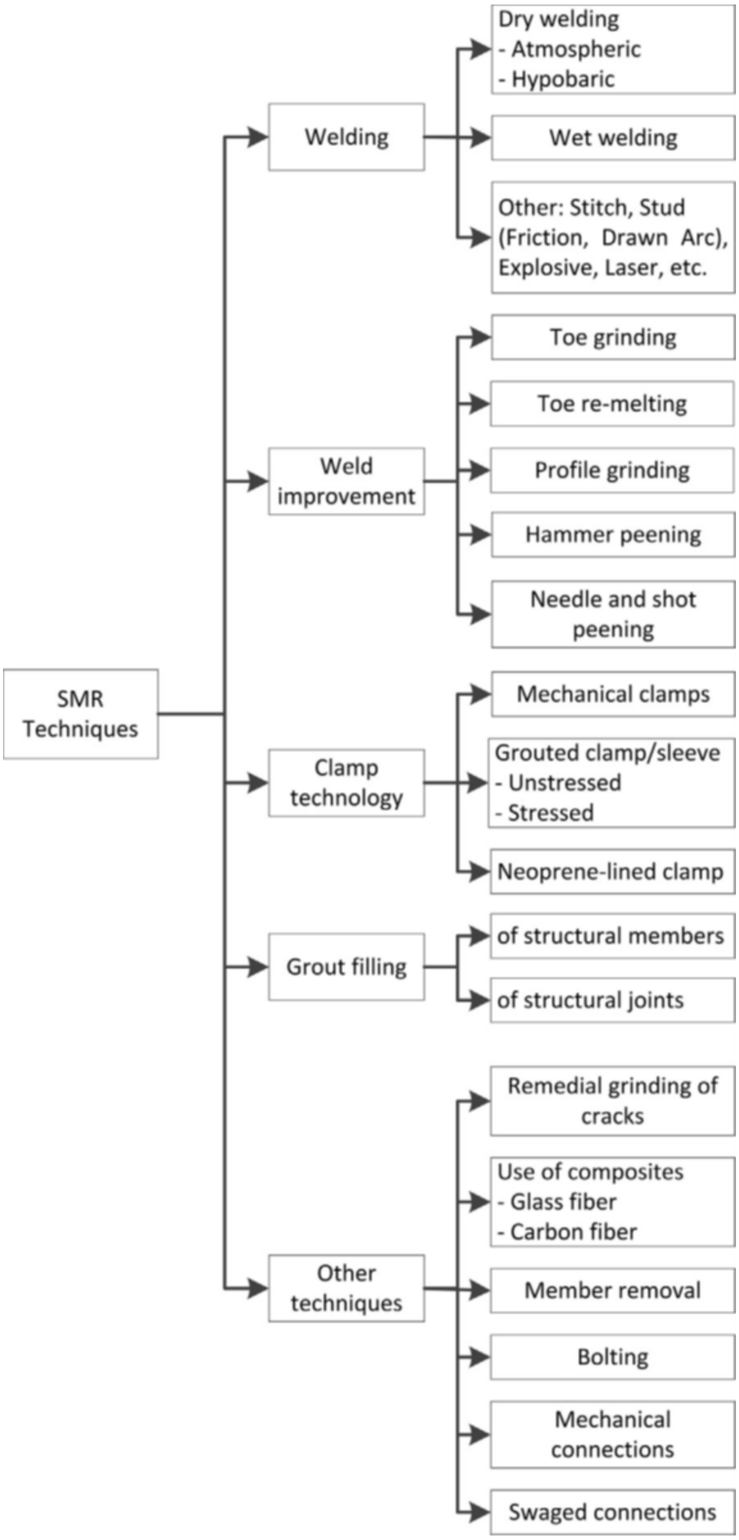


Figure 4.1: Different SMR techniques [44]

G. Ersdal (2008) published a paper about the assessment of offshore structure for life extension [4]. The paper is focused on the assessment of offshore structures for life extension and not the mitigation aspects. However, the paper summarises several projects about life extension in general. Here a study into robustness of material is included by Drugli et al. (2003) and Lange et al. (2004). There are studies on ageing facilities by A. Stacey et al. (2000) Sigurdsson et al. (2000), DNV (2000), A. Stacey et al. (2002), Stacey and Sharp (2004), Galbraith et al. (2005), BAE Systems (2002) and Wintle et al. (2006). Leinum et al. (2006) did an investigation into material risk in ageing offshore structures. Wintle and Sharp (2007) did a study where requirements that should be put in place for life extension of ageing offshore production structures. A study of global experiences with cathodic protection of offshore pipelines and flowlines was done by Lee et al. (2007) and many research projects regarding inspection planning of aging offshore structures was done by Sørensen (2006), Sørensen and Ersdal (2006), Sørensen (2007), and Sørensen and G. Ersdal (2007) [4]. Wintle and Sharp (2008) published requirements for life extension of ageing offshore production installations for PSA – Norway [41]. However, the common thread between the mentioned articles above are scattered data and limited life extension information regarding strengthening methods to ensure and extend the operational life of a jacket platform.

A. Stacey et al. (2008) published a paper on life extension issues for ageing offshore installations [39]. Most of the paper is focused on structural integrity management of ageing offshore structures. There are recommended mitigation methods for corrosion such as anode systems, epoxy for the splash-zone area and survey and inspection programme for the corrosion protection coating (CPC) and anodes. This is to make sure inadequacy can be identified and the anodes and/or CPC can be replaced to ensure continued cathodic protection of the structure. The paper concludes with more relevant information about life extension is needed, since the current standard and codes do not cover the issue in a sufficient manner.

In 2010 a report published by SINTEF by Per Hokstad et al. detailed several issues related to aging and the management of life extension of offshore facilities [36]. The report was highly detailed and filled in several knowledge gaps related to ageing. However, one of the main recommendations for further research and development was: *Developing a general guideline for design of life extension processes encompassing the entire facility, e.g. by means of case study.* This summarises the need for a general life extension framework related to the entire platform, and not just parts of it by implementation of case studies and real-world experiments.

In 2014 P. J. Haagensen et al. published an article summarising the repair and upgrading of the Veslefrikk B platform in 1999-2000 [35]. This was a floating production platform which had developed extensive fatigue cracking. The life extension programme was successful which added an estimated additional operation time of 20 years. The main part of the repairing consisted of adding structural members to carry the increased loads and the addition of vertical floating members to provide more stability. In addition, welding was used to upgrade critical high stress areas. Cover plate welds that were found to be fatigue critical were removed and replaced. The static and fatigue strength of the horizontal braces were improved by the addition of new longitudinal stiffeners, and strengthening and extension of existing ones. Free stiffener ends were sniped and the welds were improved by grinding and needle peening. Burr grinding was used to improve the fatigue life. In places the grinding was followed by needle peening to minimise the risk for fatigue cracking. The choice of mitigation method was determined by the level of mitigation needed, as in what type of detail and the magnitude of stress it would be subjected to [35]. After the repairing, the platform was reassessed and the fatigue life for the welds and members were estimated again. The repair programme was successful and the inspection history of the toe burr grinding and hammer peened welds indicate fatigue life improvements [35]. In summary, the repair and inspection programme show that fatigue cracking mainly occurs in hot spot areas. If these areas are given sufficient care during design and construction, the fatigue crack occurrence may be significantly reduced. The paper states that extensive use of improvement methods is important to reduce the extent of fatigue cracking on platforms operating in the North Sea. It is clear that the weld improvements have a widespread effect on life extension on offshore platforms.

Abe Nezamian et al. (2012) briefly mentions mitigation options in the paper about state of the art in life extension for existing offshore structures [49]. The paper suggests four approaches to SMR:

1. Remove damage
2. Reduce the loadings
3. Undertake localised SMR
4. Undertake global SMR

The paper also presents a following summary to various SMR techniques that are available. The summary mentions: Welding and weld improvement, clamping, grouting of member and joints, bolting, removal of members, adding bracing, removal of marine growth and coating and lastly epoxy grouts [49]. However, the information is mentioned very briefly and no details are given about an implementation framework or how the different techniques improve the platform in what way.

There are numerus books published about offshore structures, life extension and assessment for life extension. Many of the books have similar layout and information. Because of this, one comprehensive and well-written book was chosen to be reviewed. *Offshore structures: Design, construction and maintenance* written by M. A. El-Reedy published in 2012 has comprehensive information about different topics related to life extension of offshore structures. This book is about the design, construction and maintenance of offshore platforms in detail. It is based around standards such as API and ISO and other technical codes and practices. In addition, the book focus on the ageing of offshore structures and provides up-to-date and advanced techniques for integrity management and inspection planning to implement maintenance and mitigation systems for life extension [34]. The book provides several techniques for repair of offshore platforms. It is recommended that damages to the deck should be repaired after risk assessment and inspection if degradation is found. The repair of deck is relatively easy as parts can be replaced. A new helideck can replace a degraded one. A new staircase can replace a corroded one, and so on. As marine growth accumulates on the legs, the diameter increases, as such the lateral load increases. Removal of marine growth is therefore recommended as a method of load reduction which can enhance structural capacity. For jacket repair, there are many methods for strengthening and repair. The main element mentioned is clamps. For legs that have severe corrosion damage, the traditional repair procedure is as follows: Remove the corroded part of the leg, fix the half-cylinder around the leg, place the other part and connect it with bolts and finally reinstall the bracing by clamps. A method for buckling repair is also described. The use of clamps is also recommended here in addition to dry welding [34].

The welding processes that can be considered are [34]:

- Dry welding of topside
- Dry welding at or below the sea surface. Welding processes such as Gas Tungsten Arc Welding (GTAW), Shielded Metal Arc Welding (SMAW) and Flux Cored Arc Welding (FCAW) are main methods used for this type of situation.
- Hyperbaric welding using habitats. The main processes are GTAW and SMAW, although FCAW and Gas Metal Arc Welding (GMAW) can also be employed.

The information about grouting and clamps were detailed here, and not mentioned in the standards. However, the book is based around ISO and API codes and need to be adjust for the use in the NCS. And again, there is no framework that provides these mitigation solutions in a clear and easy way to be implemented, which is very similar to the mentioned research from above.

G. E. Beyg and A. Taheri (2017) investigated the pile ageing effect of fixed offshore platforms located in the Persian Gulf. It concluded with that the performance of jacket platforms could be further improved with careful planning and execution of a maintenance and strengthening strategy, particularly in terms of ageing effect of piles [85].

4.3 Mitigations Related to Stiffeners, Bracing and Brackets for Strengthening

4.3.1 Bracing

R. Tremblay et al. (2008) presented a comprehensive experimental programme on the inelastic response of large size steel bracing members where HSS local buckling and fracture were delayed when reducing the cross-section slenderness and increasing the brace overall slenderness [69].

K. H. Nip et al. (2010) did a study on seismic loading on concentrically braced frames. Stainless steel specimens exhibited higher stiffness than hot rolled carbon steel and cold-formed carbon steel [68]. Stainless steel specimens showed higher tensile and compressive resistance and maintained higher tensile stiffness, compared to carbon steel specimens with similar characteristics and slenderness. These conclusions can have implications on the overall structural response of framed structures such as offshore jacket structures [68].

Xiaoye Yu et al. (2015) presented a paper about braced frames and their relationship between lateral stiffness, internal forces and bracing patterns to achieve optimal and efficient design [48]. Different patterns of bracing were tested. The conclusion from the study was: Mega X braces or double inversed V braces lead to the stiffest four-bay and four-story frame. For designing stiff braced frames, large vertical forces should be avoided. Selecting diagonal braced panels and avoiding independent vertical braces can lead to less internal forces [48]. However, the study was limited to four-bay and four-story frames and not directly relevant to offshore steel jacket structures.

4.3.2 Stiffeners

A stiffened panel is an assembly of stiffeners and panels. Internal stiffeners are commonly employed to increase the strength of tubular joints in offshore steel jacket structures.

P. Gandhi et al. (2000) did fatigue and corrosion tests on steel tubular joints in air, seawater and seawater with cathodic protection. It showed that internally ring-stiffened steel tubular joints were efficient at reducing stress concentration factors and had an enhanced fatigue life. In addition, cathodic protection ensures the delay of crack initiation [77].

In terms of buckling of thin-walled stiffened plates, buckling is a nonlinear phenomenon. Many structures utilize stiffened plates, and estimation of their maximum load carrying capacity is important. Nakai et al. (2004) studied the effect of pitting corrosion on the local strength of hold frames. Dunbar et al. (2004) addressed the effect of local corrosion on plates and stiffened panels. Local corrosion of the central area of a plate gives the worst buckling capacity for a square plate [76]. Eivind Steen et al. (2001) presented a new model for the buckling strength assessment of stiffened panels [90].

M. M. K. Lee and A. Llewelyn-Parry (2005) experimented with strength prediction for ring-stiffened DT-joints in offshore steel jacket structures. It was found out that internal ring-stiffeners do not significantly affect the ductility of tubular joints and stiffeners placed at the saddle position provide better strength enhancement than those at the crown positions [81].

Liam Gannon et al. (2014) presented a nonlinear analysis of stiffened plates in view of weld-induced residual stress and distortion using FE analysis. Compressive residual stress decreases as plate slenderness increases [78]. M. Tekgoz et al. (2014) presented ultimate strength assessment of welded stiffened plates. As plate thickness increases, compressive strength reduces due to compressive residual stress that overtake areas occupied by tensile residual stress [89]. Jung Min Sohn et al. (2014) did assessment of stiffened blast walls in offshore facilities under explosions where understandings were presented to be useful for the future design of blast walls [80]. Heba Wael Leheta et al. (2015) presented a paper on ship structural integrity using new stiffened plates such as Y-shaped stiffeners. The Y-stiffener profiles gave greater safety margin and greater ultimate strength in bottom/deck panels in comparison to T-stiffener profiles. The most critical failure mode under axial compression stress for conventional stiffener profiles is either torsional buckling or unstiffened plate buckling failure modes [79].

Y. Garbatov et al. (2016) presented numerical and experimental analysis on the load carrying capacity of corroded stiffened plates in terms of non-uniform corrosion degradation [76]. It was found out that corrosion degradation has a great influence on the ultimate strength reduction of the material.

4.3.2 Brackets

Brackets are connected to the beam or column of an offshore platform to endure extra stress concentrations. Deciding on the precise shape and size of a bracket is important. Since a thicker bracket increases the welding requirements and increases the weight added to the member.

A study on the efficient design of brackets for ships and offshore structures was done by Tae-Won Kim et al. (2013). A low carbon steel with carbon content of 0.12 % was developed for the application of offshore structures which indicated high weld-ability. The mechanical properties of the cast steel fulfilled the required target values for offshore structures [75].

Fabrication of a new type of bulb bracket through a casting process was developed. Brackets with a double circle curved hypotenuse of the triangular type was more effective in comparison with the bracket with a straight-line hypotenuse of the triangular type [75].

S. E. Lee et al. (2015) studied the ultimate strength of steel brackets used in platforms and ships [52]. It was shown that the most efficient way to increase the ultimate strength of the steel bracket was by increasing the thickness with recommendations to increase the breadth rather than the height to enhance load-carrying capacities. Residual steel brackets were found to have less ultimate strength than triangular brackets. However due to severe uncertainties in geometrical and boundary conditions, further research was recommended [52].

4.4 Recent Research on Weld Improvement Techniques

Kengo Anami et al. (2000) presented fatigue strength improvement of welded joints by hammer peening and TIG dressing [64]. Hans-Peter Günther et al. (2005) showed the positive effects of Ultrasonic Impact Treatment (UIT) to extend the fatigue life of welded details, not only for new structures but also for existing structures, through experiments [59].

M. M. Pedersen et al. (2009) experimented with post-weld treatment of high strength steel welded joints in the medium-cycle fatigue. The experiment concluded with that high strength steel is favourable in the medium-cycle fatigue range. UIT showed a consistent high level of weld improvement, even under stress ranges up to the yield strength of the base material. TIG dressing is the best suited post-weld treatment technique for mass implementation according to the data presented in the study [53].

R. Baptista et al. (2011) presented through numerical simulations that hammer peening is an efficient technique for fatigue life improvements [62]. S. H. J. van Es (2012) wrote a thesis on the effect of TIG dressing on fatigue strength of welds. TIG dressing showed significant improvement in terms of crack initiation when compared to specimens without any applied TIG techniques [58]. Gary B. Marquis et al. (2013) presented a paper on fatigue strength improvement of steel structures by the use of High-Frequency Mechanical Impact (HFMI) [46].

F. Lefebvre et al. (2014) showed the fatigue lives of butt welds of the S690 steel has been improved by the hammer peening procedures [63]. In 2014 E. Mikkola et al. published an article regarding fatigue life assessment of welded joints [37]. In welds, fatigue crack initiation and propagation typically starts at high stress concentration points, such as the weld toes [37]. These local hot stress areas are due to welding defects, such as lack of penetration, undercuts, uneven toe shape and sizes, residual stresses from the welding process and poor workmanship [37]. Equivalent crack length method for determining the fatigue life of welded structures was proposed. H. Gao et al. (2014) presented a paper on UIT on multi-pass welds where the results showed that UIT is an effective method to release and redistribute the residual stress [66]. Y. Morikage et al. (2015) presented a paper about the effect of compressive residual stress on fatigue crack propagation and the use of hammer peening on welds. Hammer peening showed to reduce the fatigue crack growth rate in comparison to the non-hammer peened specimen [60]. Guenhael Le Quilliec et al. (2016) presented a similar conclusion. A significant improvement in fatigue strength was noted after treatment in comparison to specimens that were not treated with hammer peening [61].

Schulze V. et al. (2016) presented a thorough paper about surface modification by machine hammer peening and burnishing [51]. The result showed a clear change of surface characteristics which directly affect fatigue performance, corrosion resistance and wear/tear [51]. It was displayed that surface modifications have many applicable possibilities such as post processing of welded joints to reduce tensile residual stress and increasing the overall fatigue life of the element. F. B. Yalchiner et al. (2017) presented a recent paper on the application of HFMI techniques with potential application to offshore structures [57]. It is stated that using HFMI for aged offshore structures reduces maintenance costs, increases safety levels of the structure and extends the intended design life. HFMI is also faster applied than for example burr grinding and can also be applied underwater [57].

4.5 Recent Research on Strengthening of Tubular Members

Ingar Scherf and Birger Etterdal (1999) published cost-efficient life extension methods for North Sea jacket platforms in the Ekofisk field using reassessment techniques. Four jacket structures were analysed and mitigated to extend the service life in 1995-1996. The jackets were strengthened using grouting in the joint connections, diagonal braces and tubular members, which was documented to be a cost-effective and reliable mitigation method [43]. Birger Etterdal et al. (2001) summarised high-strength grouting related to the four jacket platforms mentioned above in the Ekofisk field [50]. It is shown that grouting reinforcement of tubular joints is an effective method to increase the static strength of the joint. The bending stiffness of the tested tubular members increased and the increase in axial capacity of grout-reinforced columns was significant [50].

T. S. Thandavamoorthy et al. (1999) presented through a large experimental programme a study on rehabilitation of damaged steel tubular joints of offshore platforms that the strength of internally ring-stiffened joints was almost twice that of unstiffened joints of the same dimensions [45].

J. M. Goggins et al. (2006) did experimental investigation that deals with the response of tubular steel members under cyclic axial loading conditions [67]. T. G. Ghazijahani et al. (2014) did experiments on dented steel tubular members under bending [73]. Intact specimens failed by yielding while dented specimens failed by deepening in the dented region when the dent was located in the compression-side. When the dent was on the tension-side of the tube, there was minimal development of the dent but the load carrying capacity was reduced due to the dented area [73]. The size and position of a dent was shown thorough experiments to directly affect the load carrying capacity of the tubular members. The testing gives insight when it comes to dented members and whether to keep and strengthen them or remove them. However, it was concluded with that more testing and experiment is required to account for the wide range of tubular sections with different geometries [73]. Sang-Rai Cho et al. (2015) presented experimental and numerical investigations on the dynamic response of tubular structures subjected to dynamic impact loadings [70]. The results from the testing can be used to pick reasonable dimensions as well as predict the residual strength of tubular structures. However, the application of the results for offshore jacket structures is not mentioned and therefore unconfirmed [70].

H. Ahmadi et al. (2015) did parametric FE analysis on welded tubular DKT-joints for offshore jacket structures. The developed equations were concluded to be theoretically reliable for the use of fatigue design life of offshore structures. Still, the accuracy of the predictions need to be verified against experimental test results [74]. Roberto Taier (2013) did a paper on fatigue analysis of tubular welded joints on fixed offshore platforms by using FE analysis. However, with no experiment results to demonstrate the relevancy of the FE analysis, the results are limited in practicality [91].

Zhaolong Yu and Jørgen Amdahl (2016) did analysis of offshore tubular members against ship impacts [71]. The results showed that current design force-displacement curves should be increased to account for larger modern supply vessels.

Since the substructure of jacket platforms are made of fixed tubular joints, they cannot be flexible. However, the joint connections usually exhibit some degree of flexibility [38]. This local flexibility at tubular joint connections can allow for better load distribution. Riaz Khan et al. (2016) commented that several of the codes and standards such as API RP2 SIM (2014) and DNV GL has mentioned the use of local joint flexibility of tubular joints, but they are fairly limited in scope and not well-defined [38]. In addition, it is stated that laboratory testing of local joint flexibility has been limited. Riaz Khan et al. comments on several studies, equations and data from as late as the 1980s up to 2014 on the role of local joint flexibility. The paper concludes with that flexible joints are able to dissipate energy when subjected to cyclic forces. But it’s clearly stated that the codes and standards can lead to confusion due to little clarity. Local joint flexibility is however not the most sufficient solution since steel jacket structures are required to be well-planted into the seabed and have minimal flexibility in the local joints.

F. H. Øyasæter et al. (2017) presented a paper on the effect of corrosion on the buckling capacity of tubular members where a formula was proposed and used effectively to evaluate the buckling capacity of corroded tubular members [72].

4.6 Recent Research on Grouting of Tubular Members

Grouted connections have been used in the oil and gas industry for decades for increased stability and load transferring between the structure and the piles. Typically, the grouted connections are located just above the seabed and hence are constantly submerged and in contact with seawater [84]. Piles driven into the soil-foundation are typically used for fixed offshore jacket structures. This results in axial loading being the governing load criteria for the piles [82].

T. Ingebrigtsen et al. (1990) investigated static and fatigue design of grouted pile sleeve connections [83]. J. Clarke (1993) and J.D. Bogard and H. Matlock (1990) conducted field measurements studies and concluded with the time required for driven piles to reach ultimate capacity in a consistent soil can be relatively long, as much as 2 to 3 years [85]. The gain in capacity happens at the end of consolidation and is a known ageing effect, it results form a combination of mechanisms such as [85]:

- Increased earth pressure against the pile surface and foundation
- Effect of sustained loads on the piles
- Chemical reactions between the piles, steel, soil and seawater

- Effect of cyclic and non-linear loading

Marcus Klose et al. (2008) commented on how the use of grouted connection for offshore wind turbines gave the same benefits it has given to offshore jacket structures [92]. The use of grouting has a long history of providing benefits for steel tubular members and offshore jacket structures.

David Igoe et al. (2014) did preliminary field trials for a new type of drilled and grouted pile design [82]. The pile was installed to its target depth of 17.7 m with relative ease, in under 3 hours. Design calculations for traditional drilled and grouted piles were used to estimate the pile capacity and were compared to the measured results. The pile ultimate tension showed to be significantly higher than some more conservative design method predictions [82].

Peter Schaumann et al. (2015 and 2017) did experiments with small and large-scale fatigue tests in submerged conditions to show how water affects the grouted connections. The testing showed a reduction of tolerated load cycles in wet conditions, clearly showing grouting is affected by wet conditions and proper measures should be taken into account to ensure that the grouting does not get wet during placing/pumping [84].

Fidelis R. Mashiri (2017) presented a summary of recent research on fatigue of tubular joints that were used in agriculture, road and minding industries [47]. The cyclic loading in these structural systems typically produces high-cycle fatigue behaviour which results in failure after a certain time. One of the concluding remarks points out that concrete-filled tubular joints resulted in a significant reduction in stress concentrations and improved fatigue life [47]. Though not directly relevant to offshore facilities, the data shows the significant of grouting in terms of mitigation for high-cycle fatigue.

4.7 Comments on the Published Literature on Strengthening Mitigations

The published data that have been cited in the sub-chapters above have certainly some useful information in terms of life assessment for life extension of offshore structures and they mention some mitigation methods. They provide some new data, but it is usually scattered and not general enough.

The common theme that is repeated throughout these papers is a lack of clear-cut framework for mitigation methods to extend the operation life of an offshore facility. There is no step-by-step analysis or case study to go by for mitigating an offshore jacket structure.

The papers that include some type of analysis or case study are limited in scope, size or application of the mitigation methods. Therefore, the results are hard to replicate in a grander scale and not useful in real-time circumstances for offshore jacket structures.

5 Proposed Framework for Strengthening Mitigations of Offshore Jacket Structures

5.1 Background on the Proposed Framework

The proposed framework for this thesis is based on two comprehensive papers by A. Aeran and O. T. Gudmestad (2017) and Ashish Aeran et al. (2017) in addition to a detailed SMR approach presented by Dr. A. F. Dier A. Aeran and O. T. Gudmestad (2017) presented a detailed guideline for estimating remaining fatigue life of ageing offshore structures. Guidance was given for selecting suitable wave scatter diagrams and suitable corrosion wastage model parameters which was highlighted through a case study. Based on the case study it was concluded with; that the use of long-term wave scatter diagram is more suitable for fatigue life assessment. The corrosion wastage models in codes were found to be conservative. Guidelines were proposed on the selection of suitable parameters, especially for cases where detailed degradation information is not available. In the second paper by A. Aeran et al. (2017) a framework was proposed for the assessment and life extension of an ageing offshore jacket structure. A case study was conducted to show the applicability of the framework and the jacket structure was successfully presented to be operational for an additional nine years [1, 3, 44].

In addition, throughout the work for this thesis several standards and published literature have been analysed. The backbone of the mitigation methods suggested in the proposed framework is backed by scientific research and data that have been put forward. The proposed framework is original work and time have been put into it to make sure it is easily understandable, even for those with limited knowledge about life extension.

For the relevancy of this thesis, the focus is going to be on *Block E – Assessment for other limit states and strengthening/inspection for extended life* [3]. The limit states that is most important to be checked is the ULS followed by the FLS.

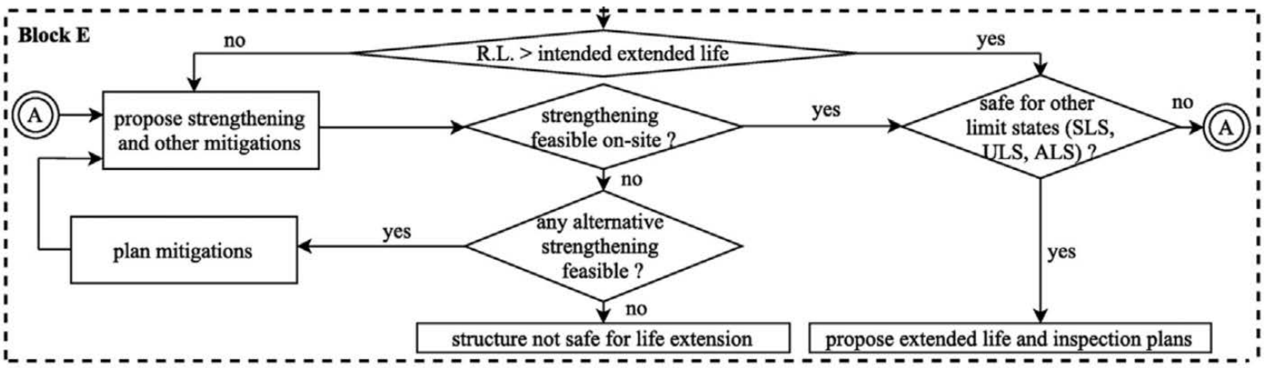


Figure 5.1: Block E – Assessment for other limit states and strengthening/inspection for extended life [3]

5.2 Proposed Framework and its Features

The proposed framework is presented in Figure 5.2.

The framework is to be referred to after life extension assessment and fatigue damage analysis have been performed. The framework is dependent on what type of damage or life extension measures are needed to extend the life of the jacket structure. For the sake of this thesis and the case study and due to time constraints, only the jacket-legs and tubular members of the structure has been prioritized and not the topside. Optimal selection of mitigation techniques saves time, money and ensures the safe continuation of the production and process facilities' operations. Selection is however difficult since it requires knowledge of available techniques and their variants. The strengths and weaknesses of the mitigation methods and their requirements to be implemented such as equipment needs, economical costs, infrastructure support, regulatory requirements and so on are time consuming. Other criterions include technical performance, reliability of the mitigation techniques, inspection requirements post-implementation, timescale of application, problem areas, environmental and water-depth challenge etc. This is a major challenge for practicing engineers in the presence of limited quantitative data. The framework is meant to assess practicing engineers come to a reliable and sufficient solution for life extension of an offshore jacket platform in the NCS.

The proposed framework shows in detail and what type of measures are recommended related to what type of damage are present in the jacket platform. It begins with a total assessment of the jacket structure and what kind of damages or cracks are identified. After the assessment, damage scenarios are to be identified, whether they are cracks or other damages related to total the structure, the members and damages such as impacts/dents. In the mitigation part, there is a clear distinguish between major and minor strengthening requirements. Major strengthening requirements are defined as the need for welding, additional equipment for repairing and mitigation, and is generally more time consuming. The major strengthening requirements are for damages or scenarios where total structural integrity is in danger, which can lead to major accidents. Minor strengthening is requirements for damages or scenarios where the total structural integrity is not fully-yet in danger, but mitigation options are needed for continued operation of the facility. For fatigue and non-fatigue cracks, several mitigation options are recommended. The options depend on the severity of the cracks and their location. The optimal choice is one that will not only repair the faults, but also prevent future cracks happening in the same area.

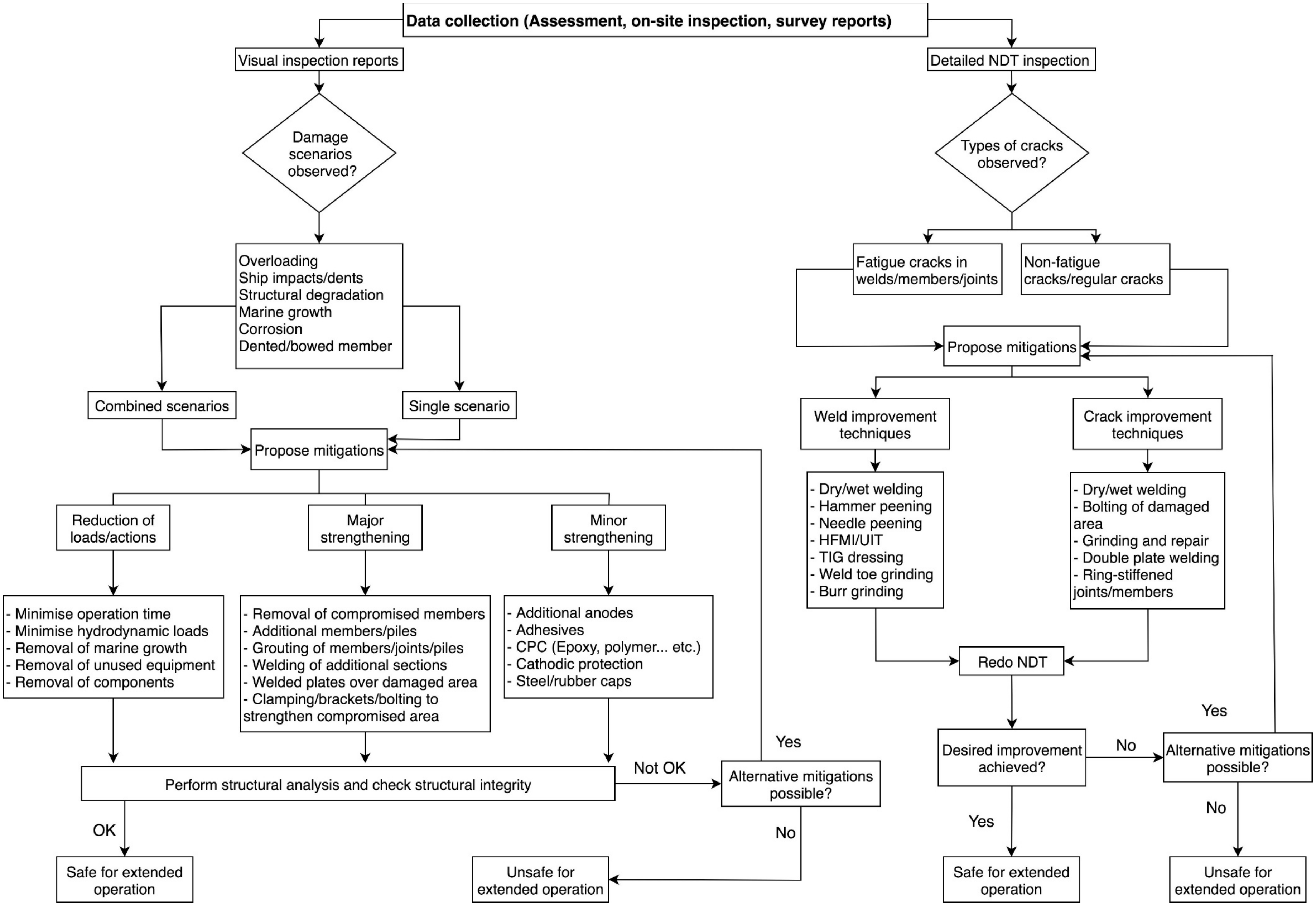


Figure 5.2: Proposed framework for mitigation of offshore jacket structure

5.3 Description of Mentioned Mitigation Methods

The proposed framework mentions several mitigation methods. The goal of this chapter is to explain some of the mentioned techniques in more detail before the proposed framework is applied to a case study.

5.3.1 Welding

5.3.1.1 Dry welding of Topside

For repair and welding of topside the procedure is generally an uncomplicated process. The area should be designated as a temporary hazardous area and routine safety producer must be followed. Dry welding of topside is the most used form of welding, limited only by the requirements for hot work [34].

5.3.1.2 Dry welding at or Below the Sea Surface

It is noted that both cofferdam and hyperbaric habit welding techniques have proven track records since the 1970s, particularly in the North Sea [34].

- Cofferdam: A watertight structure surrounds the welding site and is open to the atmosphere. This method is limited to shallow water depths.
- Hyperbaric habitat welding: The chamber is filled with gas equal to the hydrostatic head at the weld depth.
- Pressure-resistant chamber: A pressure chamber surrounds the work site. Once everything is in place and the chamber is sealed, the chamber is dewatered and the pressure can then be reduced to one atmosphere as the surface.

In general, the only thing that limits atmospheric welding at or below the sea surface is the depth. Dry welding at or below the sea surface guarantees a good weld, but is limited by water depth and potential costs [34].

5.3.1.3 Hyperbaric Welding

This method is the most commonly used welding technique for primary structures and pipelines. The welding site is enclosed by a working habit, and dewatered by filling it with gas. The pressure of the gas will be at equal pressure at a point close to the bottom of the chamber, and the maximum pressure difference will be at top of the chamber which will depend on the height of the chamber. The depth of hyperbaric welding is only limited by access and is therefore and excellent welding process for wet welding and deep-water welding. This process is however rather complicated. The welding process has to be specially optimised for hyperbaric conditions, and as such the technique is limited in terms of usage [34].

5.3.2 Post-Weld Improvement Methods

Welding is a fabrication method that joins materials, usually metals by inducing heat to the base material. A filler material is typically added to form a weld pool. This will cool and usually forms a stronger bond than the base material would alone. Improvement of fatigue strength of welded joints by application of different post-weld treatments have received much attention lately. In general, the weld toe stress concentration factor will be reduced by post-weld treatments [53]. Fatigue damage in welded structures, weld toes and welded joints is a well-known phenomenon that needs to be addressed and mitigated to achieve optimal length of the life extension programme [57]. The post-weld treatment needs to be done in a satisfactory matter to reduce local stress concentration factors and defects. Fatigue cracks normally instigate and grow in the vicinity of welds when subjected to variable loading over time. Table 5.1 shows the different post-weld improvement techniques and their effect on the weld geometry and their mechanical effects.

Table 5.1: Examples of weld improvement methods and their key effects [57]

Method	Weld geometry improvement		Mechanical effects
	Increasing and smoothing transition	**Eliminates defects**	**Induces compressive residual stresses**
Grinding	X	X	
TIG peening	X	X	
Shot peening			X
Hammer/Needle peening	X	X	X
HFMI	X	X	X

TIG dressing is the most effective treatment in the medium-cycle regime. UIT on the other hand seems to be the most effective in the high-cycle regime [53].

5.3.2.1 Tungsten Inert Gas (TIG) Dressing

TIG dressing removes weld imperfections such as undercuts, inclusions and cold laps. This method is accomplished by re-melting the weld toe, thus forming a smooth transition between the weld face and the base material [53, 54, 65]. This results in removal of flaws and reducing local stress concentration factors [54]. From research and experiments, it is clear that TIG dressing can achieve significant improvements on the weld toe radius, with most studies focusing on fillet welds [56, 58, 64]. TIG dressing through experiments have shown to have the smoothest transition between the weld face and base material. A major concern with TIG dressing is that it can lead to excessive softening of the base material. There is also a slight tendency towards undercuts in weld treated by TIG dressing. TIG dressing is highly effective but requires high skill level and proper cleaning of the weld area before treatment [54, 56]. TIG dressing is found to be one of the best suited post-weld treatment method for handling imperfections and irregularities in the weld. The speed of TIG dressing is approximately the double of burr grinding but slower than UIT [53].

5.3.2.2 Burr Grinding

The main purpose of burr grinding is to remove minor weld defects in the weld toe, while simultaneously reducing the stress concentration factor of the weld toe by machining [53]. The usage of burr grinding leaves the grinding marks parallel to the direction of loading, which stops them from acting as crack initiation sites. Two-stage burr grinding procedure have been reported to significantly improve fatigue life by Hansen et al. (2005). The disadvantages of burr grinding are that burr grinding is slow and difficult due to the high hardness of the material such as steel [53].

5.3.2.3 High-Frequency Peening (HFP) – HFMI and UIT

HFP such as UIT operates in similar way to ordinary hammer peening, but at a noticeably higher frequency which reduces vibration and notice [53, 54]. HFMI improve the local weld geometry in addition to the surface quality and introduces high compressive residual stresses. HFMI causes the base material to plastically deform leading to changes in the microstructure, the local geometry and the residual stress state in the region of work done [57]. UIT needs only a force of approximately 30 N to operate, whereas ordinary hammer peening tools require a force of more than 200 N against the base material being treated. UIT is significantly more comfortable and applicable for the operator, which may lead to better fatigue life results [53, 59]. High strength steels are most suitable for the application of post-weld treatment methods like UIT as they can build up high compressive residual stresses. This suppresses the fatigue crack initiation and can increase the fatigue strength [59].

HFP improves the fatigue life of the welded joint by plastic deformation of the weld toe. Tensile residual stress is relived and beneficial compressive residual stresses are introduced. The sharp notch in the weld toe is blunted and the treatment leaves behind a smooth trace. Finally, by mechanically hardening the surface material, local fatigue strength of the material in the notch is increased. UIT can be performed at high speed and is by far the fastest treatment, the compressive residual stresses introduced by UIT may be relaxed due to the high stresses [53]. UIT is able to deliver a more gradual transition from the weld metal to the base material, reducing local stress concentrations [54].

5.3.2.4 Hammer Peening

Hammer peening is manually performed using a pneumatic or an electrical hammer and is considered to be an effective and consistent method for improving the fatigue strength of welds, even poor-quality welds [51, 54, 61]. The weld is plastically deformed, which results in beneficial compressive residual stresses in the plate and reduces local stress concentration [54, 65]. However, the procedure is noisy and it is hard to perform for long periods of time due to vibration transition directly from the hammer peening equipment. Hammer peening requires approximately 200 N for operation [53, 54].

5.3.2.5 Shot Peening

The shot peening process is a mechanical surface treatment where large number of shots are propelled against the surface of the weld at high velocity using compressed air. Shot peening can cover large areas at low costs. However, application on larger scale is rarely applied since only a thin surface layer of the plate is deformed, which is open to corrosion damage [54].

Masnaji R. Nukulwar and Shailesh S. Pimpale (2016) analysed the fatigue life of welded joints with and without shot peeing. The result after experiments showed that yield stress and ultimate tensile strength of the material after shot peening had increased noticeably and a clear amount of compressive stress was introduced in the material [93].

5.3.2.6 Needle Peening

Needle peening uses small spikes called needles powered by a pneumatic source in order to hit the surface. The impacting needles stretch and create indentations. The sourcing surface opposes the stretching caused by this and introduce regional compressive stresses. This results in a compressive layer of the deformed material that hinders crack propagation under cyclic loading which in turn increases the fatigue life of the material. Needle peening has low equipment requirements and high adoption potential [86].

5.3.3 Corrosion Mitigation Options

5.3.3.1 Mitigation using Epoxy Coating

Epoxy coating is an effective way to combat corrosion creation. Epoxy coatings create a hard-adherent layer on top of the steel members that provide great corrosion resistance. Epoxy coatings can come in the form of spray or paintings, depending on the chemical compound in them. The main advantage of epoxy coatings is their ability to be formulated for specific performance requirements. It is the particular selection and mixture of the epoxy and hardener components that determine the final characteristics and suitability of the epoxy coating for a particular situation [94]. When epoxide resin is combined with polyamine hardener, a chemical reaction happens that results in curing which can take several minutes to several hours. This turns the mixture into liquid epoxy coating which results in an extremely strong and durable compound once applied and allowed to turn solid. The coating will have resistance to high temperatures and several highly corrosive chemicals [94]. The level and amount of hardener in the mixture, decides the properties of the epoxy coating. In the offshore industry, epoxy coatings are popular due to their quick-drying abilities, good water resistance, and ease of application. They are often used on steel members to resist corrosion from alkali, acid and other damaging compounds found in and near offshore environments [94]. Examples of different epoxy coating are given in Table 5.2, with their main advantages and disadvantages [95]:

Table 5.2: Epoxy coating systems and their main advantages and disadvantages

Epoxy coating systems	Advantages	Disadvantages
Amine-epoxy systems	- Effective solvent and alkali resistance - Acid resistance - Good mechanical strength and hardness - Excellent barrier to moisture and chemical	- Mildly toxic - Short recoat life/short protection life - Dries relatively slowly
Polyamide-epoxy systems	- Excellent water and alkali resistance - Moderate acid resistance - Good adhesive capabilities - Moderate weather resistance	- Coating quality is depended on temperature - More viscous than other epoxies

Siloxane-epoxy systems	- Excellent weather resistance - Excellent acid resistance - Good abrasion resistance	- Low heat capacity - Low solvent resistance
Coal-tar-epoxy systems	- High saltwater and freshwater resistance - Relatively cost effective - Good protection against cathodic discharge	- Regulatory restrictions - Takes a long time to coat

5.3.3.2 Mitigation using Cathodic Protection Systems

Using cathodic protection stops the aggression of corrosion and extends the Corrosion Protection Coating (CPC) applied to the structure. Cathodic protection stops corrosion by converting anodic (active) areas on the metal surface to cathodic (passive) areas by supplying electrical current from an alternate source. As long as the current arrives at the steel (cathode) faster than oxygen, no corrosion will occur [96]. Figure 5.3 shows the anode protects the steel from corrosion by creating a link between the steel and the anode.

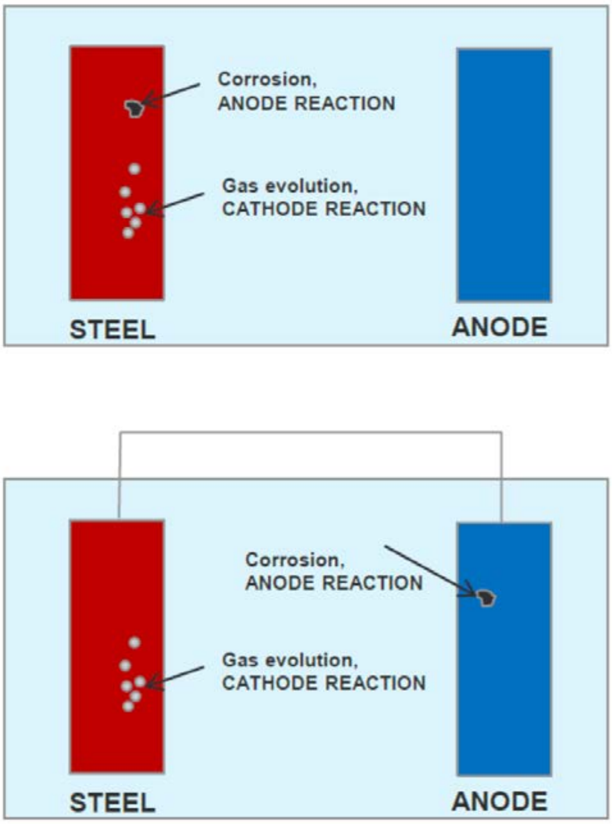


Figure 5.3: Display of how the anode protects the steel from corrosion [96]

5.3.4 Load Reduction methods

Load reduction methods such as minimising and reducing operational time on the facility has a positive effect on the load bearing capabilities of the jacket platform. By reducing operations and limiting the amount of time drilling and production units are operative, the jacket will not be affected by wear and tear as much as during normal operational time. Every use of equipment, operations and loadings will degrade the structure over time.

Removal of marine growth, unused equipment and removal of unnecessary components relives the structure of extra weights. The members will experience less loading, and the piles experience less loading due to the reduction of the total weight of the platform.

5.3.5 Added New Members and Additional Sections

5.3.5.1 Added New Members

By adding new members to the original jacket structure, it can handle the loading it experiences through its life much better. New members redistribute the weight and loading that are experienced by the original tubular members. This increases the life of the original members, since they have more ways to redistribute all the loads and actions. The new members have to fit the jacket structures' geometry. They need to be the same dimension or as close to the original tubular members to ensure no disparity in the overall structural stability.

5.3.5.2 T-sections and channel sections

The addition of extra section such as T-sections or channel sections can improve and increase the load carrying capacities of a member greatly. T-sections have been used in onshore construction for a long time, however their application for mitigations offshore have been limited. T-sections are load-bearing sections made of reinforced concrete, wood or metal. T-sections are also known with different names such as T-beams or T-bars. They are structural beams with a "T" shaped cross section, hence the name T-sections. Channel sections have the shape of a "half-square". Similar to T-sections they can be used to mitigate members that are close to failing due to loading. Additional sections are relatively cheap and easy to install. However, important parameters such as the length, width, breadth and weight of the sections have to correct in relation to the members that are being mitigated. Incorrect dimensions can lead to overload and failure, if not instantly then over time.

5.3.6 Strengthening with Clamps

Clamps are generally made from low-carbon steel, and they can be hinged or split. Clamps may be used to repair a member by installing an additional brace. The key use of clamps is in repairing primary structural joints [34].

There are four major clamp types which are traditionally used in offshore platform repair [33]:

- Stressed mechanical friction clamp
- Unstressed grouted repair clamp
- Stressed grouted clamp
- Stressed elastomer-lined clamp

They are classified because of their installation and fixing method, rather than terms of usage.

5.3.6.1 Stressed Mechanical Friction Clamps

The stressed mechanical friction clamps are steel-to-steel friction claps that is connected by long tension bolts. They are generally used for strengthening and repair of damaged members or for connecting new members. These are usually repairs or strengthening of jacket components damaged by vessel impacts, fabrication and installation flaws, and fatigue and corrosion damage. The connection between the clamp and tubular member is susceptible for crevise corrosion; therefore, periodically inspection is required. Accurate offshore survey is needed before installation and the clamps require very tight tolerance in fabrication [34]. The major advantage with using these clamps is stated as large forces can be transferred through friction over a short clamp length, limited only by the hoop resistance of the member. Stressed mechanical friction clamps have good load transfer capacity and are the fastest clamps to deploy. They can be used for tubular members to strengthen, replace or add new members - but are unsuitable for tubular joints [34].

5.3.6.2 Unstressed Grouted Repair Clamps

These grouted clamps use short bolts. The sleeve is placed around the tubular member or joint with the annular space filled with grout. The only means of load transfer from the tubular member to the clamp is the bond at the grout/steel interface. Therefore, to increase the load capacity, the clamp length need to be increased. The unstressed grouted repair clamps offer a versatile method for strengthening or repairing tubular members and joints since they require less accurate offshore survey. In jacket structures, the application for these clamps are for pile or sleeve connections. They have been used to overcome fatigue cracks and member damage by vessel impact [34].

The main advantages are:

- Reasonable transfer capacity
- Ideal clamping for members and joints
- Good for strengthening dented members

The main disadvantages are:

- Length may be unacceptably long
- Grout seal may lead to leakage without proper fitting
- Loss of friction due to grout leakage

5.3.6.3 Stressed Grouted Clamps

These clamps are formed when two or more pieces of strengthened plates are stressed by ways of long stud-bolts onto a tubular member after grout has been inserted and permitted to cure in the annular space between the clamp and the tubular member. As such, these clamps are a hybrid between stressed mechanical friction clamps and unstressed grouted clamps. They offer the benefits of stressed mechanical friction clamps in terms of high strength-to-length ratio, and the benefits of unstressed grouted clamps in terms of the ability to absorb significant tolerances. Because of this, stressed grouted clamps are the most popular forms of clamps used. They have good transfer capacity, good tolerance for fit-up, ideal for clamping of members and joints, and particularly good for the repair of joints [34].

However, the disadvantages are:

- Unfitted grout seals may lead to grout leakage

- Loss of friction due to grout leakage

5.3.6.4 Stressed Elastomer-Lined Clamps

These clamps have an elastomer lining bonded to the inside faces of the clamp saddle plates. The strength is derived from external bolt loads, which impart compressive force normal to the interface of the liner and tubular member. The clamps are not well-suited for primary structural repair, but rather secondary components where stiffness is not critical to effectiveness. Typically, they are used to seal holes in caissons and for the attachment of other components. In summary, stressed elastomer-lined clamps are one of the quickest clamps to deploy. They have poor axial and bending load transfer capacity. They are ideal for clamping on intact tubular members or for adding members and appurtenance supports [34].

5.3.7 Strengthening by Grouting of Joints and Members

Using grout to fill structural members, particularly tubular members is a cheap and effective answer to several repairs and strengthening problems [34].

Some of the benefits are as follows:

- Grout can be used to prevent further deformation of tubular members, which have dent-damage.
- Improves the strength and fatigue performance of tubular joints
- Improves the structural integrity of the facility

5.3.7.1 Joint Grouting

The steps to perform joint grouting is stated as filling a chord with grout in the region of the tubular joint. Grouted joints have the chord member fully filled with a grout material. The grout can be placed through small inlets and outlets, which can be drilled and tapped into the tubular wall. The grouting will increase their strength, improve ductility and increase radial stiffness of the member. It also restricts local chord wall deformations, which reduces deformation-induced bending stresses and associated stress concentration factors. This will improve the fatigue life. Summarised, joint grouting increases the strength and fatigue performance of a tubular joint [34].

5.3.7.2 Grout Filling of Members

Filling members with grout increases the cross-sectional strength and its overall stability. This is a relatively easy process to provide strengthening of tubular members, especially compression members [34]. The filling prevents local buckling and increases the axial load. It is however important that the grout completely fills up the member, as small voids can lead to reduced load-carrying capacity. Void formation should be avoided. One major disadvantage of grout filling of members is that the increased mass may result in overstress of the members under seismic or in-place conditions. In addition, grout filling has tiny benefits for tension members [34]. The increased strength of the member and the added mass to the total weight of the structure is an interesting dilemma that must be effectively answered before any filling begins.

5.3.7.3 Grouting of Piles

By grouting the area between the jacket leg and the pile, platform loads may be transferred to steel piles. The load is transferred from the structure across the grout to the files. Grouting in this area therefore increases the load-carrying capacity of the piles [34].

5.4 Summary of the Mitigation Methods

At last, Table 5.3 and 5.4 show what type of measures can solve several problems at the same time. All the mentioned mitigation techniques in the literature survey, proposed framework and the mentioned methods described in detail have been put into the tables. Table 5.2 shows the mitigation techniques and their equipment needs and the offshore timescale. Table 5.3 shows how the different mitigation techniques can solve several damage scenarios at once.

Table 5.3: List of mitigation methods and their equipment and time requirements [44]

Technique	**Used offshore**	**Equipment needs**	**Offshore installation timescale**
Dry welding	Yes	Heavy	Very slow
Wet welding	Yes	Moderate	Quick
Toe grinding	Yes	Low	Moderate
Remedial grinding	Yes	Low	Moderate
Hammer peening	Yes	Low	Quick
TIG dressing	Yes	Low	Moderate
Burr grinding	Yes	Low	Quick
Needle peening	Yes	Low	Quick
HFMI/UST	Yes	Low	Quick
Shot peening	Yes	Moderate	Quick
Stressed mechanical friction clamps	Yes	Moderate	Moderate
Unstressed grouted repair clamps	Yes	Moderate	Moderate
Stressed grouted clamps	Yes	Moderate	Slow
Stressed elastomer-lined clamps	Yes	Moderate	Moderate
Unstressed grouted connections	Yes	Moderate	Moderate
Pressurized connections	No	Light	Slow
Grout filling members	Yes	Light	Quick
Grout filling joints	Yes	Light	Quick
Grout filling piles	Yes	Moderate	Moderate
Bolting	Yes	Light	Moderate
Member removal	Yes	Moderate	Quick
Adhesives	Yes	Light	Quick
Composites	Yes	Light	Quick
Additional bracing	Yes	Moderate	Moderate
Ring-stiffened joints	Yes	Moderate	Moderate
Corrosion protection coating	Yes	Light	Quick
Addition of extra sections	Yes	Moderate	Moderate

Table 5.4: List of mitigation methods their improvement abilities [44]

	Improvement on:			
Technique	**Corrosion resistance**	**Dent/defects - Member**	**Dent/defects/cracks - Weld**	**Fatigue life**
Dry welding	Yes	Yes	Yes	Yes
Wet welding	Yes	Yes	Yes	Yes
Toe grinding	No	No	Yes	Yes
Remedial grinding	No	No	Yes	Yes
Hammer peening	No	No	Yes	Yes
TIG dressing	No	No	Yes	Yes
Burr grinding	No	No	Yes	Yes
Needle peening	No	No	Yes	Yes
HFMI/UST	No	No	Yes	Yes
Shot peening	No	No	Yes	Yes
Stressed mechanical friction clamps	Yes	Yes	No	Yes
Unstressed grouted repair clamps	Yes	Yes	No	Yes
Stressed grouted clamps	Yes	Yes	No	Yes
Stressed elastomer-lined clamps	Yes	Yes	No	No
Unstressed grouted connections	Yes	Yes	No	Yes
Grout filling members	No	Yes	No	Yes
Grout filling joints	No	Yes	No	Yes
Grout filling piles	No	Yes	No	Yes
Bolting	No	Yes	No	No
Member removal	Yes	Yes	No	Yes
Adhesives	Yes	Yes	No	Yes
Composites	Yes	Yes	No	Yes
Additional bracing	No	Yes	No	Yes
Ring-stiffened joints	No	Yes	No	Yes
Corrosion protection coating	Yes	No	No	No
Addition of extra sections	No	No	No	Yes

6 Application of the Proposed Framework on a Jacket Structure – Case Study

The proposed framework is applied to an existing offshore steel jacket platform to show the application of the different suggested mitigation methods. The initial structure is modified by applying additional weight to the topside to stimulate different damage-modes. This makes the showcase of the mitigation methods and their improvement factor considerably less complex.

6.1 Considered Structure for Case Study

For this case study a fixed steel jacket platform located in the NCS is used. The Martin Linge platform is one of the biggest steel jacket structures in NCS, located in the Hild oil field. The platform has a total weight of 38000 tons, where the jacket structure weights 10000 tons and the topside weights 28000 tons. The platform is located approximately 45 km west of the Osberg field [15, 97, 100].

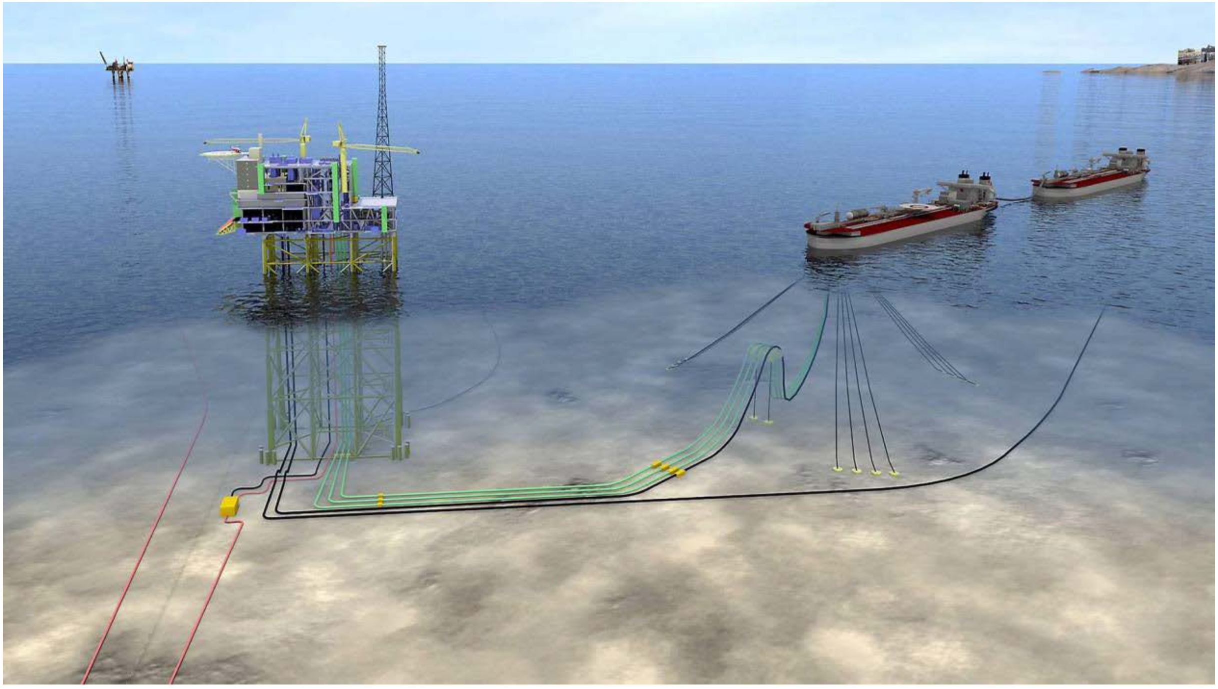


Figure 6.1: Concept illustration of the Martin Linge platform [97]

The jacket is a fixed installation that consists of 8 main legs and mainly X-bracing between the six horizontal elevations. The members used for the jacket-legs are hollow, tubular sections made with S355 steel. The jacket is at a depth of 114 metres and will be supported to the seabed with the use of pile clusters that are located at the four bottom corners of the jacket-legs [97, 100]. The finite element SAP model of the structure is shown in Figure 6.2 and the elevation of the jacket is shown in Figure 6.3.

6.2 Considered Loading and ULS Check Results for Undamaged Structure

The considered load cased for ULS checks are shown in Table 6.1.

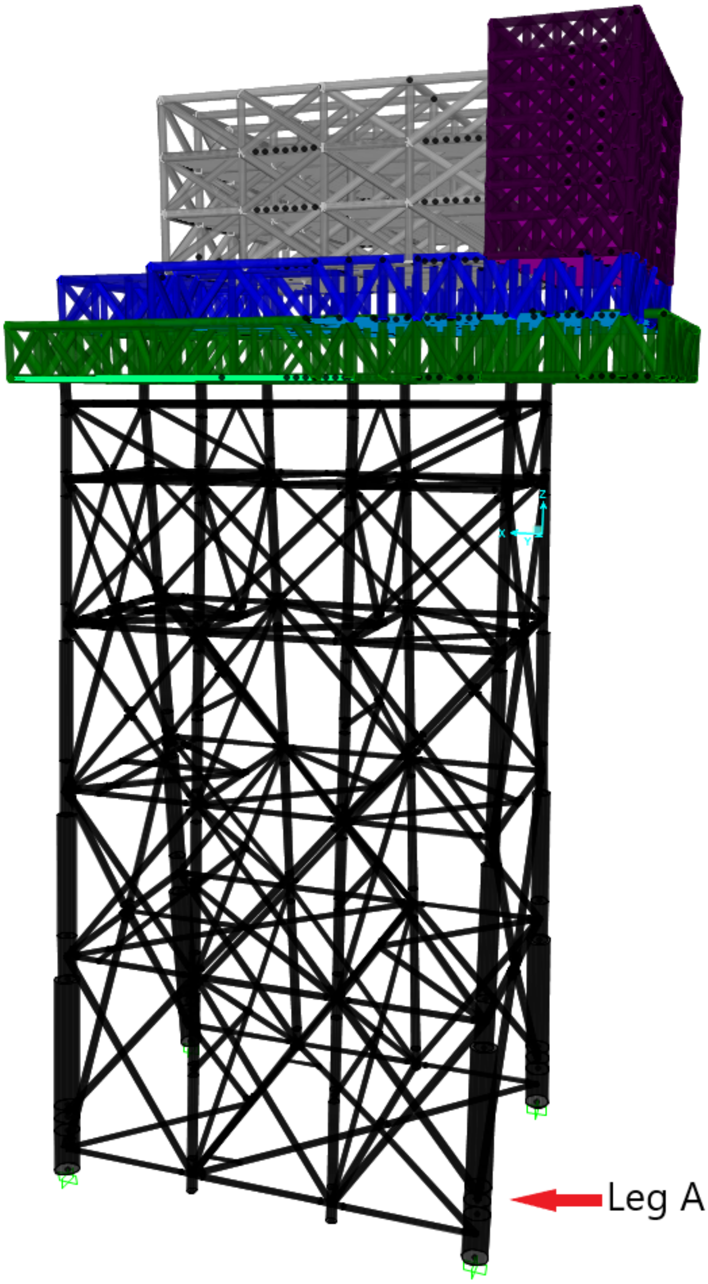


Figure 6.2: 3D view of the jacket structure with topside

Table 6.1: Load cases that were performed on the jacket structure

Case load name	Type
Dead	Linear static
MODAL	MODAL
Stoke wave – 0°	Linear multi-step static
Stoke wave – 45°	Linear multi-step static
Stoke wave – 90°	Linear multi-step static
Stoke wave – 135°	Linear multi-step static
Stoke wave – 180°	Linear multi-step static

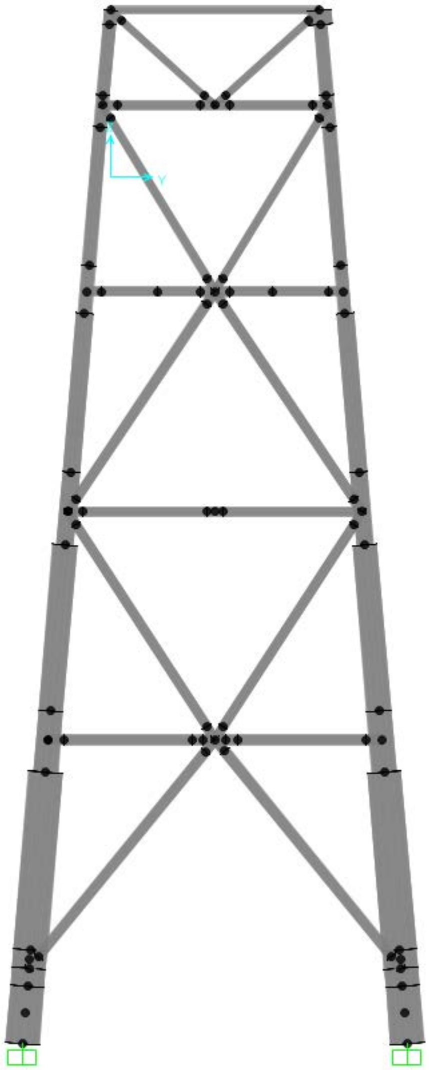


Figure 6.3: Plan view of the jacket-legs

Code check and analysis of jacket members is performed as per NORSOK N-004. For the ULS assessment, a 100 year return wave with wave height of 28.8 m and time period of 15.5 s were used.

Table 6.2: load combinations used in the ULS analysis [100]

Load case	Permanent actions	Variable actions	Environmental actions	Direction wave	Direction current
ULS_{A1}	1.3	1.3	0.7	0°	0°
ULS_{A2}	1.3	1.3	0.7	45°	45°
ULS_{A3}	1.3	1.3	0.7	90°	90°
ULS_{A4}	1.3	1.3	0.7	135°	135°
ULS_{A5}	1.3	1.3	0.7	180°	180°
ULS_{B1}	1.0	1.0	1.3	0°	0°
ULS_{B2}	1.0	1.0	1.3	45°	45°
ULS_{B3}	1.0	1.0	1.3	90°	90°
ULS_{B4}	1.0	1.0	1.3	135°	135°
ULS_{B5}	1.0	1.0	1.3	180°	180°

The jacket structure was checked for structural integrity by performing a total ULS check of the whole platform. Figure 6.4 shows Unity Check (UC) values of the jacket structure. Lower UC values represent a more safe and stable structure.

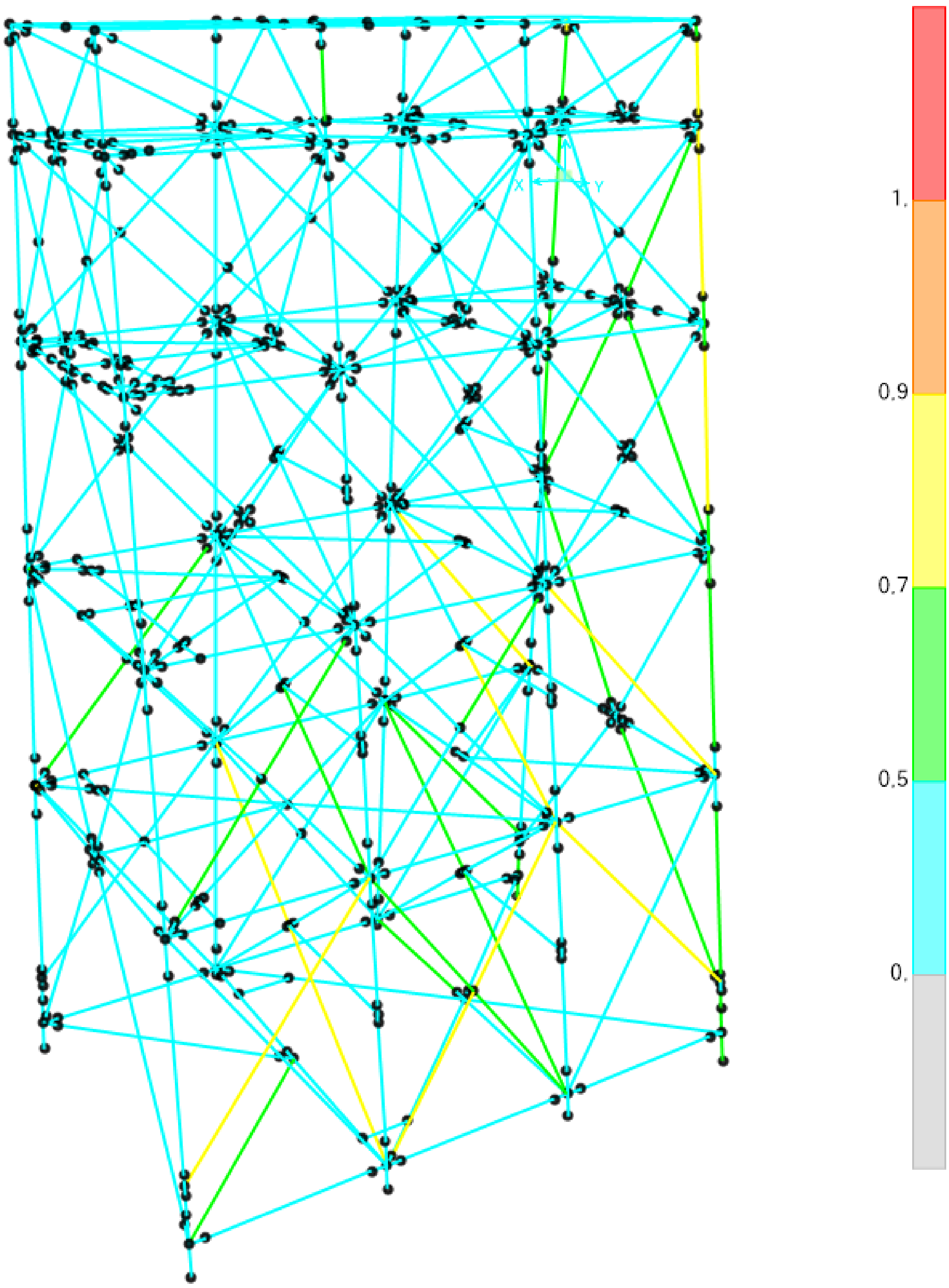


Figure 6.4: Zoom of the initial UC values for undamaged structure

6.3 Considered Failure Cases in Damaged Structure and Strengthening Requirements

The undamaged model is modified to stimulate certain damage scenarios. The considered damage scenarios are shown in Figure 6.5.

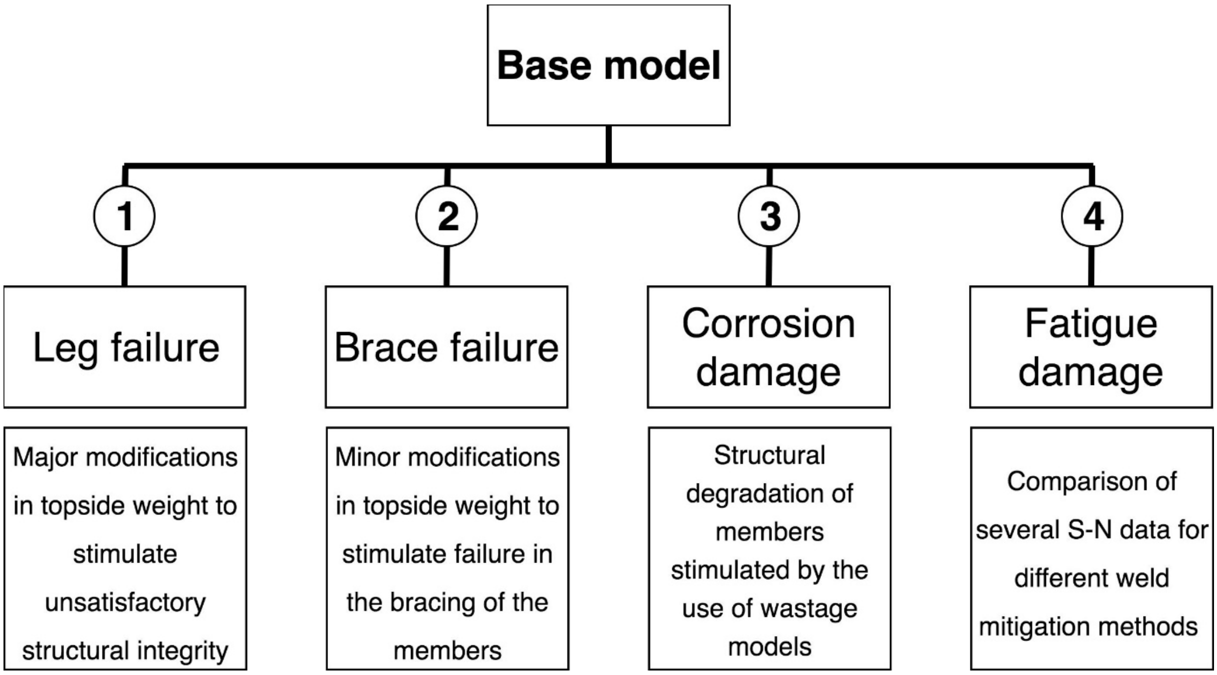


Figure 6.5: Considered damage failure cases

The considered damage scenarios are individually considered to address major strengthening requirements and minor strengthening requirements.

- Major strengthening:

Major strengthening is defined as a structure which fails the UC analysis, as in the UC values are well above 1.0. The result is that major strengthening is needed to mitigate this effect.

- Minor strengthening:

Minor strengthening is defined as UC values below 1.0, but over 0.9. This is done to show that minor mitigation methods are effective for solving minor issues related to ageing offshore jacket structures. The minor strengthening is performed to mitigate the corrosion damage.

For the welding, a theoretical approach was taken due to time limitations. Several S-N curves of tubular members were compared with each other with different weld mitigation techniques. The S-N curves showed clearly how mitigation methods such as TIG dressing, hammer peening and grinding can improve the weld, and thereby the fatigue life.

Figure 6.6 shows the considered strengthening requirement cases for the jacket structure. Any combination of leg member failure, corrosion damage and brace member failure is considered to need major strengthening requirements. For minor strengthening, corrosion damage is considered, and finally the fatigue damage needs post-weld mitigation improvements.

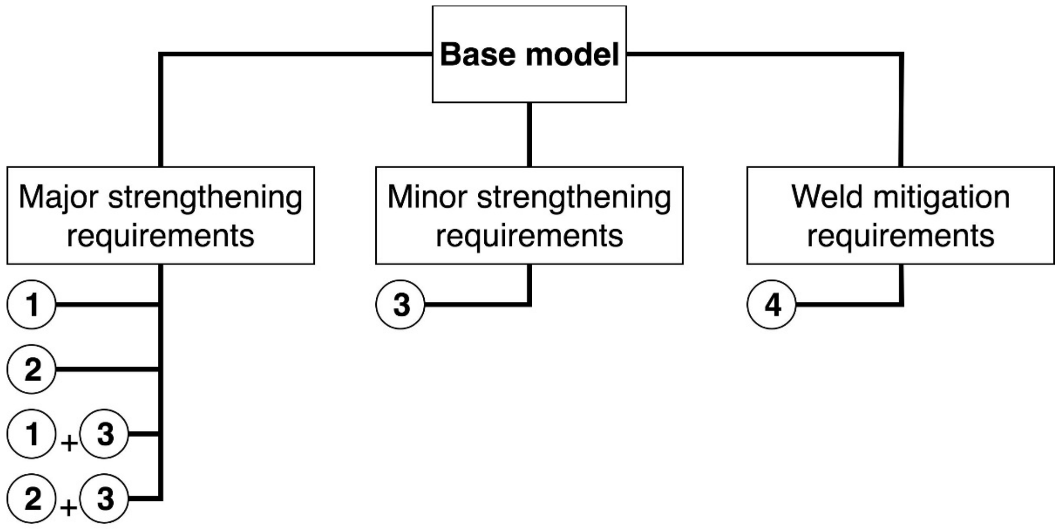


Figure 6.6: Considered strengthening requirement cases

6.4 Overview of Mitigation Methods used in the Case Study

The mitigation methods used in the case study to mitigate the different damage-modes are shown in Figure 6.7.

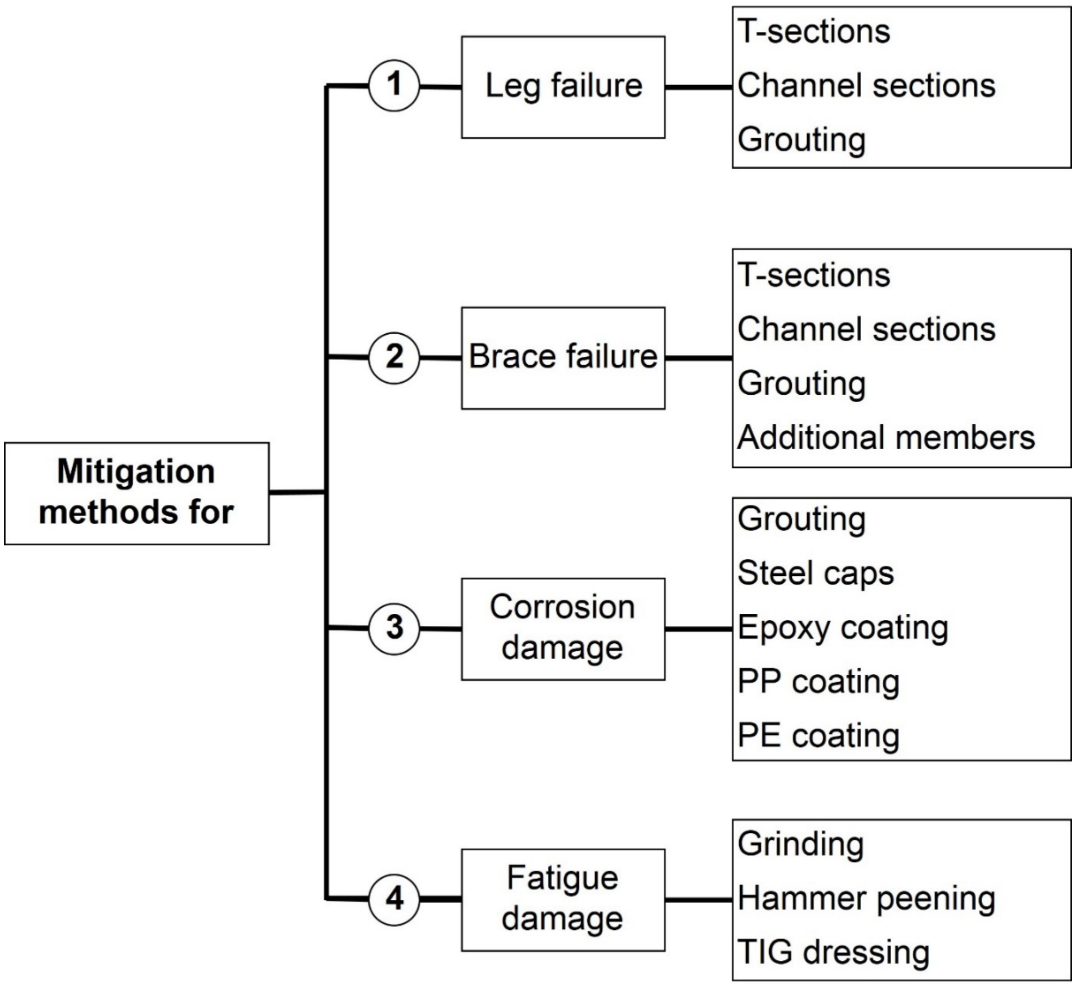


Figure 6.7: Graphical overview of the mitigation methods used in the case study

6.5 Damaged Structure Mode 1 – Failure of Leg Member

In this damage-mode, additional weight (as in major modifications) are performed on the initial structure to stimulate additional weight/modulus on the topside.

This additional weight can represent additional modulus, equipment or living quarters that affect the structure throughout its operational life. This needs to be mitigated to secure and extend the life of the platform for continued operations. The weight per unit volume of the living quarters were modified from 106.57 kg to 350 kg. This was done to save time instead of designing additional models.

The following tables and figures show the design check of the jacket structure after extra weights were added.

Table 6.3: UC check of Leg A (undamaged and after added weight)

Leg A	**UC value – Undamaged structure**	**UC value – Added weight**
Part 1	0.731	1.036
Part 2	0.776	1.091
Part 3	0.817	1.120
Part 4	0.671	0.881
Part 5	0.621	0.780

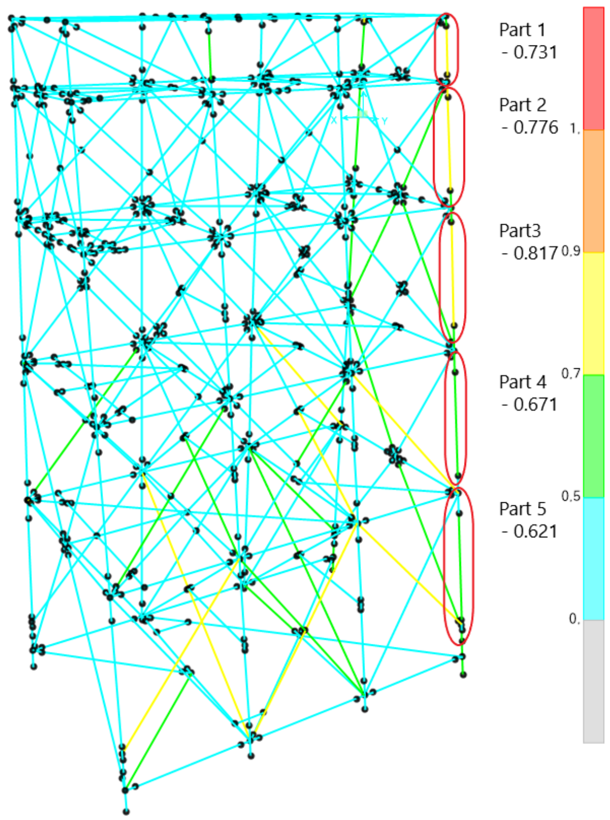


Figure 6.8: Initial UC values of Leg A

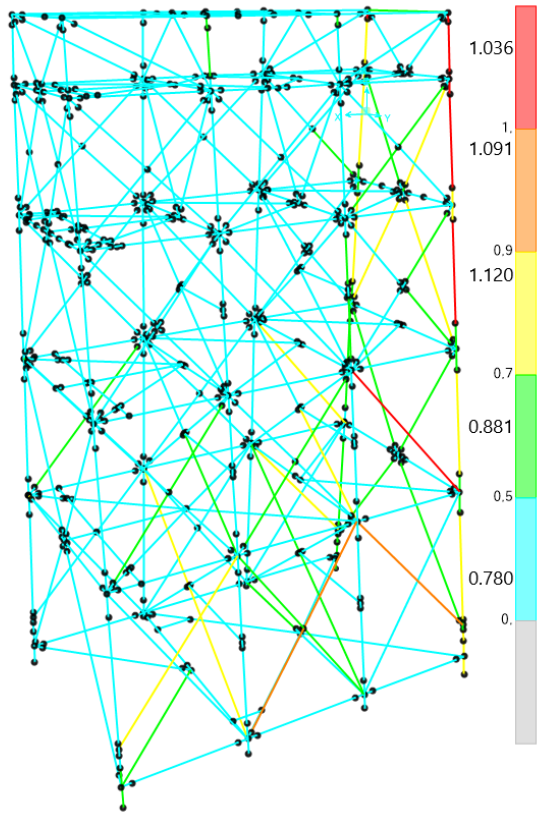


Figure 6.9: The UC values for stimulated failure of the legs

From Figure 6.9, the red colours show UC values over 1.0 which indicates unsafe structural integrity.

6.5.1 Mitigation Option 1 – Addition of T-sections

Additional T-sections were used to alleviate the extra loading on Leg A. T-sections were added to part 1, 2 and 3 of Leg A.

The T-sections are of the same steel type as the legs. As shown in Figure 6.10, it was important for the T-sections to not be thicker, bigger or longer than the original hollow, tubular member it was attached to. The calculation and comparison of the cross sectional properties of the added T-sections and tubular members from SAP2000 and analytical formulas from Excel spreadsheets is in Appendix B.

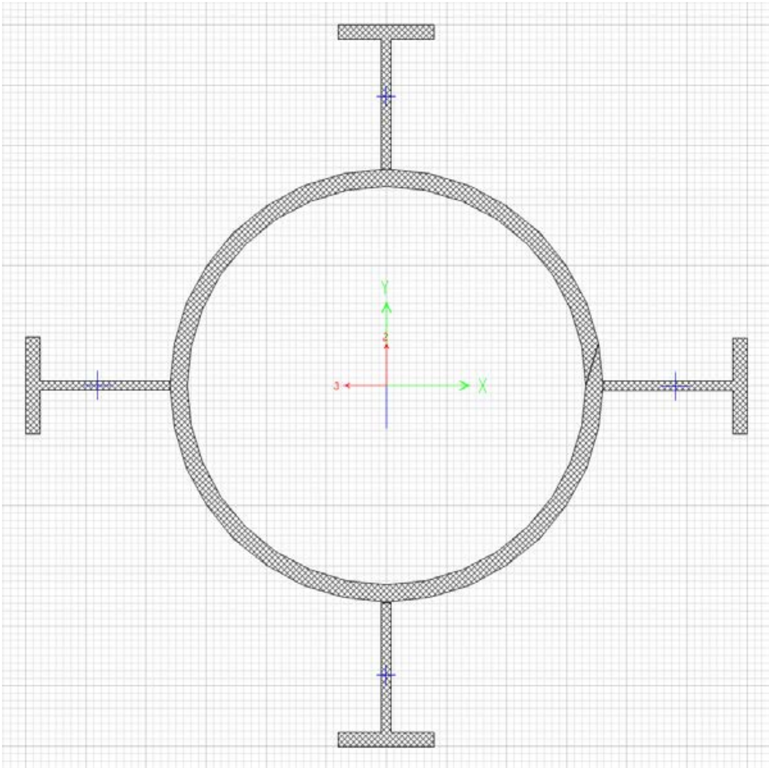


Figure 6.10: Added T-sections to the original hollow, tubular member

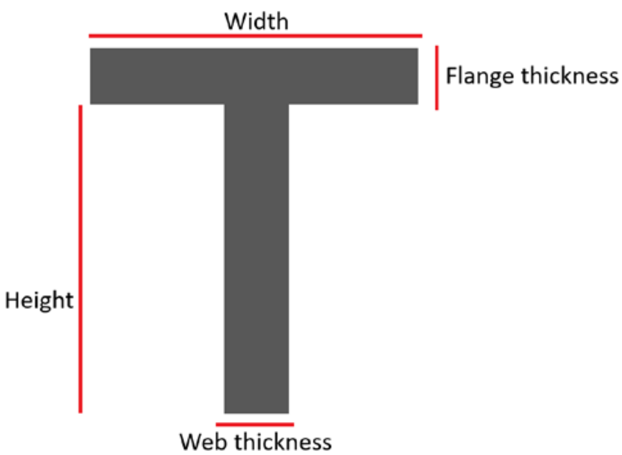


Figure 6.11: The T-section

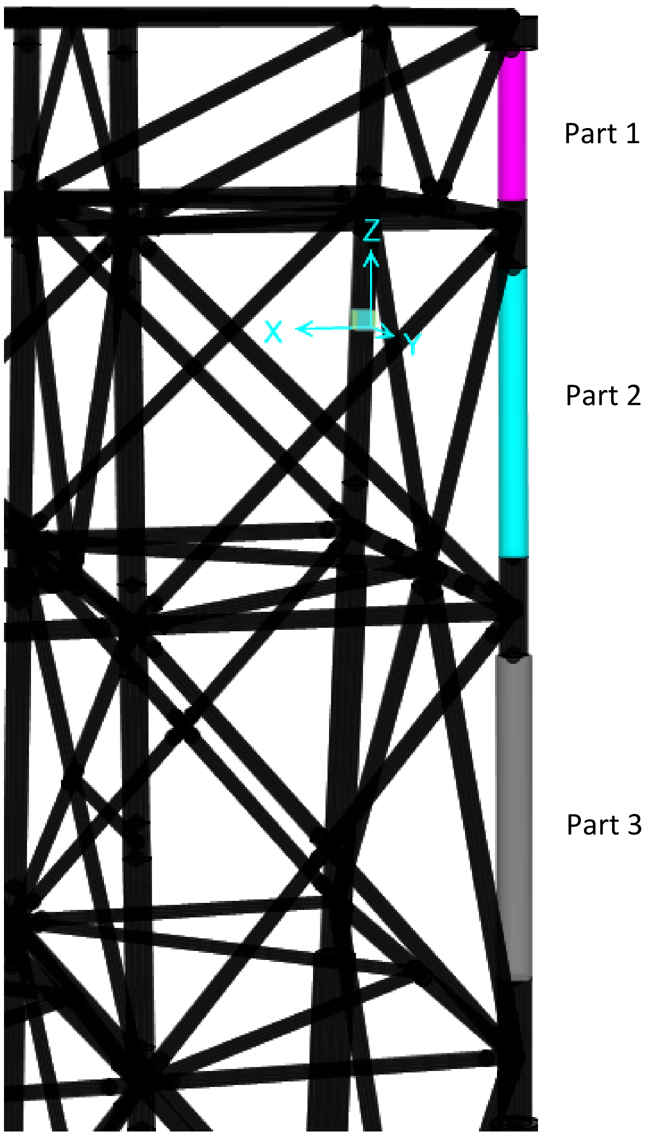


Figure 6.12: Zoom of part 1, 2 and 3 of Leg A that were mitigated

Table 6.4: Dimension of the original tubular members and the T-sections

Leg A	**Original tubular dimensions [mm]**	**Added T-section dimensions [mm]**
Part 1	Outer diameter: 1800 Wall thickness: 100	Height: 600 Width: 400 Flange thickness: 90 Web thickness: 70
Part 2	Outer diameter: 1800 Wall thickness: 70	Height: 600 Width: 400 Flange thickness: 65 Web thickness: 45
Part 3	Outer diameter: 2300 Wall thickness: 50	Height: 600 Width: 400 Flange thickness: 45 Web thickness: 30

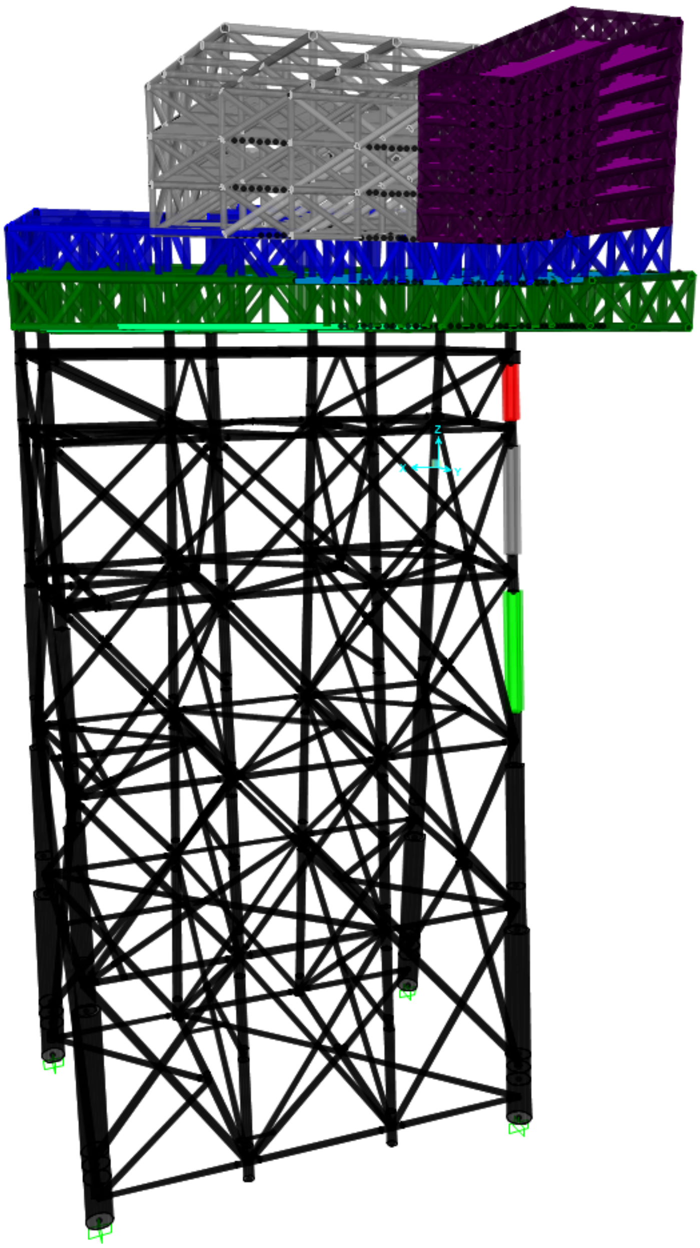


Figure 6.13: Full view of the platform with added T-sections on part 1, 2 and 3 of Leg A

The analysis was performed and the UC values are shown in Table 6.5.

Table 6.5: UC values for Leg A before and after added T-sections in X- and Y-direction

Leg A	**UC value – Damaged structure mode 1**	**UC value – Added T-sections in X- and Y-direction**
Part 1 (Added T-sections)	1.036	0.762
Part 2 (Added T-sections)	1.091	0.780
Part 3 (Added T-sections)	1.120	0.820
Part 4 (Original Tubular Member = OTM)	0.881	0.898
Part 5 (OTM)	0.780	0.784

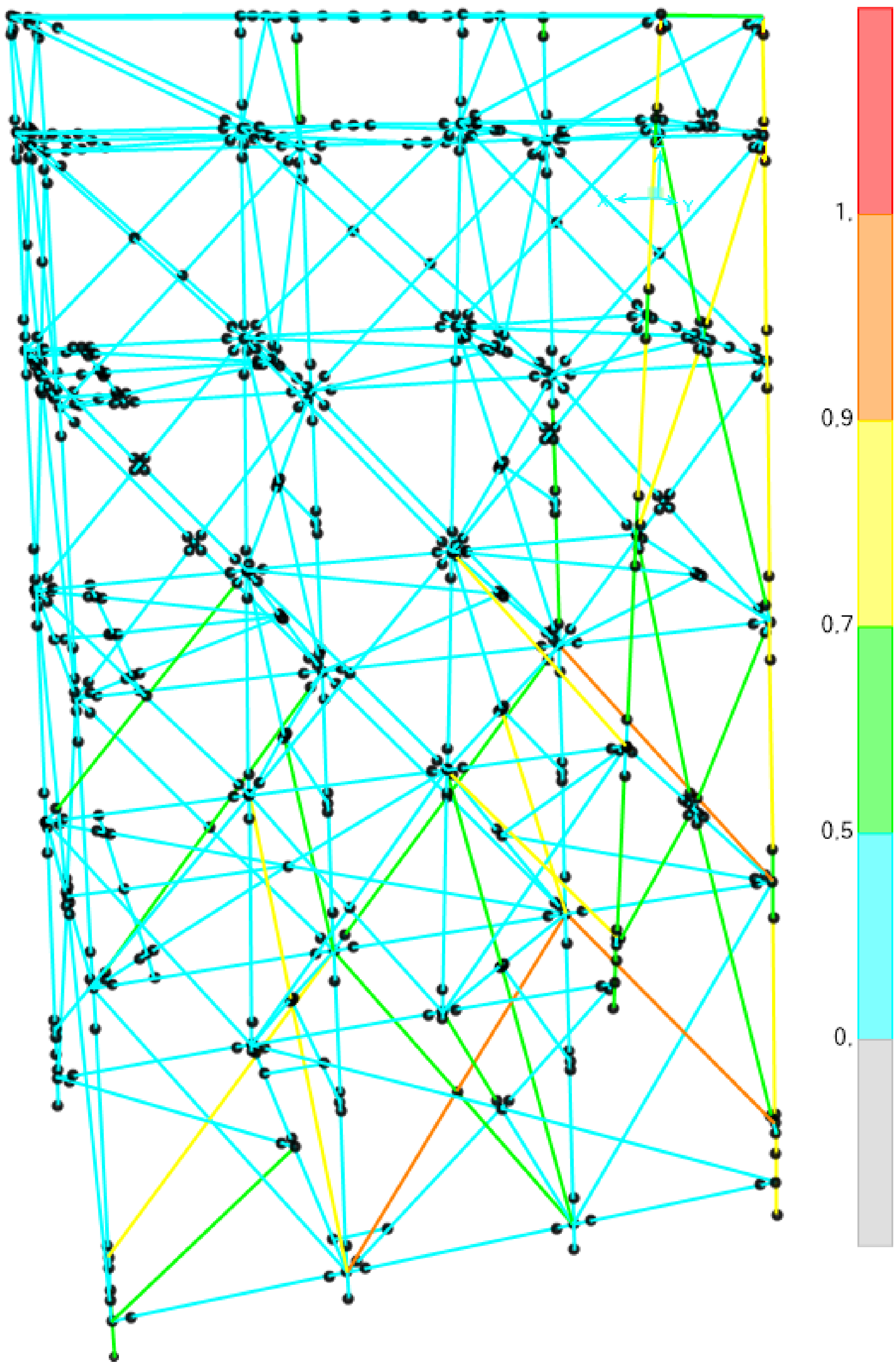


Figure 6.14: The UC value for the jacket after the added T-sections

From Table 6.5 and Figure 6.14, it is visibly shown that the added T-sections have a positive effect on the mitigated parts and mostly the whole structure. Part 1, 2 and 3 of Leg A that were supplemented with T-sections have all UC values that is very close to the initial UC values.

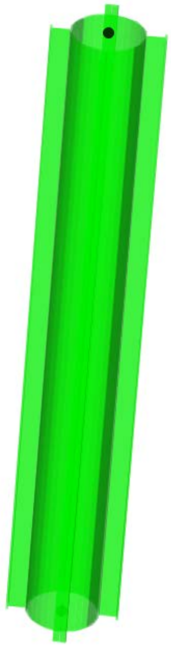


Figure 6.15: 3D zoom of the T-section

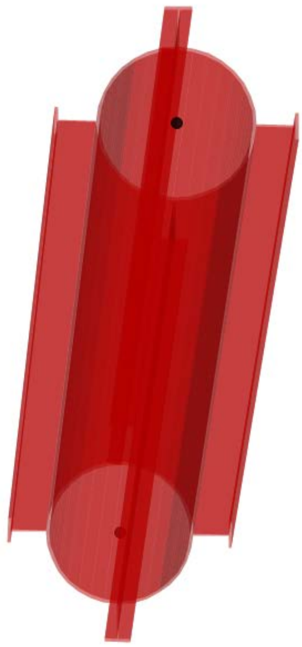


Figure 6.16: 3D zoom of the T-section

The T-sections were also modified to only be added in X-direction and Y-direction. This was done to see if they have equal or greater positive values on mitigating the leg, which would help in terms of material and repairing cost savings.

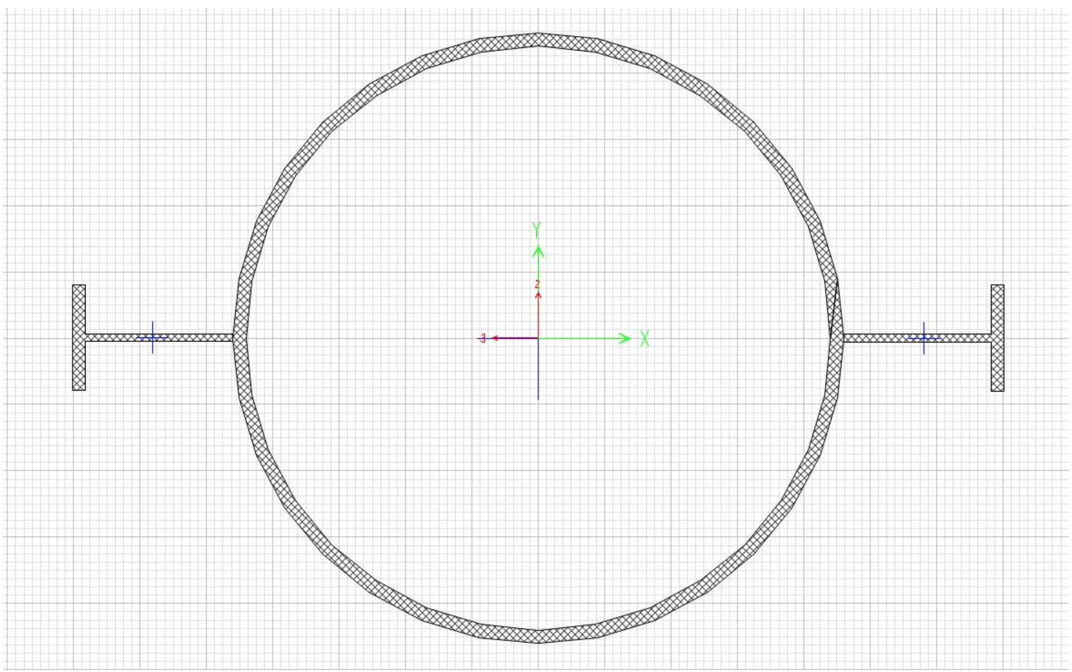


Figure 6.17: T-sections in X-direction

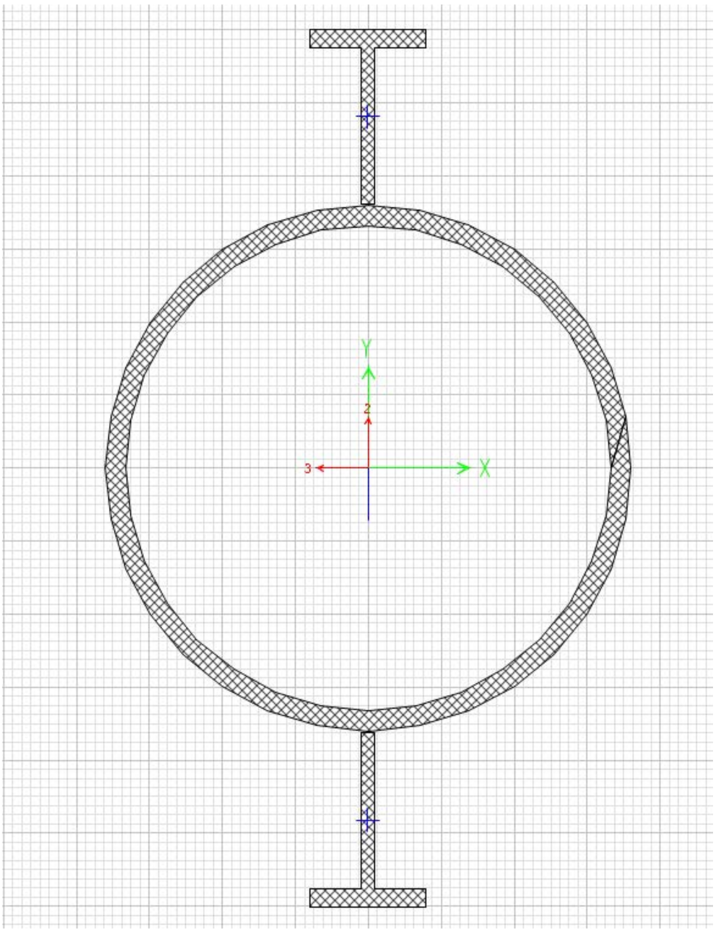


Figure 6.18: T-sections in Y-direction

However, from the Table 6.6 it is displayed that the results were not as favourable as the T-sections that were added in both directions. Leg A experiences loading in all directions due to the complex nature of the topside weight and the loadings on the structure. Therefore, from the results it is recommended to have T-sections in both X-direction and Y-direction for optimal results.

Table 6.6: UC values for all the added T-sections

	UC values			
Leg A	Damaged structure mode 1	T-section in X- and Y-direction	Only X-direction	Only Y-direction
Part 1	1.036	0.762	0.900	0.858
Part 2	1.091	0.780	0.928	0.945
Part 3	1.120	0.820	0.962	0.950
Part 4	0.881	0.898	0.892	0.890
Part 5	0.780	0.784	0.784	0.782

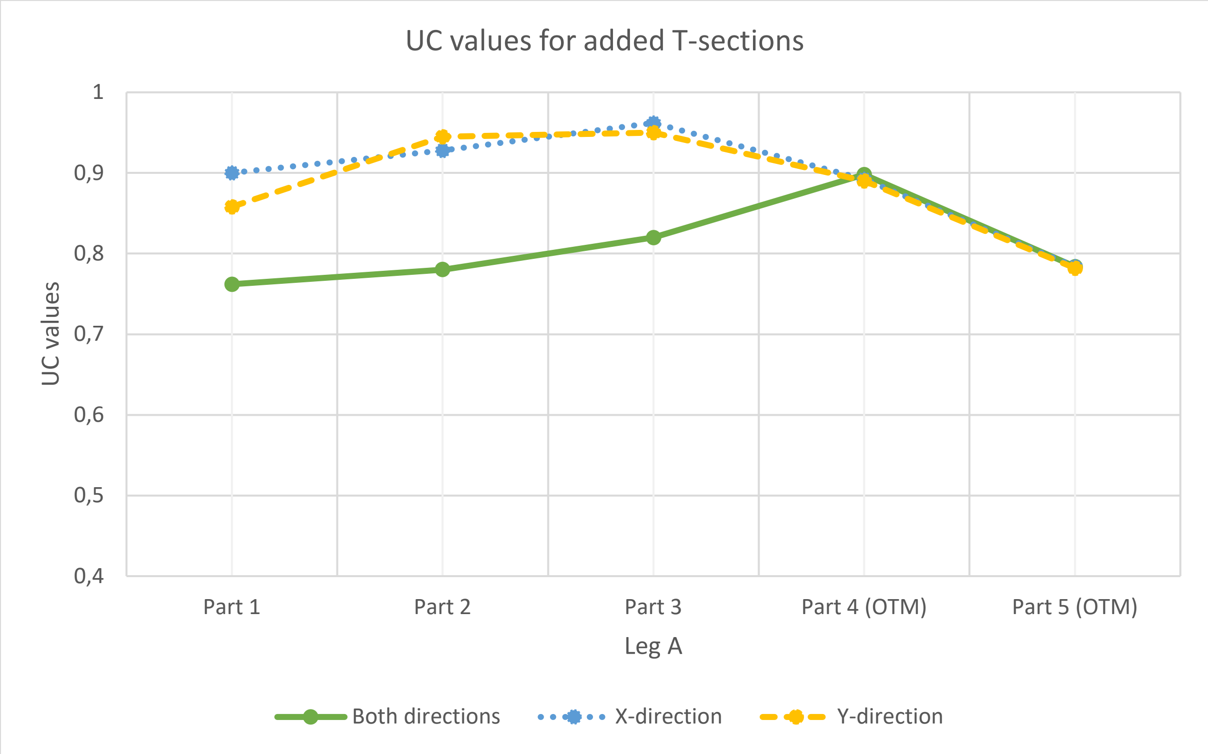


Figure 6.19: Graph of UC values for all the added T-sections

6.5.2 Mitigation Option 2 – Addition of Channel Sections

Comparable to the added T-sections, channel sections were added in a similar matter. The channels were added in X-direction, Y-direction and in both directions. The sections were the same material as the original member. Again, it was made sure that the dimension of the added channel sections were not thicker, bigger or longer than the original tubular members. The calculation and comparison of the cross sectional properties of the added channel sections on the tubular member from SAP2000 and analytical formulas from Excel spreadsheets is in Appendix B.

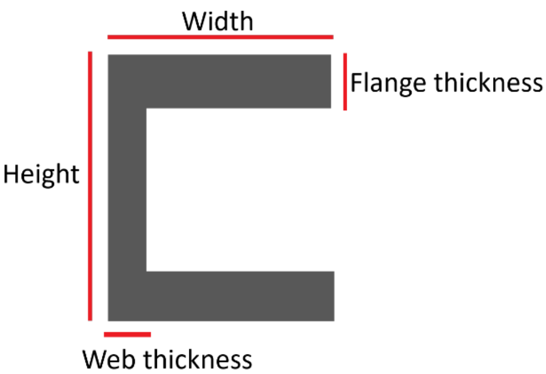


Figure 6.20: The channel section

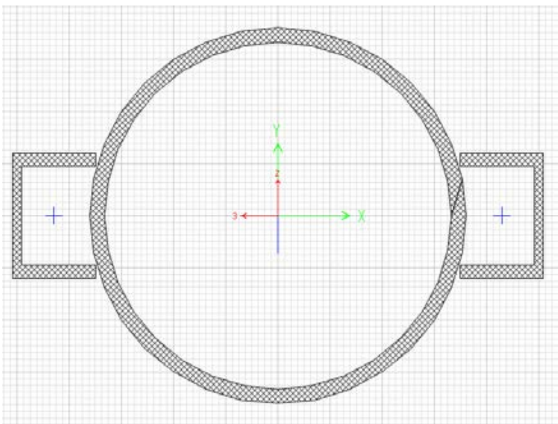


Figure 6.21: Channel sections in X-direction

Table 6.7: Dimensions for the original tubular members and added channel sections

Leg A	Original tubular dimensions [mm]	Channel section dimensions [mm]
Part 1	Outer diameter: 1800 Wall thickness: 100	Height: 600 Width: 400 Flange thickness: 90 Web thickness: 70
Part 2	Outer diameter: 1800 Wall thickness: 70	Height: 600 Width: 400 Flange thickness: 65 Web thickness: 45
Part 3	Outer diameter: 2300 Wall thickness: 50	Height: 600 Width: 400 Flange thickness: 45 Web thickness: 30

For the first part of the analysis, the channels were added in X-direction.

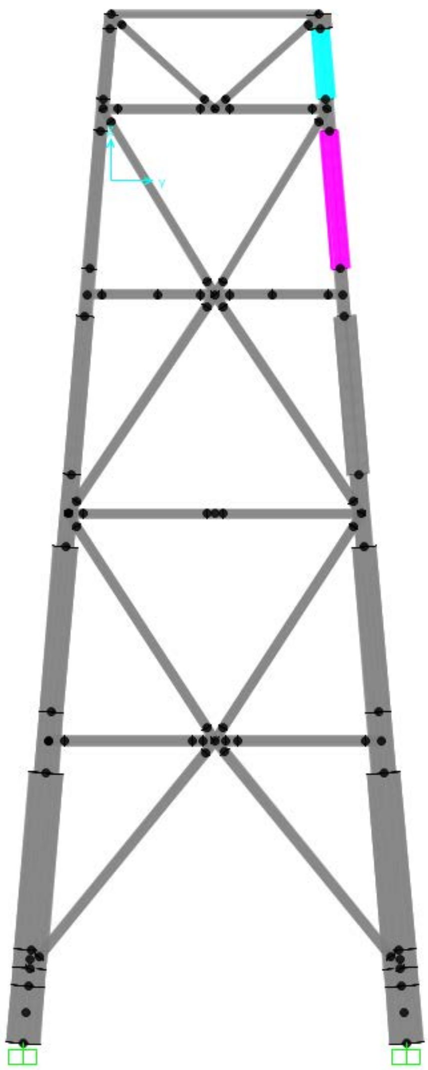


Figure 6.22: Plan view of Leg A with mitigated Part 1, 2 and 3

Table 6.8: Channel section only in X-direction

Leg A	UC value – Damaged structure mode 1	UC value - Channel section in X-direction
Part 1	1.036	0.842
Part 2	1.091	0.861
Part 3	1.120	0.907
Part 4 (OTM)	0.881	0.897
Part 5 (OTM)	0.780	0.785

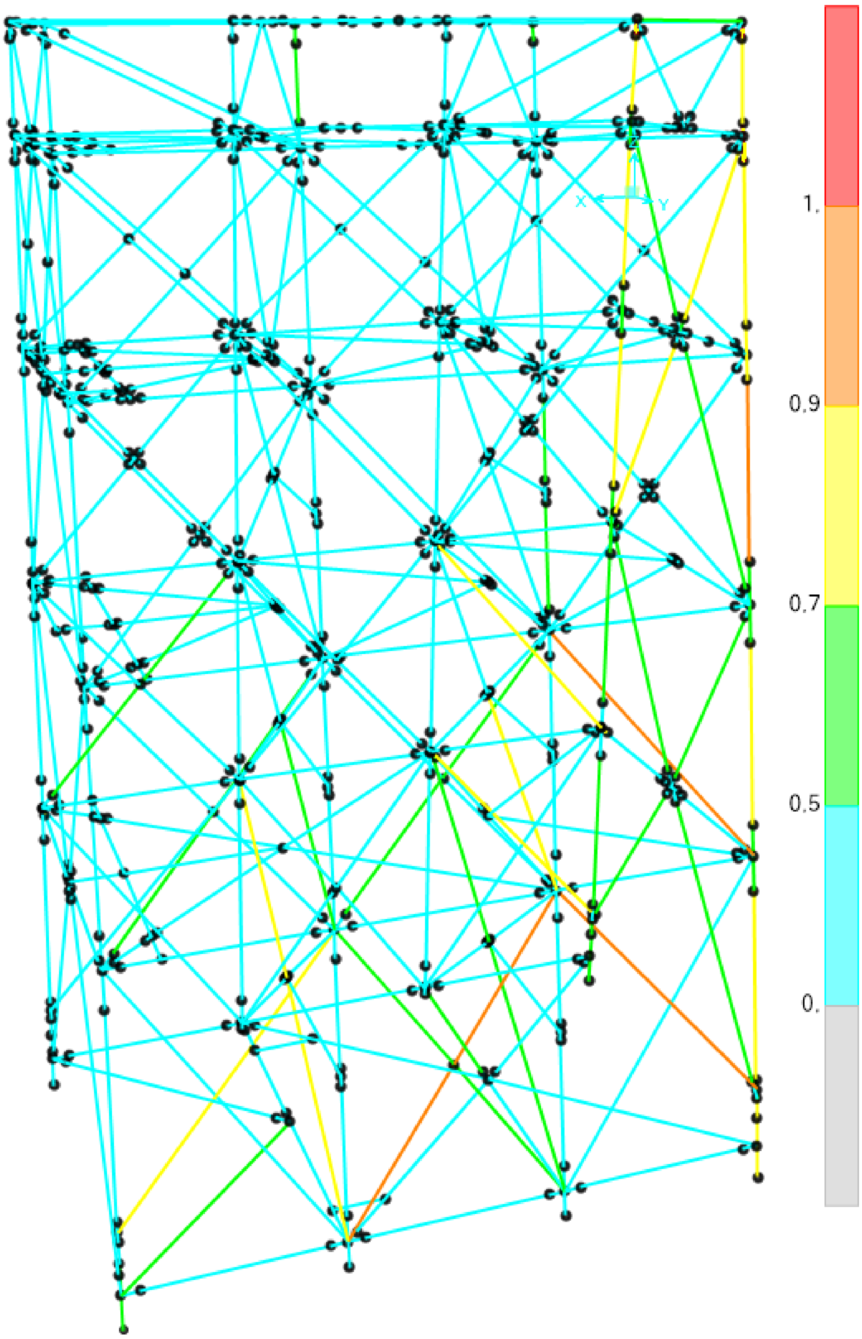


Figure 6.23: The UC values for the jacket with added channel sections in X-direction

Figure 6.24: 3D view of the channel section attached to the tubular member

The UC values show improvement, because all the members have gone below 1.0. However for part 3 of Leg A the improvement is minimal. The value is over 0.9 and close to failure.

For the next part, the channel sections were added only in Y-direction.

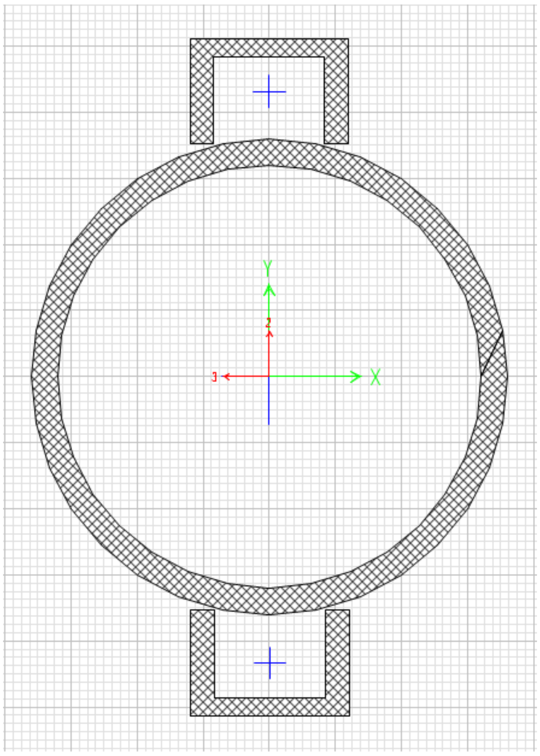


Figure 6.25: Channel sections in Y-direction

The analysis was performed and the results are shown below:

Table 6.9: Channel sections only in Y-direction

Leg A	**UC value – Damaged structure mode 1**	**UC value - Channel section in Y-direction**
Part 1	1.036	0.782
Part 2	1.091	0.870
Part 3	1.120	0.896
Part 4 (OTM)	0.881	0.896
Part 5 (OTM)	0.780	0.785

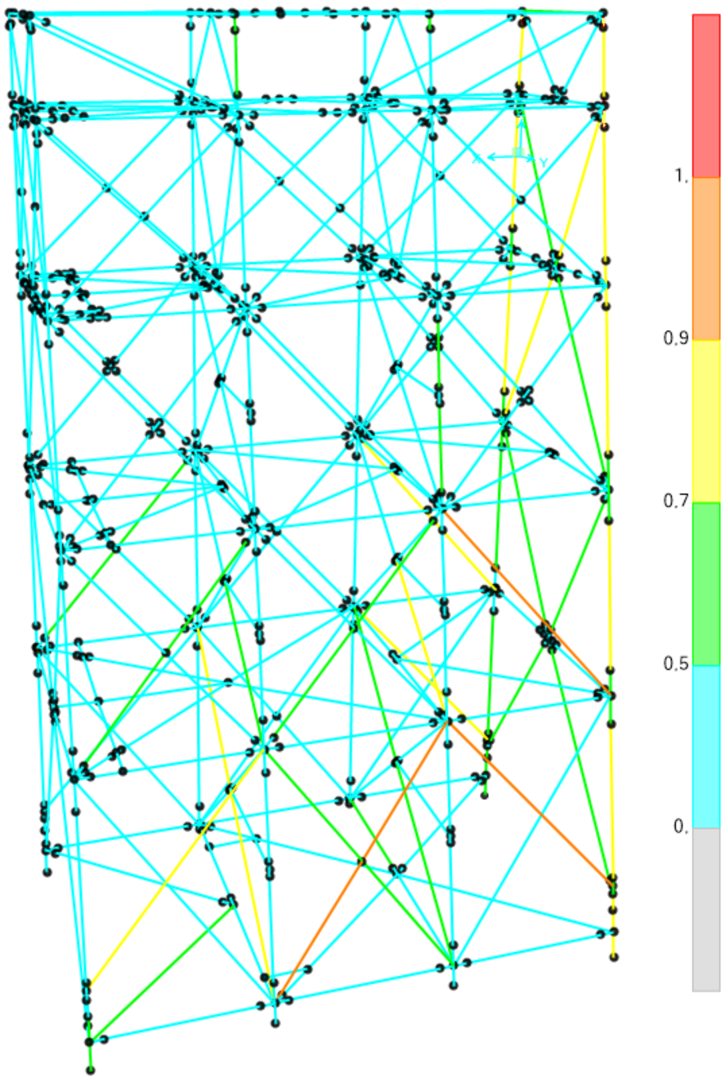


Figure 6.26: The UC values for the jacket with added channel sections in Y-direction

Comparing the results for the channel sections in X-direction and Y-direction show that the Y-direction supplementations give the overall best improvement. All of UC values are again below 1.0. For part 3, the UC value went under 0.9 which is respectable compared to the results for the same part for channel sections in X-direction.

For the last part, channel sections were added in both directions. Similar to the T-sections from mitigation option 1.

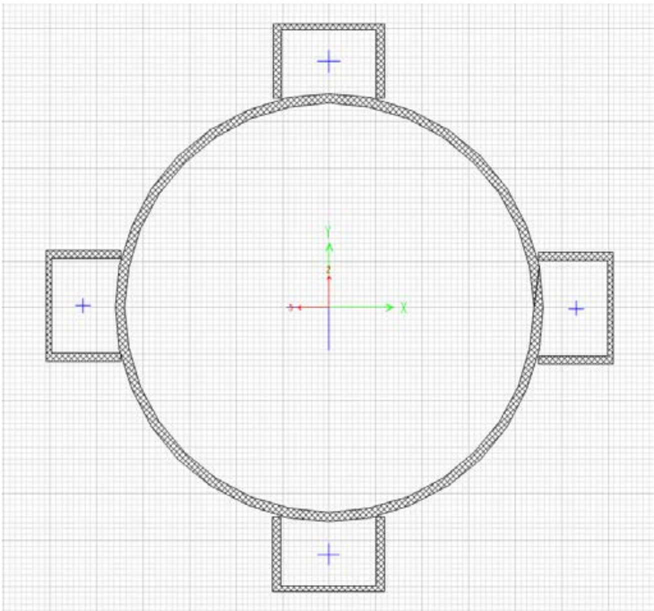


Figure 6.27: Channel sections in X- and Y-direction

Figure 6.28: 3D view of the channel section in both directions attached to the tubular member

Table 6.10: Channel sections in X- and Y-direction

Leg A	**UC value – Damaged structure mode 1**	**UC value – Channel sections in X- and Y-direction**
Part 1	1.036	0.659
Part 2	1.091	0.681
Part 3	1.120	0.736
Part 4 (OTM)	0.881	0.908
Part 5 (OTM)	0.780	0.788

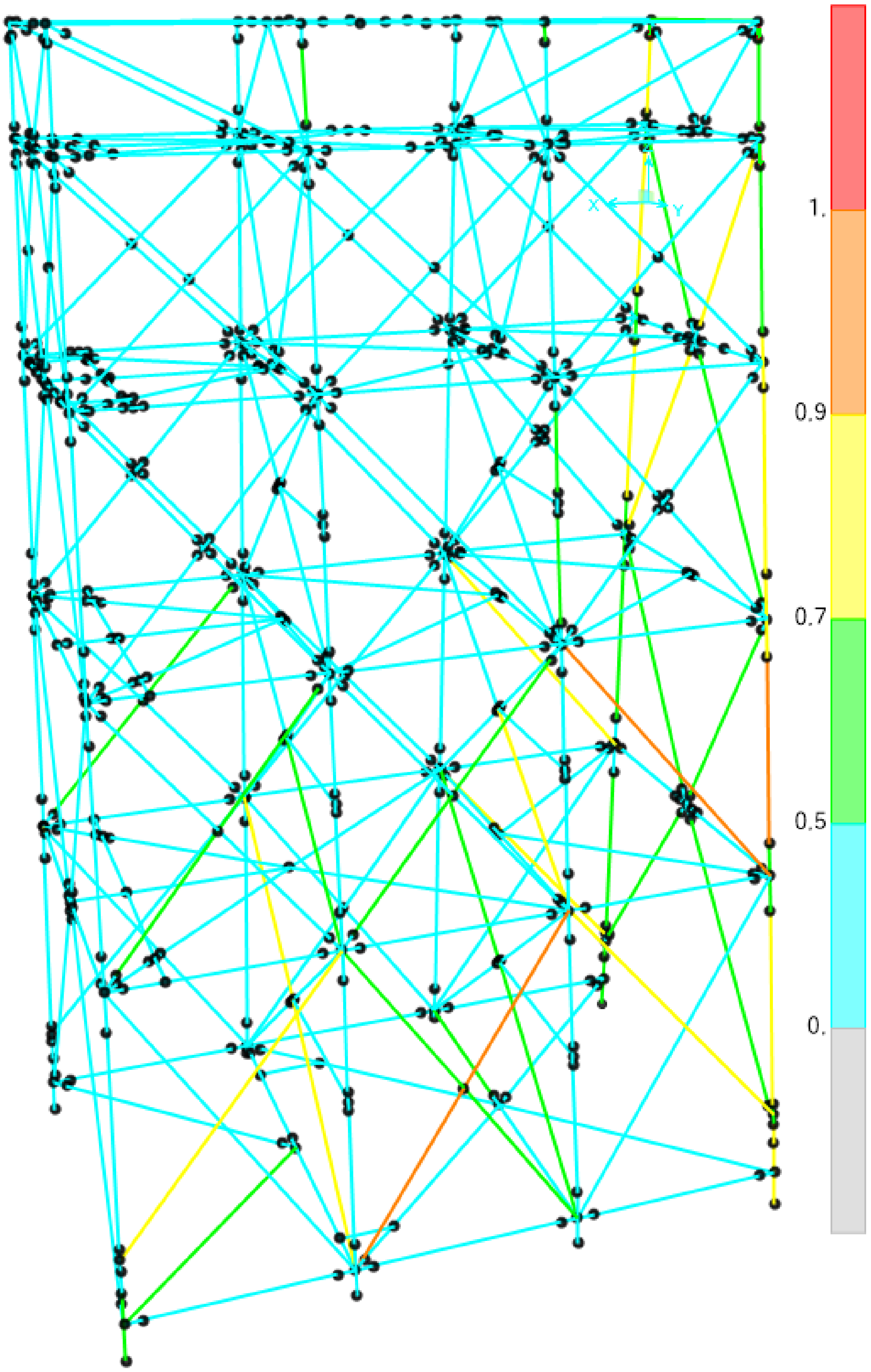


Figure 6.29: The UC values for the jacket after adding channel sections in both directions

The result for the added channel sections in both direction show clear improvement in the 3 parts of Leg A that were mitigated. The values are much lower than the channel sections only in X-direction or Y-direction. Comparing the channel sections in X-direction, Y-direction and in both direction, is done in Figure 6.30.

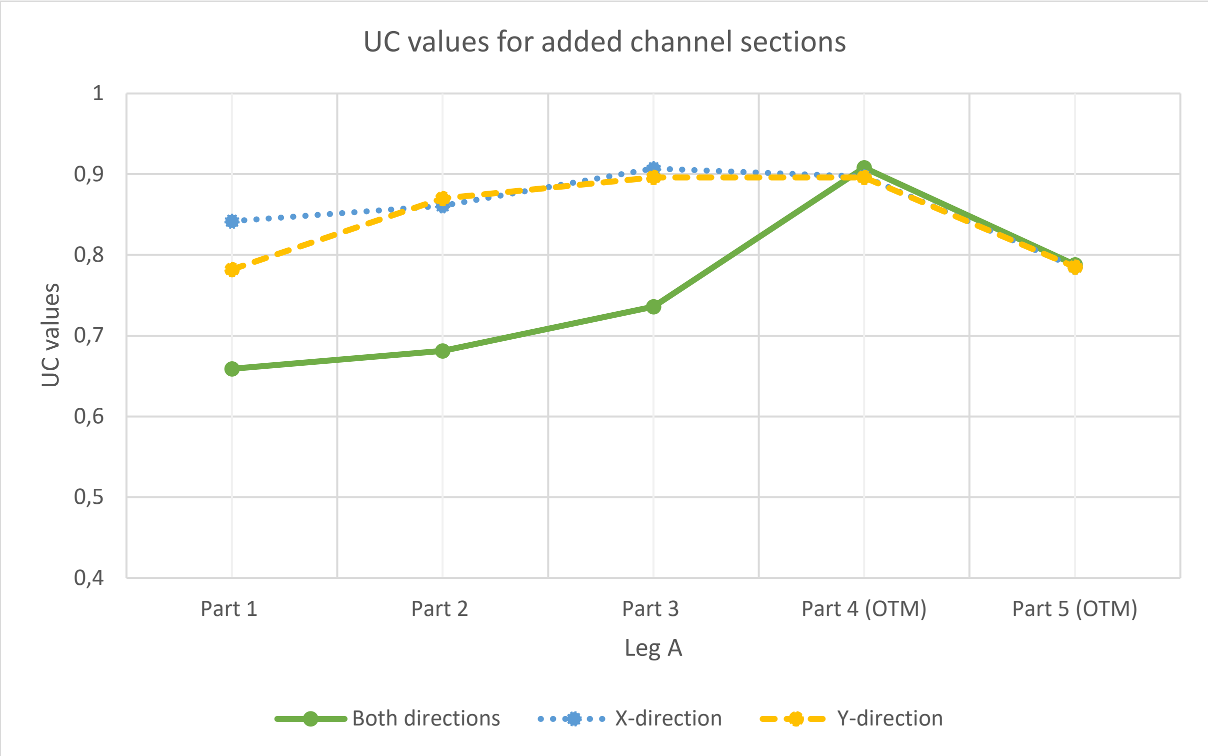


Figure 6.30: The UC value for the channel sections that were tested

One thing to remark is that with channel sections in Y-direction, no parts of Leg A has UC values lower than 0.9. With channel sections in both directions, the UC values for part 1, 2 and 3 are considerably lower than for channel sections only in X- or Y-direction. However, the increased weight resulting from channel sections in both directions have increased the loading on part 4 and 5 of Leg A which are original, unmitigated tubular members.

6.5.3 Mitigation Option 3 – Grouting of Members

Grouting as explained is a common and effective method to increase the capacity of members and secure the structural integrity of a construction. Two types of grouting were used to compare the results between them. The grouting info was taken from Densit, which develops grouts for onshore and offshore applications. Ducorit grouts are pump-able material especially developed for grouted structural connections.

The products are characterised by [101]:

- High strength and outstanding fatigue properties
- Minimal shrinkage
- High early-age strength
- Low hydration heat
- High bond between the steel and Ducorit grouts

In addition, due to viscosity and high inner cohesion of the mixed material, there is no risk of washing out cement particles, separation or mixture with water when cast below sea level [101]. All of these characteristics made Ducorit grout a great choice for the grouting option. The Ducorit grout is mixed with water and pumped through flexible hoses into the tubular steel members. This allows the grout to be applied above and below sea level.

Table 6.11: Material data of S1 and S2 grout provided by Densit [101]

Properties	**Ducorit S1 Grout**	**Ducorit S2 Grout**
Compressive strength, MPa	110	120
Static modules of elasticity, E, GPa	35	47
Dynamic modules of elasticity, $E_{d,}$ GPa	37	48
Tensile strength, MPa	5	6
Flexural strength, MPa	13.5	11
Density, kg/m^3	2250	2350
Poisson's ratio	0.19	0.18
Compressive strength class	C80/95	C90/105

The grouting was performed on part 1, 2 and 3 of Leg A. Special care was added to make sure the grouting "fills up" the member completely, without any space between the tubular members and the grout. Avoiding void formation is important, grouting without voids is able to handle loadings more efficiently. Figure 6.31 shows the steel hollow tubular member filled with grouting. Figure 6.32 shows the tubular members of Leg A that were filled with grout.

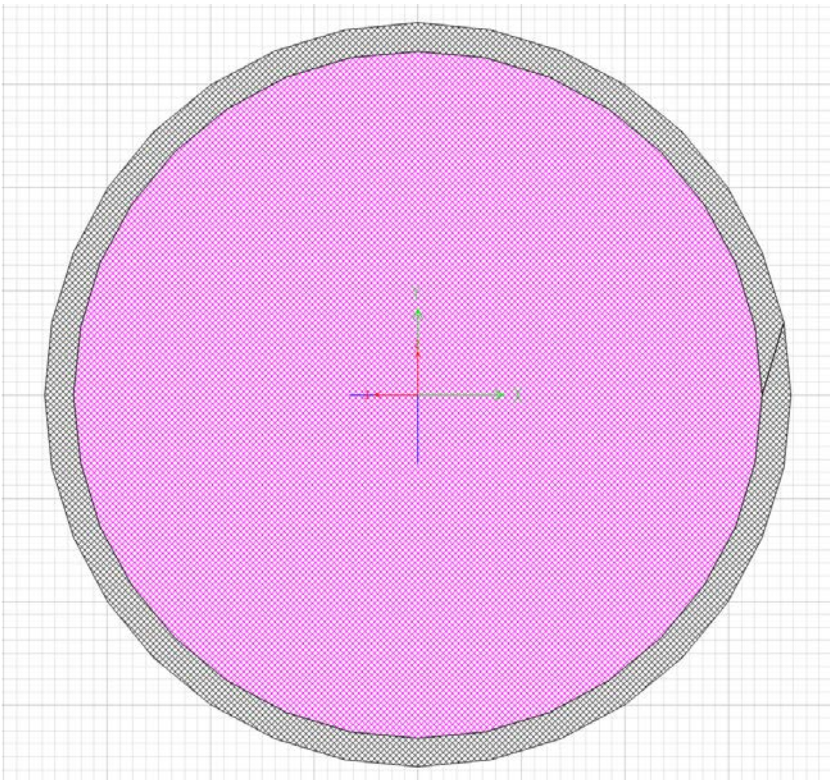


Figure 6.31: Steel tubular member filled with grout

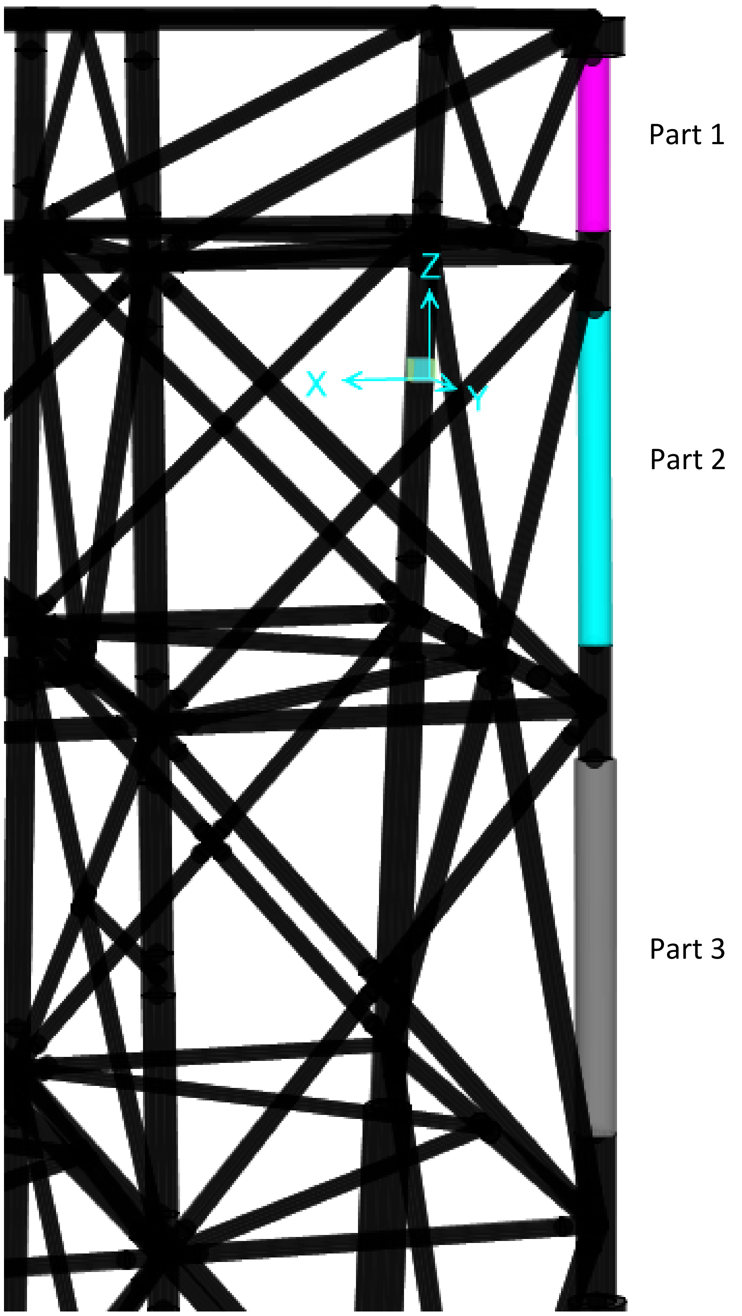


Figure 6.32: Part 1, 2 and 3 of Leg A were filled with grouting

Firstly, S1 Ducorit grout was tested which resembles C80/95 concrete.

Table 6.12: UC values for the members with S1 grout

Leg A	**UC value – Damaged structure mode 1**	**UC value – After S1 grout**
Part 1	1.036	0.744
Part 2	1.091	0.643
Part 3	1.120	0.462
Part 4 (OTM)	0.881	0.937
Part 5 (OTM)	0.780	0.801

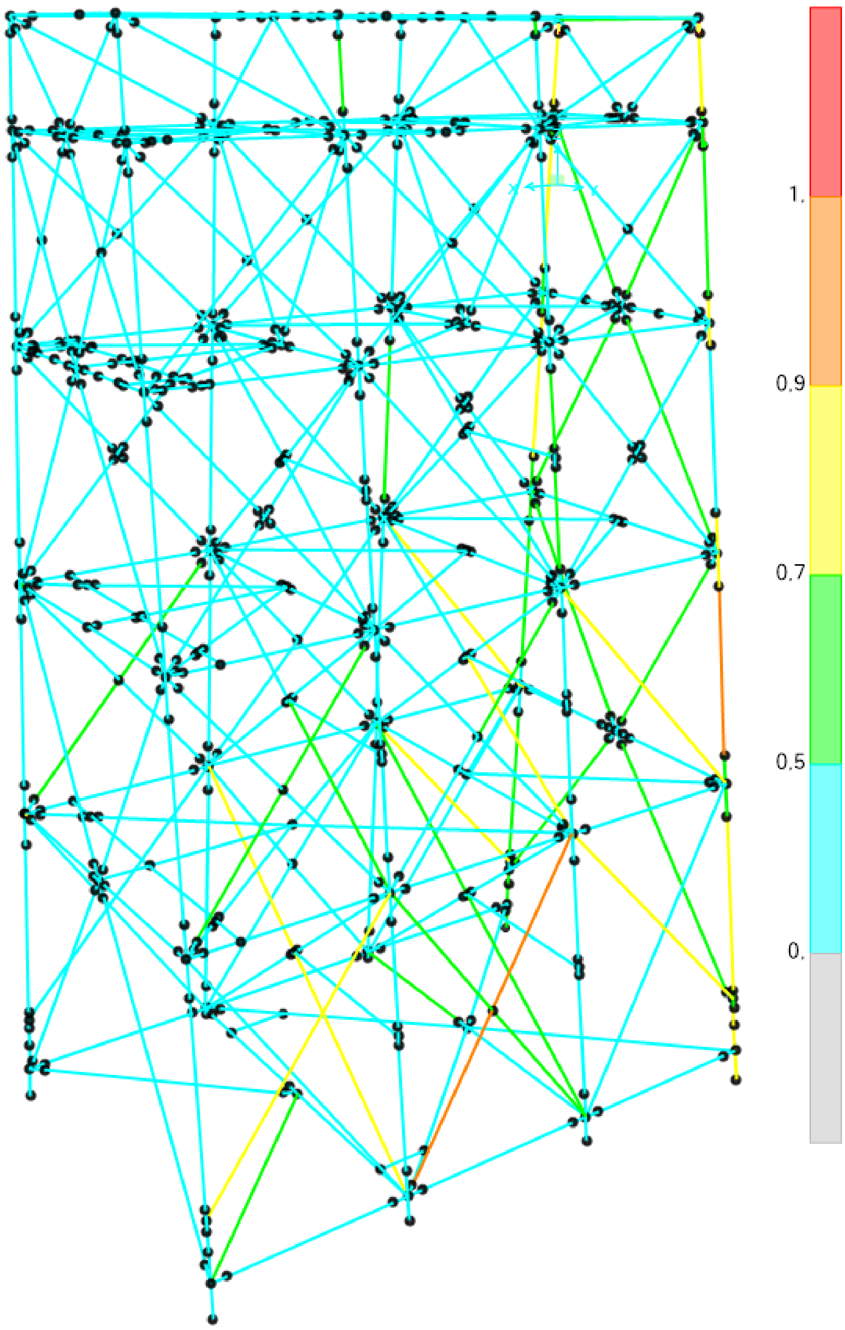


Figure 6.33: UC values of the jacket with S1 grout

Secondly, S2 Ducorit grout was tested which resembles C90/105 concrete.

Table 6.13: UC values for the members with S2 grout

Leg A	**UC value – Damaged structure mode 1**	**UC value – After S2 grout**
Part 1	1.036	0.692
Part 2	1.091	0.582
Part 3	1.120	0.401
Part 4 (OTM)	0.881	0.943
Part 5 (OTM)	0.780	0.803

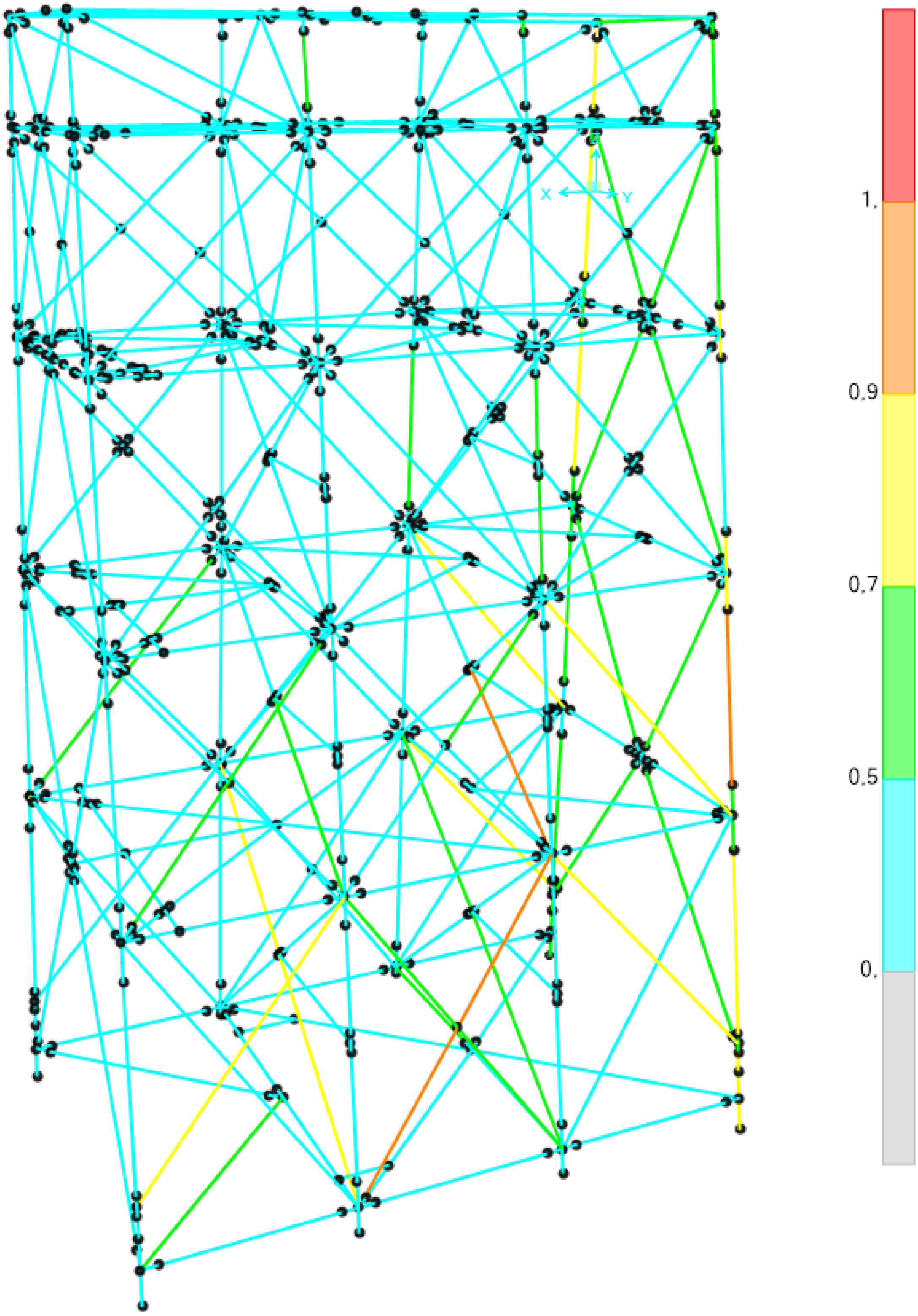


Figure 6.34: UC values of the jacket with S2 grout

The UC values for part 1, 2 and 3 of Leg A show a clear improvement due to the grouting. S2 grout is a tad better than S1 grout due to the compressive and tensile strength of the grout being slightly larger. The original tubular members (part 4 and 5 of Leg A) have higher UC values due to the increased weight because of the grouting.

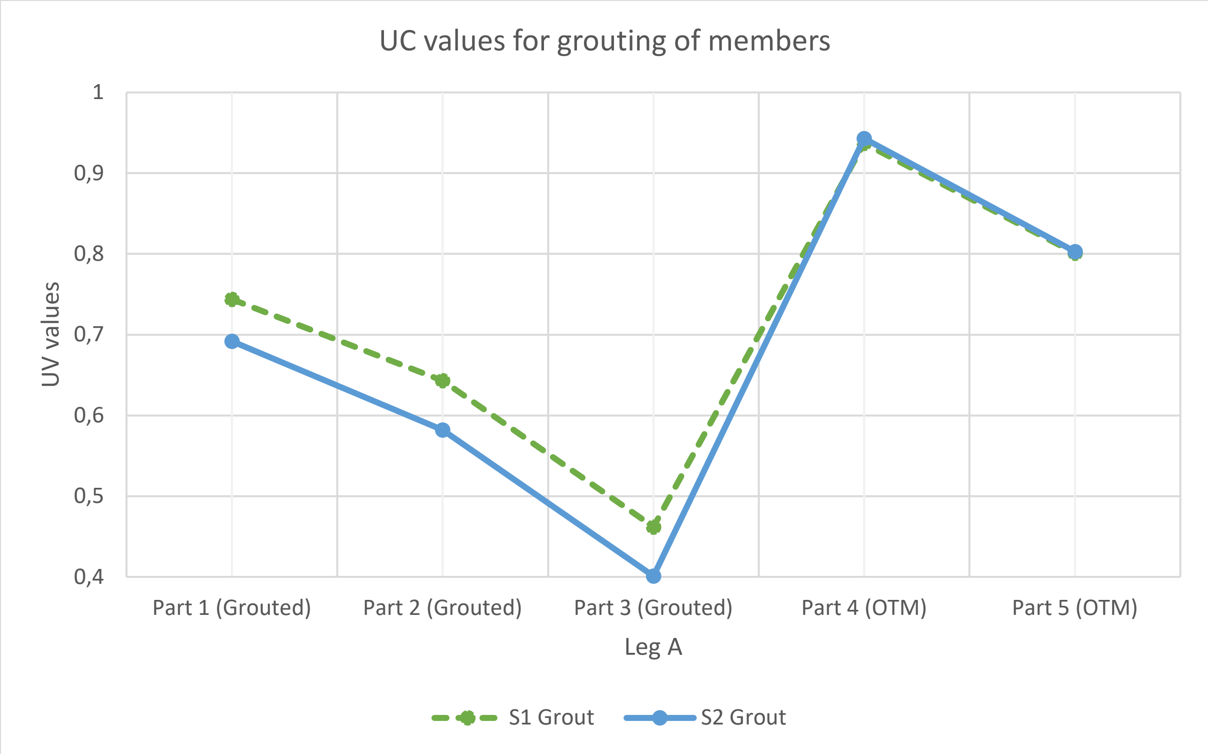


Figure 6.35: Graph of the UC values for the grouting

6.5.4 Summary of the Mitigations for Damaged Structure Mode 1 – Failure of Leg Member

The summary of the best mitigation options with UC values for each option is shown in Table 6.14.

Table 6.14: Summary of the best mitigation options for failure of leg member

		The best UC values from the mitigation options		
Leg A	Damaged structure mode 1	T-sections in X+Y-direction	Channel sections in X+Y-directions	S2 grout
Part 1	1.036	0.762	0.659	0.692
Part 2	1.091	0.780	0.681	0.582
Part 3	1.120	0.820	0.736	0.401
Part 4 (OTM)	0.881	0.898	0.908	0.943
Part 5 (OTM)	0.780	0.784	0.788	0.803

The mitigations for the leg members show that the grouting has the best effect in terms of load carrying capacities for part 1, 2 and 3. The UC values are the lowest compared to the other methods. However, for overall structural stability the T-sections are the best choice due to the fact that none of the tubular members of Leg A has UC values over 0.9.

6.6 Damaged Structure Mode 2 – Failure of Brace Member

To stimulate failure of the brace members, additional weights were added to the topside of the jacket structure, similar to how it was done to stimulate failure of leg members of the considered jacket structure.

For the bracing connected to Leg A, they were mitigated with grouting and T-sections since they gave the overall best results in terms of results for mitigation options for Leg A. In addition, Extra members were added, to see how it compares with the added T-sections and grouting.

Table 6.15: UC value for the two braces connected to Leg A

Member	**UC value – Damaged structure mode 2**	**UC value – Undamaged structure**
Brace 1	1.004	0.869
Brace 2	0.929	0.789

From the Table 6.15, the initial condition of the undamaged structure is stable. None of the UC values surpasses 0.9. After the added weight, the UC values are over 1.0 for Brace 1 and close to 1.0 for Brace 2.

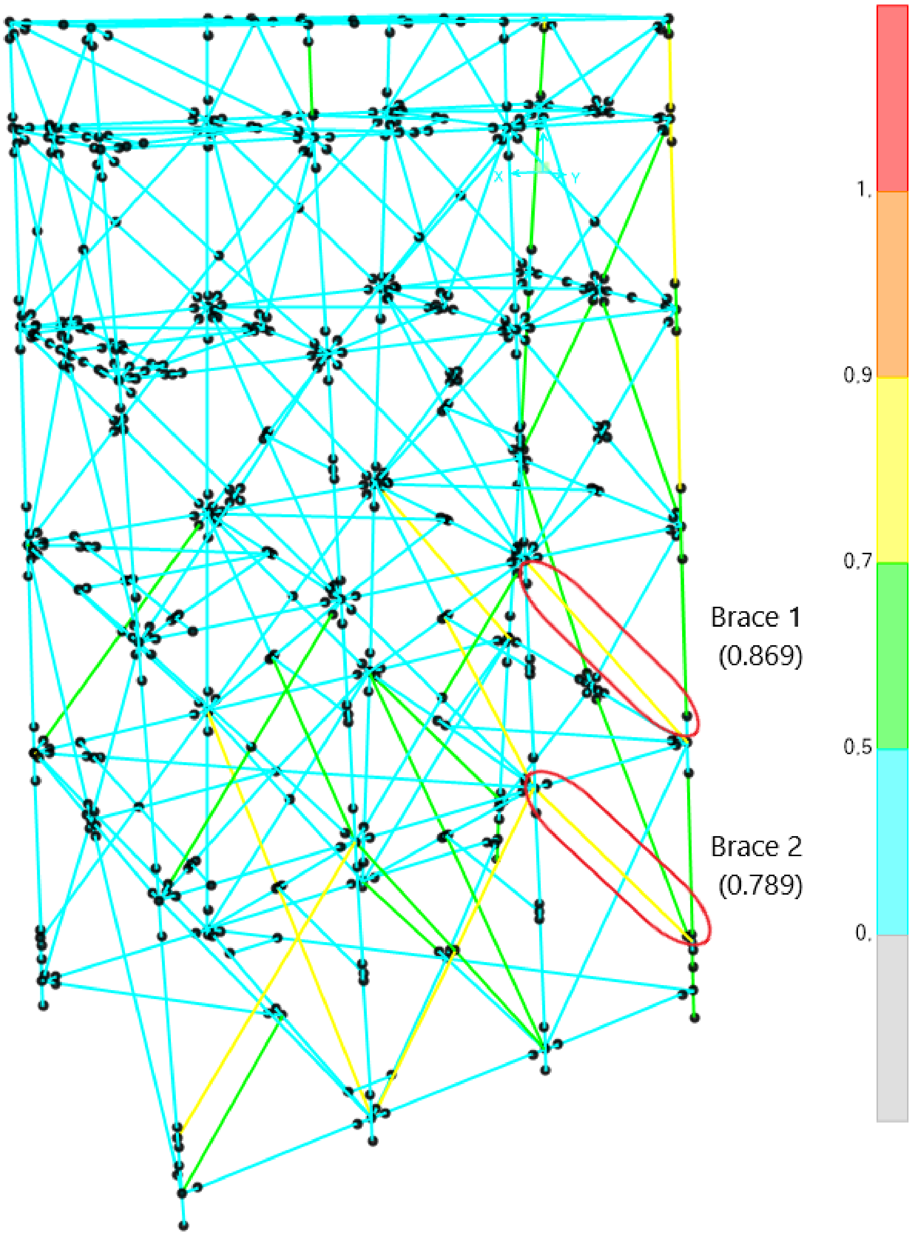


Figure 6.36: Initial UC check of undamaged structure

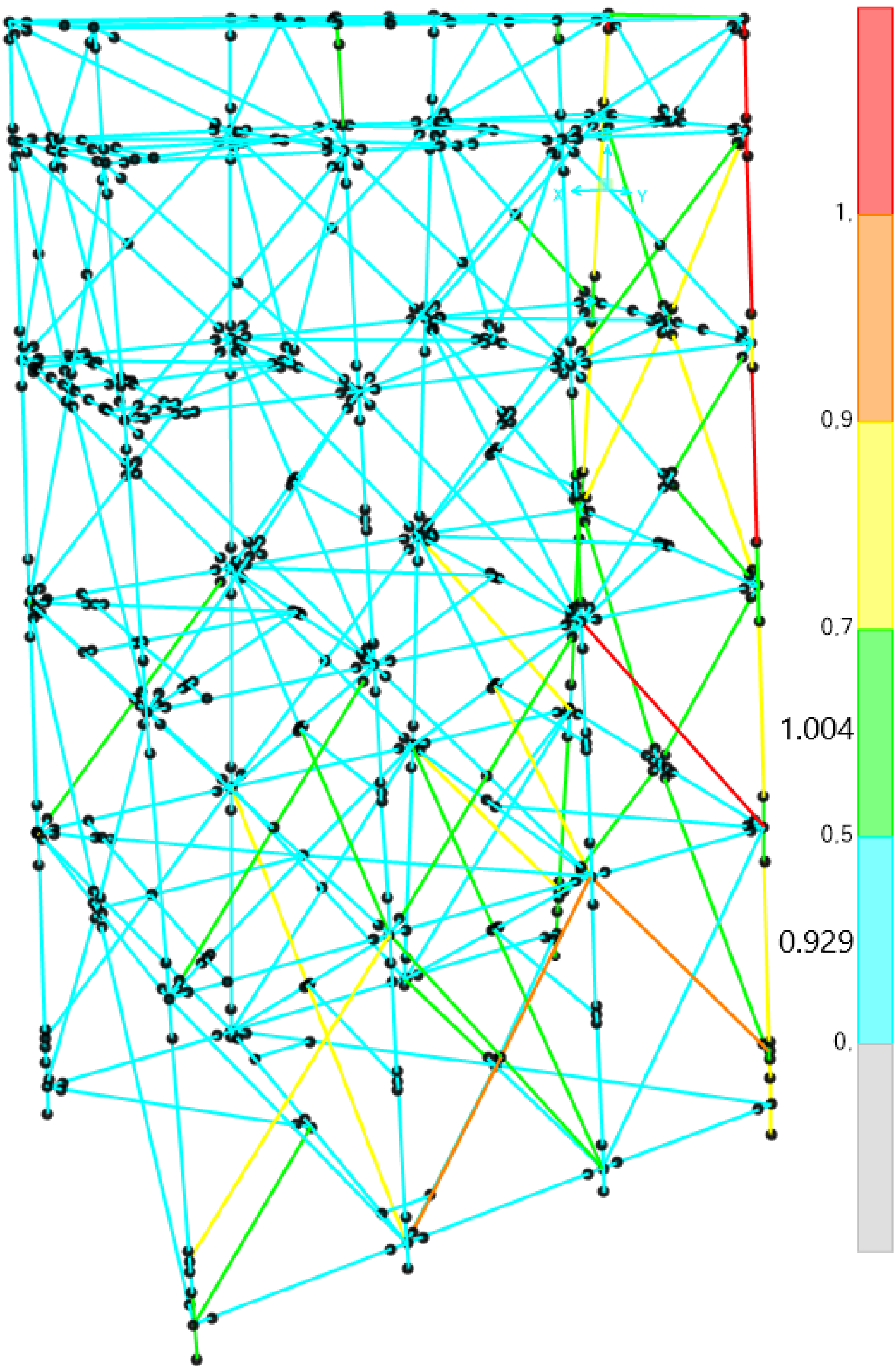


Figure 6.37: UC check of braces after the added weight

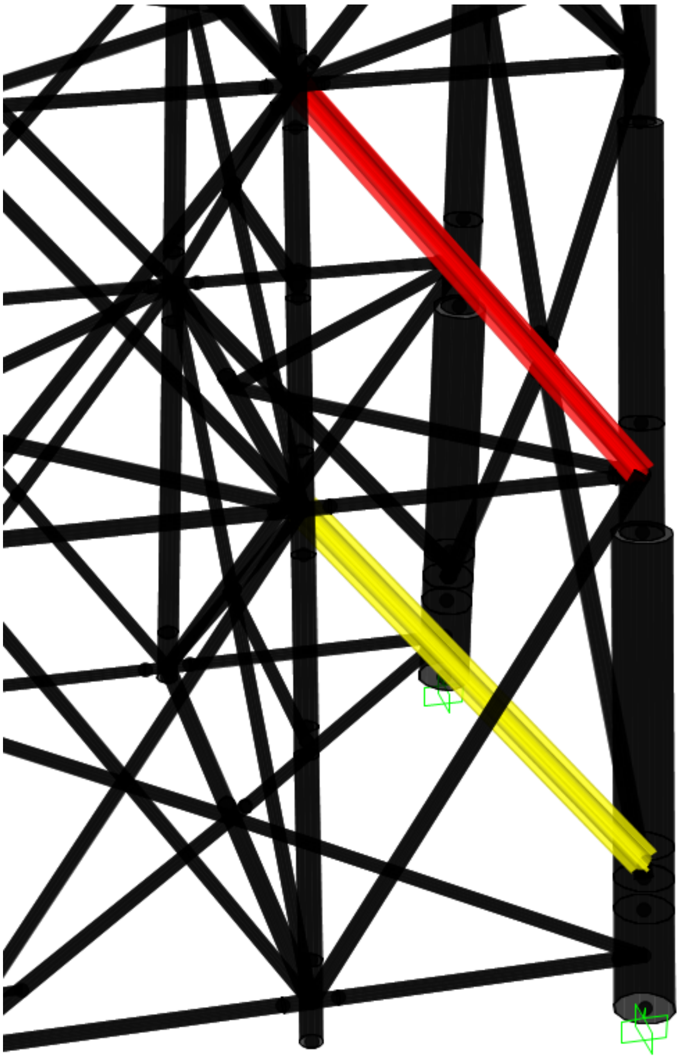


Figure 6.38: Zoom of Brace 1 (red) and Brace 2 (yellow)

6.6.1 Mitigation Option 1 – Addition of T-sections

Similar to the legs, the two braces were added T-sections. The results from the analysis are shown below:

Table 6.16: Dimensions for the two braces and added T-sections

Member	Original tubular dimensions [mm]	Added T-section dimensions [mm]
Brace 1	Outer diameter: 1210 Wall thickness: 50	Height: 500 Width: 300 Flange thickness: 45 Web thickness: 35
Brace 2	Outer diameter: 1400 Wall thickness: 50	Height: 500 Width: 300 Flange thickness: 45 Web thickness: 35

Table 6.17: UC values for Brace 1 and 2 after added T-sections

Member	UC value – Damaged structure mode 2	UC value – Added T-sections in X- and Y-direction
Brace 1	1.004	0.609
Brace 2	0.929	0.697

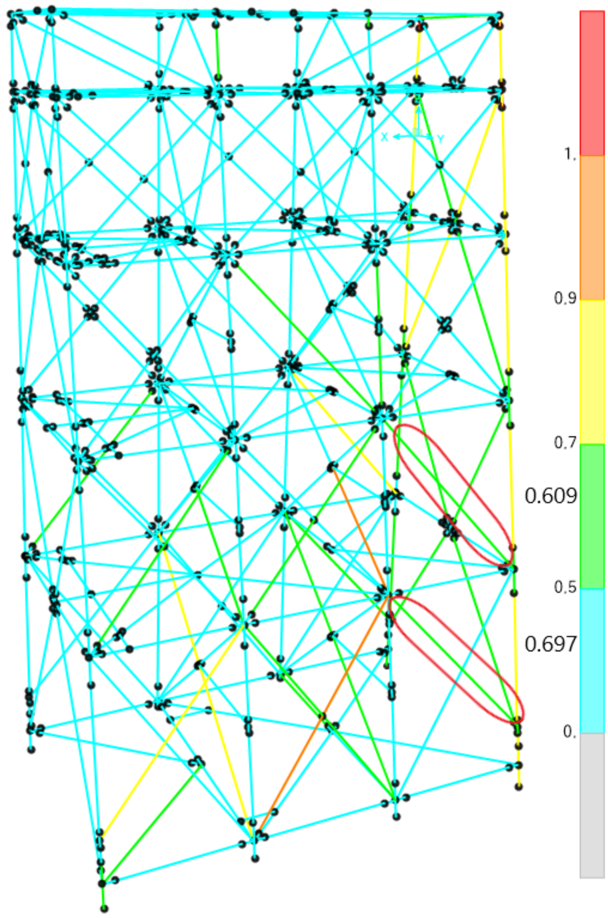


Figure 6.39: UC values for Brace 1 and Brace 2 after added T-sections

These results are exceptional. Since the UC values are well below 0.80, the T-sections were optimised to save material costs and add less weights to the member.

Table 6.18: Dimensions for the two braces and added T-sections that were optimised

Member	Original tubular dimensions [mm]	Optimised T-section dimensions [mm]
Brace 1	Outer diameter: 1210 Wall thickness: 50	Height: 300 Width: 250 Flange thickness: 25 Web thickness: 15
Brace 2	Outer diameter: 1400 Wall thickness: 50	Height: 400 Width: 300 Flange thickness: 25 Web thickness: 15

The T-sections were also added only in X-direction and Y-direction. However, the results show that they are not optimal. The T-sections should be added in both X- and Y-direction for optimal performance. The results for the optimised T-sections show they have a good balance between cutting material costs and still adding enough strength to the member to carry the loading.

Table 6.19: UC values for Brace 1 and 2 after added T-sections

	UC values			
Member	Damaged structure mode 2	Optimised T-sections in X- and Y direction	T-sections only in X-direction	T-sections only in Y-direction
Brace 1	1.004	0.815	1.051	1.059
Brace 2	0.929	0.803	0.994	1.049

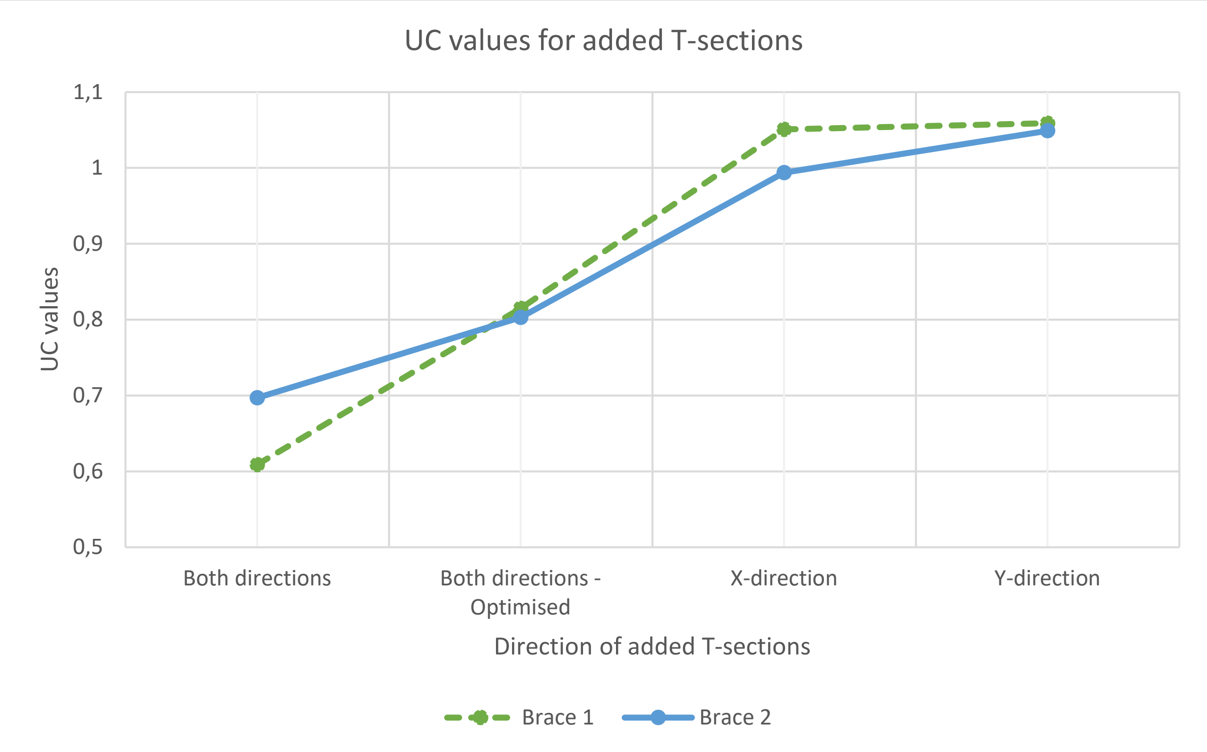


Figure 6.40: Graph of UC values for added T-sections to the bracing

6.6.2 Mitigation Option 2 – Grouting

Grouting was used to mitigate the two braces. Ducorit S1 and S2 grouting were used.

Table 6.20: UC values for Brace 1 and 2 after using S1 and S2 grout

	UC value		
Member	Damaged structure mode 2	S1 grout	S2 grout
Brace 1	1.004	0.840	0.785
Brace 2	0.929	0.805	0.758

The results show that S2 grout gives slightly better UC value results due to the higher compressive and tensile strength.

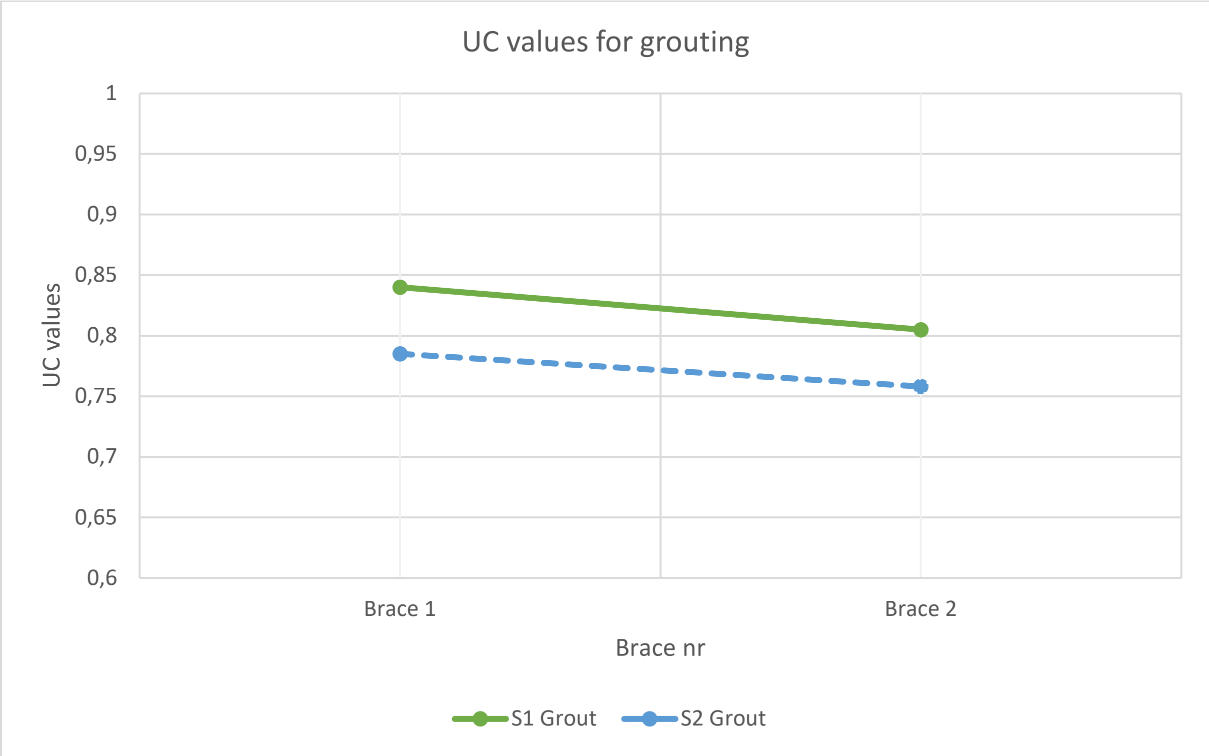


Figure 6.41: Graph of UC values for the grouting of the braces

6.6.3 Mitigation Option 3 – Adding New Members

New members were added to the two braces. The braces went from Y-bracing to X-bracing.

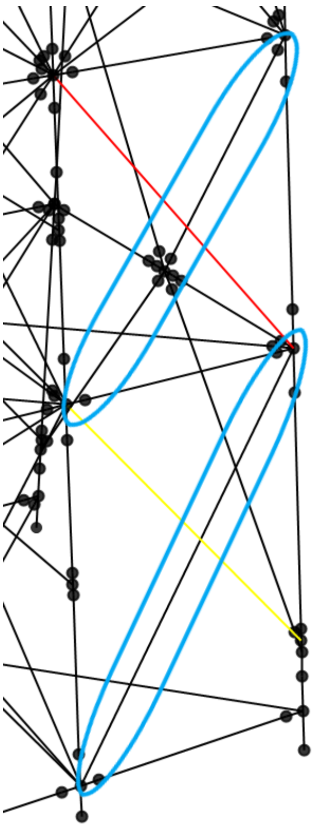


Figure 6.42: New members added are highlighted in blue

The new members were the same dimension as the original members and the same type of steel was used.

Table 6.21: UC values after adding new members

Member	**UC value – Damaged structure mode 2**	**UC value – Additional members**
Brace 1	1.004	0.860
Brace 2	0.929	0.854

6.6.4 Summary of the Mitigations for Damaged Structure Mode 2 – Failure of Brace Member

The UC values from Table 6.22 show that the new members were good mitigation options, but not as good as the added T-sections or the grouting. Adding new members is also relatively more difficult than additional sections or grouting. The new members are not effectively allocating the loading between and the rest of the original brace members, and thus are not the optimal mitigation option for the braces. The best option based on the UC values is grouting and additional T-sections.

Table 6.22: Summary of the best mitigation options for failure of the brace members

		The best UC values from the mitigation options		
Member	Damaged structure mode 2	T-sections in X+Y-direction	Grout	New member
Brace 1	1.004	0.609	0.659	0.860
Brace 2	0.929	0.697	0.681	0.854

6.7 Damaged Structure Mode 3 – Corrosion Wastage in Leg and Brace

A modified version of the initial structure was used to stimulate corrosion damage on the legs and braces near the splash-zone. For the corrosion, on-site inspection possible/not possible was considered and both options were part of the case study. A wastage model was used to reduce the thickness of part 2 of Leg A and a brace (ID 305) next to part 2 section of Leg A.

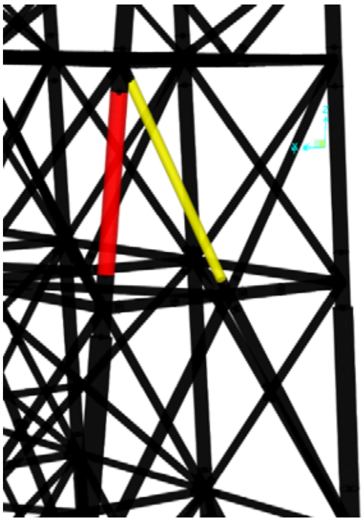


Figure 6.43: Part 2 of Leg A (red) and the brace next to it (yellow)

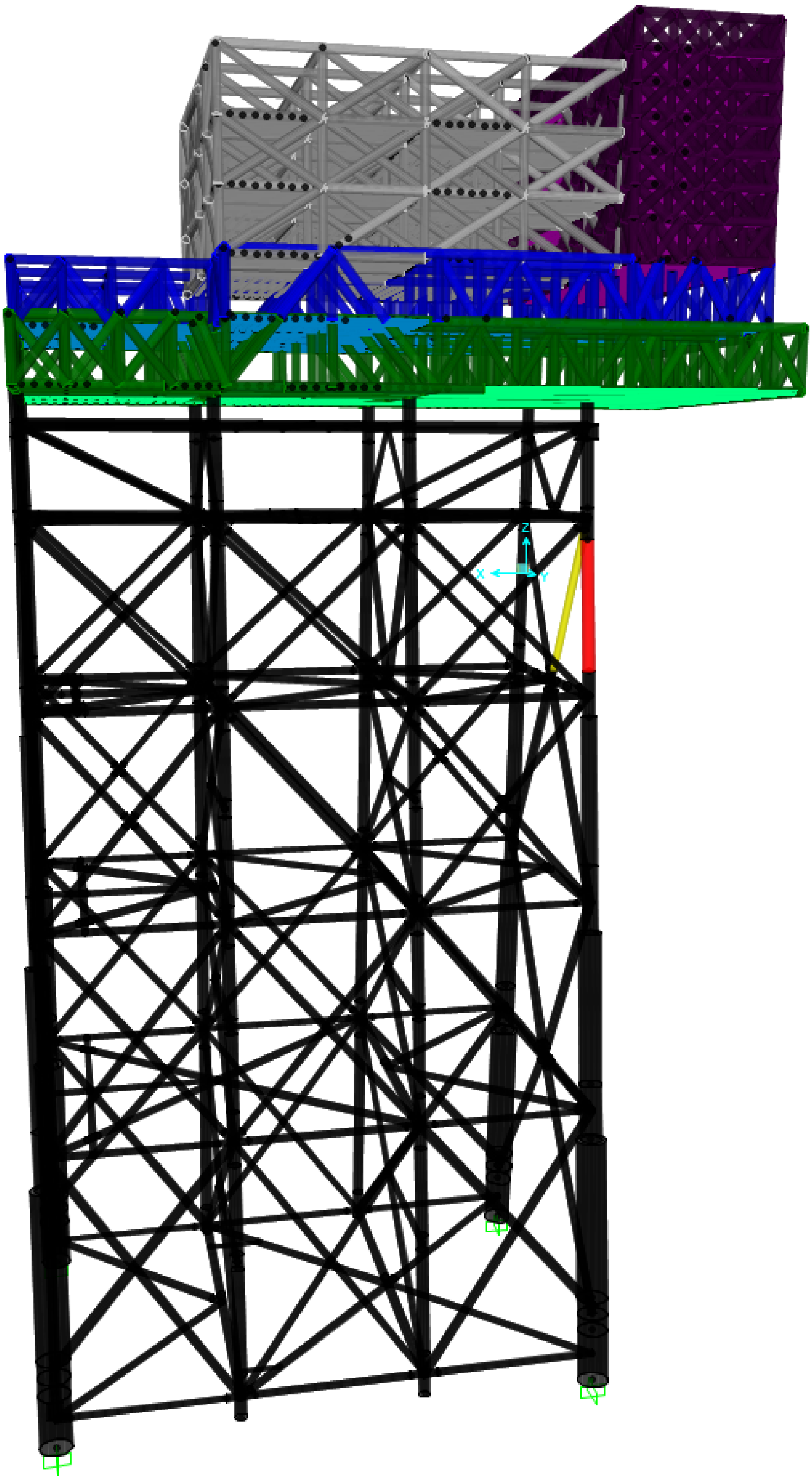


Figure 6.44: Full platform view of the area that is mitigated for corrosion

The wastage model used was provided by A. Aearn [3].

Table 6.23: Initial UC values for the brace and part 2 of leg A

Member	UC value	Size [mm]
Part 2 of Leg A	0.862	1800x70
Brace (ID 305)	0.709	1100x50

6.7.1 Considered Wastage Model

6.7.1.1 Case 1: On-site Inspection NOT possible – Uniform Corrosion

For the leg:

$$W\ (t) = A * \ (t - t_{pt})$$

A at splash-zone = 0.3

t = time = 25 years

t_{pt} = protection time = 5 years

$$W\ (5) = 0.3 * \ (25 - 5) = \ 6$$

D_{new} for (part 2 of leg A) = 1800 – 2*6 = 1788

t_{new} for (part 2 of leg A) = 70 – 6 = 64

<u>Reduced dimensions = 1788x64</u>

For the brace:

$$W\ (t) = A * \ (t - t_{pt})$$

A at splash-zone = 0.3

t = time = 25 years

t_{pt} = protection time = 5 years

$$W\ (5) = 0.3 * \ (25 - 5) = \ 6$$

D_{new} for (Brace 305) = 1100 – 2*6 = 1088

t_{new} for (Brace 305) = 50 – 6 = 44

<u>Reduced dimensions = 1088x44</u>

6.7.1.2 Case 2: On-site Inspection IS possible – Uniform or Patch Corrosion

For the leg:

$$W\ (t) = A * \left(t - t_{pt}\right)^{\beta}$$

A at splash-zone = 0.3

β at splash-zone = 0.823

t = time = 25 years

t_{pt} = protection time = 5 years

$$W\ (5) = 0.3 * (25 - 5)^{0.823} = 3{,}5308$$

D_{new} for (part 2 of leg A) = 1800 – 2*3,5308 = 1793

t_{new} for (part 2 of leg A) = 70 – 3,5308= 66.50

<u>Reduced dimensions = 1793x66.50</u>

For the brace:

$$W\ (t) = A * \left(t - t_{pt}\right)^{\beta}$$

A at splash-zone = 0.3

β at splash-zone = 0.823

t = time = 25 years

t_{pt} = protection time = 5 years

$$W\ (5) = 0.3 * (25 - 5)^{0.823} = 3{,}5308$$

D_{new} for (Brace 305) = 1100 – 2*3,5308 = 1092.94

t_{new} for (Brace 305) = 50 – 3,5308=44.47

<u>Reduced dimensions = 1092.94x44.50</u>

6.7.1.3 Case 3: On-site Inspection IS possible – No Significant or Mild Corrosion

For the leg:

$$W\ (t) = A * \left(t - t_{pt}\right)^{\beta}$$

A at splash-zone = 0.252

β at splash-zone = 0.823

t = time = 25 years

t_{pt} = protection time = 5 years

$$W\ (5) = 0.252 * (25 - 5)^{0.823} = 2{,}97$$

D_{new} for (part 2 of leg A) = 1800 – 2*2,97 = 1794.07

t_{new} for (part 2 of leg A) = 70 – 2,97= 67.03

<u>Reduced dimensions = 1794.07x67.03</u>

For the brace:

$$W\ (t) = A * \left(t - t_{pt}\right)^{\beta}$$

A at splash-zone = 0.252

β at splash-zone = 0.823

t = time = 25 years

t_{pt} = protection time = 5 years

$$W\ (5) = 0.252 * (25 - 5)^{0.823} = 2{,}97$$

D_{new} for (Brace 305) = 1100 – 2*2,97 = 1094.06

t_{new} for (Brace 305) = 50 – 2,97 = 47.03

<u>Reduced dimensions = 1094.06x47.03</u>

Table 6.24: Reduced dimensions after Case 1, 2 and 3

Member	**Original dimensions [mm]**	**Reduced dimensions – Case 1 [mm]**	**Reduced dimensions – Case 2 [mm]**	**Reduced dimensions – Case 3 [mm]**
Part 2 of Leg A	1800x70	1788x64	1793x66.50	1794.06x67.03
Brace (ID 305)	1100x50	1088x44	1092.94x44.50	1094.06x47.03

Table 6.25: UC values after Case 1, 2 and 3

	UC values			
Member	Undamaged scenario	Case 1	Case 2	Case 3
Part 2 of Leg A	0.862	0.917	0.886	0.878
Brace (ID 305)	0.709	0.912	0.893	0.857

From the values in Table 6.25, Case 1 gives the most critical UC values and as such, it is natural to mitigate it first. Every mitigation method that produces good result for this case, will also produce good results for the two other cases.

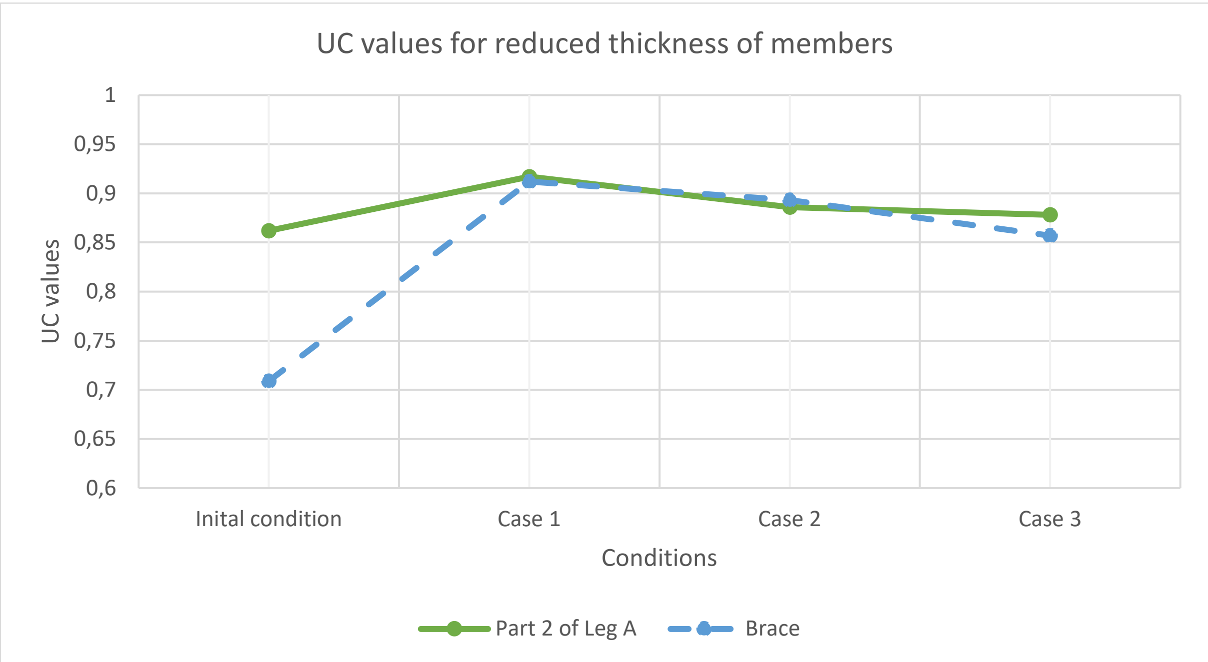


Figure 6.45: Graph of the UC values for the different conditions that were applied to reduce the member thickness

6.7.2 Mitigation Option 1: Grouting of the Members

Ducorit S1 and S2 grouting were used.

Table 6.26: UC values for S1 and S2 grout

Member	UC value – Damaged structure mode 3	S1 grout		S2 grout	
		UC value	Size [mm]	UC value	Size [mm]
Part 2 of Leg A	1.004	0.498	1788x64	0.446	1788x64
Brace (ID 305)	0.929	0.599	1088x44	0.548	1088x44

6.7.3 Mitigation Option 2 – Use of Steel Caps

Steel caps of the same material were added to the leg-member and brace-member.

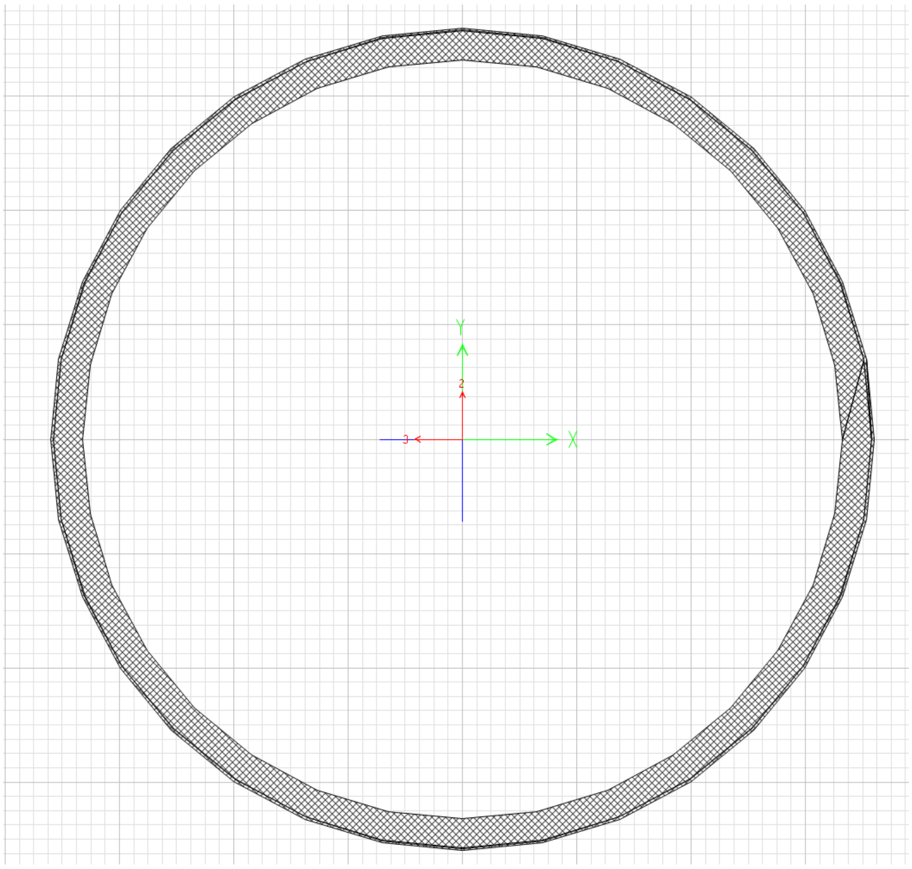


Figure 6.46: Steel caps (thin layer on the outside of the member) surrounding the tubular member

Table 6.27: UC values for the steel caps

Member	UC value – Damaged structure mode 3	UC value – Steel caps	Size [mm]	Size of rings [mm]
Part 2 of Leg A	1.004	0.799	1788x64	1810x10
Brace (ID 305)	0.929	0.750	1088x44	1110x10

6.7.4 Mitigation Option 3 – Use of Coatings

6.7.4.1 Epoxy

Epoxy coating is a common method to mitigate members in terms of corrosion damage and corrosion resistance.

Table 6.28: Material data for the epoxy

Data / **Material**	Density [gm^{-3}]	Tensile modulus, E [GPa]	Poisson's ratio	Shear modulus [GPa]	Longitudinal Tensile strength [MPa]
Epoxy	1.54	3.5	0.33	1.25	60

Table 6.29: UC value for the Epoxy coating

Member	**UC value**	**Size [mm]**	**Size of Epoxy [mm]**
Part 2 of Leg A	0.816	1788x64	1800x05
Brace (ID 305)	0.770	1088x44	1100x05

6.7.4.2 Polypropylene (PP) Coating

Table 6.30: Material data for PP [102, 103]

Data / **Material**	Density (gm^{-3})	Tensile modulus, E [GPa]	Poisson's ratio	Shear modulus [GPa]	Longitudinal Tensile strength [MPa]
PP coating	0.91	1.4	-	-	33

Table 6.31: UC values for the PP coating

Member	**UC value**	**Size [mm]**	**Size of coating [mm]**
Part 2 of Leg A	0.784	1788x64	1800x05
Brace (ID 305)	0.727	1088x44	1100x05

6.7.4.3 Polyethylene (PE) coating - Ultra High Molecular Weight Polyethylene

Table 6.32: Material data for PE [104]

Data / **Material**	Density [gm^{-3}]	Tensile modulus, E [GPa]	Poisson's ratio	Shear modulus [GPa]	Longitudinal Tensile strength [MPa]
PE coating	0.93	8.61	-	-	20-40

Table 6.33: UC values for PE coating

Member	**UC value**	**Size [mm]**	**Size of coating [mm]**
Part 2 of Leg A	0.778	1788x64	1800x05
Brace (ID 305)	0.730	1088x44	1100x05

6.7.5 Summary of the Mitigation Options for Damaged Structure Mode 3 – Corrosion Wastage in Leg and Brace

Table 6.34 shows the summary of mitigation options for corrosion damage to the brace and parts of Leg A.

Table 6.34: Summary of mitigation options for corrosion damage to the brace and parts of Leg A

		Summary of UC values from the mitigation options					
Member	Damaged structure mode 3	S2 grout	S1 grout	Epoxy coating	PP coating	PE coating	Steel caps
Brace 1	1.004	0.446	0.498	0.816	0.784	0.778	0.799
Brace 2	0.929	0.548	0.599	0.770	0.727	0.730	0.750

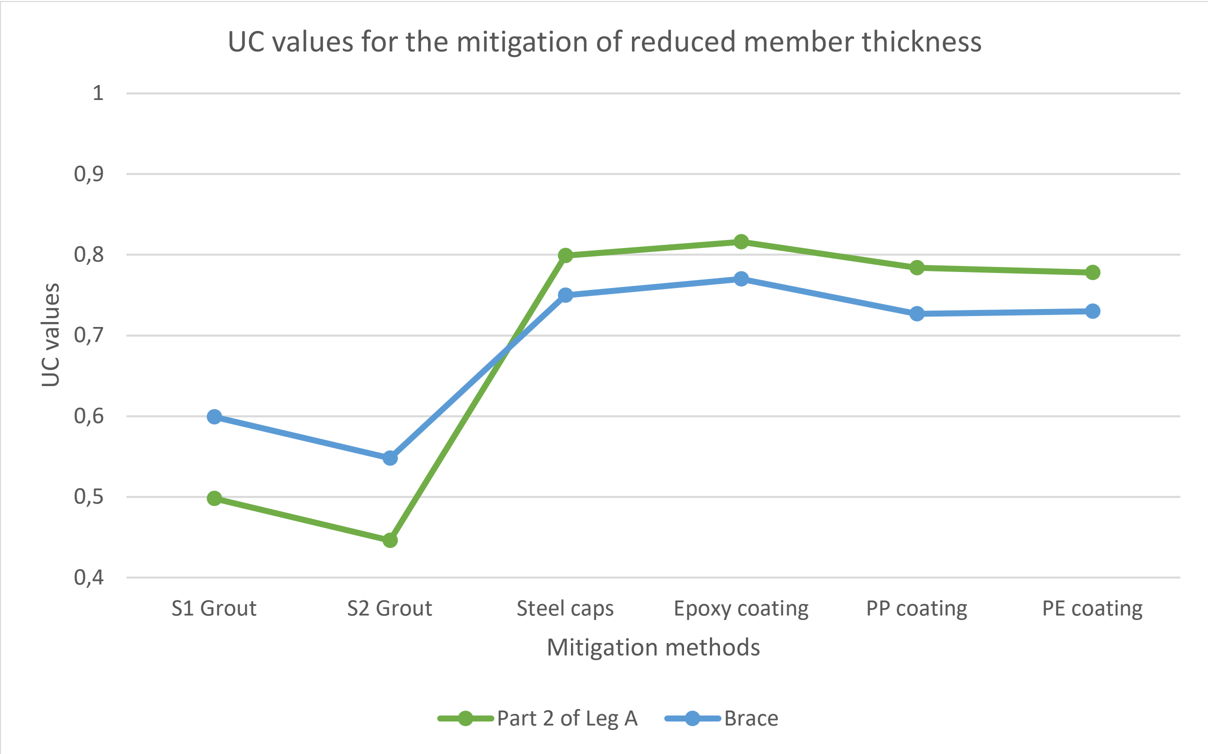


Figure 6.47: Graph of UC values for the different mitigation methods for corrosion damage

The steel caps, epoxy and PP/PE coating provide great value to the original members. The UC values are at or below 0.80. The reason for the grouting giving exceptional results is because grouting is great for adding more strength to members. Even though the diameter and the thickness were reduced, the grouting still provides adequate strength to the mitigated members. Since a corrosion wastage model was used for reducing the thickness of the members, there was no “direct” application of corrosion damage on the model because of SAP2000 limitations. Therefore, these results might give UC values slightly higher than obtained here in real-life conditions.

Cathodic protection should also be added to ensure adequate protection from the corrosive environment. Every mitigation method mentioned for the corrosion, should also be facilitated with cathodic protection after applied mitigation methods.

6.8 Failure Mode 4 – Fatigue Damage of Weld in one of the Joints

For the life extension of the welded tubular joints, a more theoretical approach was taken. S-N curves and life factor data from DNV GL, NORSOK and International Institute of Welding

(IIW) was compared with the help of mathematical and analytical tools in Matlab. The mitigation methods that were compared was hammer peening, grinding and TIG dressing. The material for the tubular joint is the same as for the tubular members, S355 steel.

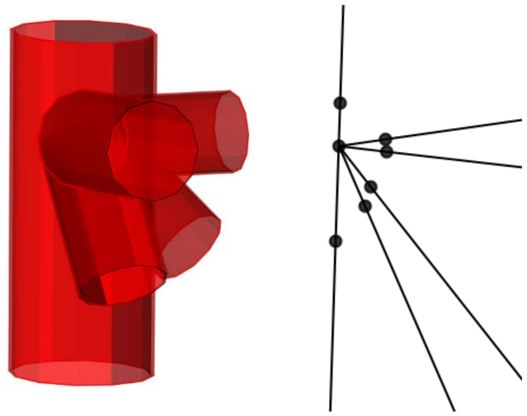


Figure 6.48: 3D model and line model of the considered joint

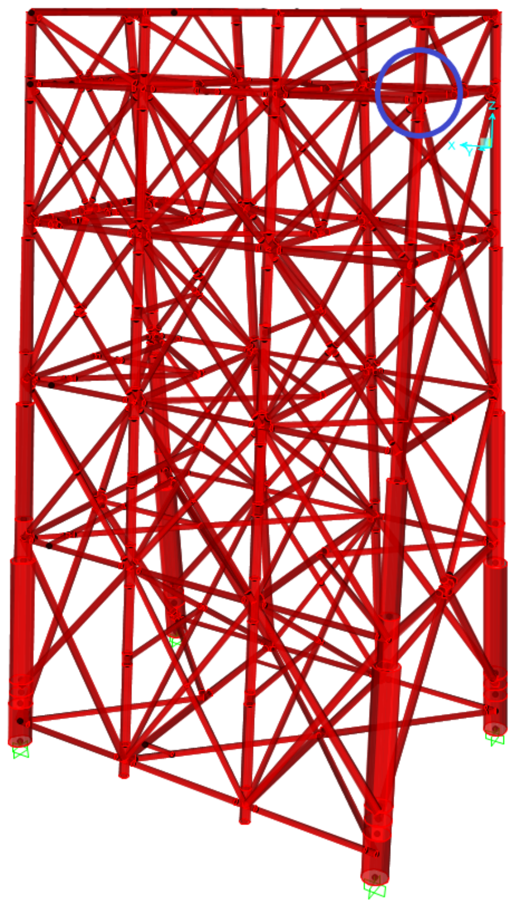


Figure 6.49: Location of the considered joint on the jacket structure

6.8.1 Baseline Fatigue Life Estimation

The baseline for the joint in the connection showed in Figure 6.48 was approximated using T curve data from DNV GL for tubular members/joints. This data was calculated by using formula in the Matlab program which can be found in Appendix A. The fatigue life was estimated by the application of Miner’s Rule in Matlab.

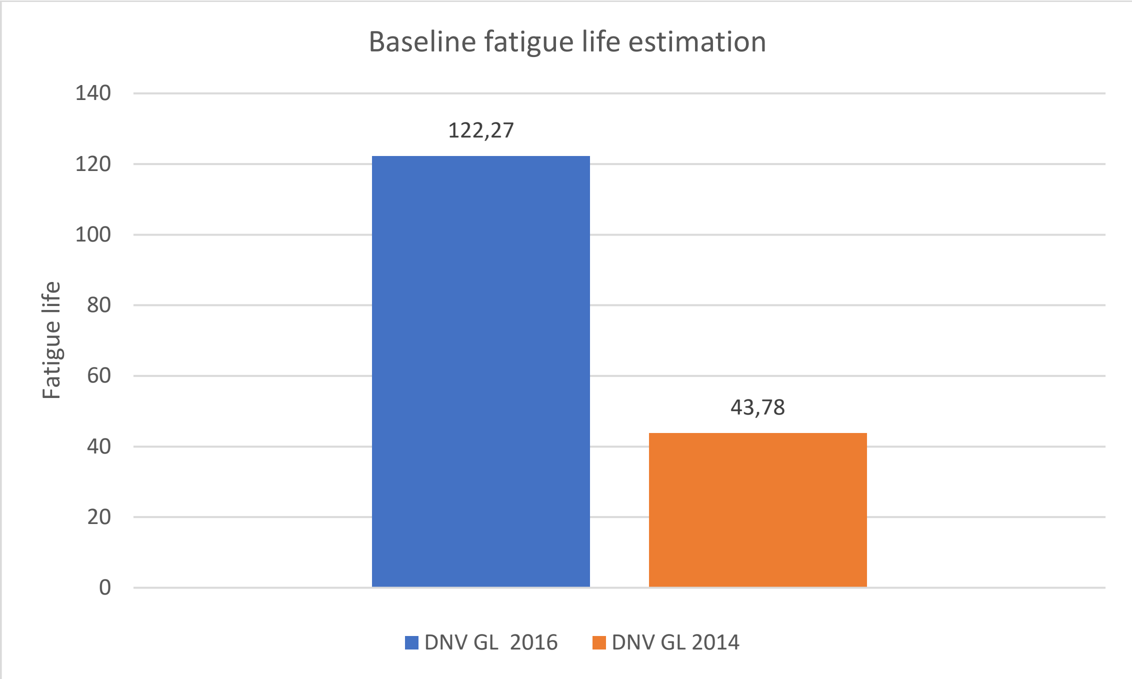


Figure 6.50: Bar graph of estimated baseline fatigue life according to DNV GL 2016 and 2014 data

From Figure 6.50, the baseline fatigue life estimation has quite a difference. The reason is because of the different parameters provided by DNV GL in their 2016 and 2014 documents (There are two versions of DNV GL-RP-C203. One older from 2014, and the newest from 2016). The stress diagram from Matlab is shown in Figure 6.51.

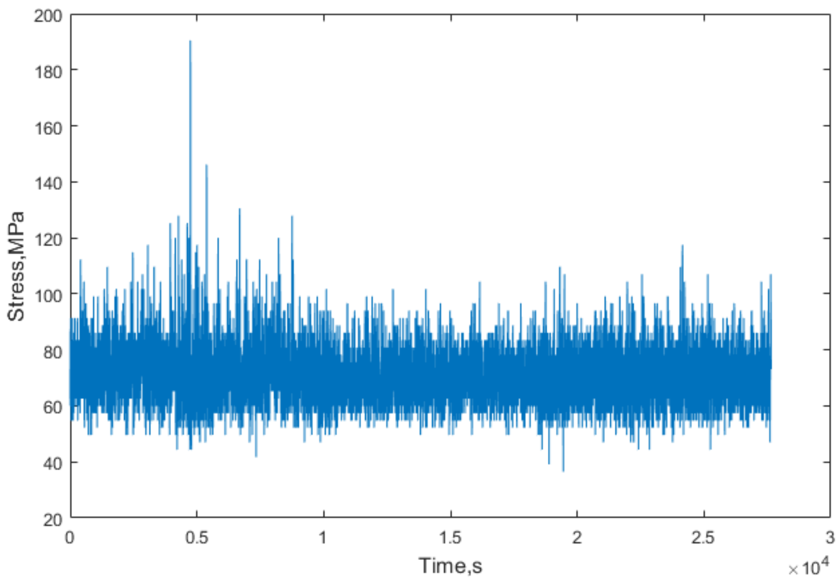


Figure 6.51: Stress and time diagram

6.8.2 Comparison of Fatigue Life using Various Post-weld Mitigation Methods

The three different post-weld treatments are compared below. There are two graphs for each treatment; one with data from the newest DNV GL document in 2016, and one with the older DNV GL data from 2014. In the graphs, there are one or more missing bars, the data for these were not found.

6.8.2.1 Hammer Peening

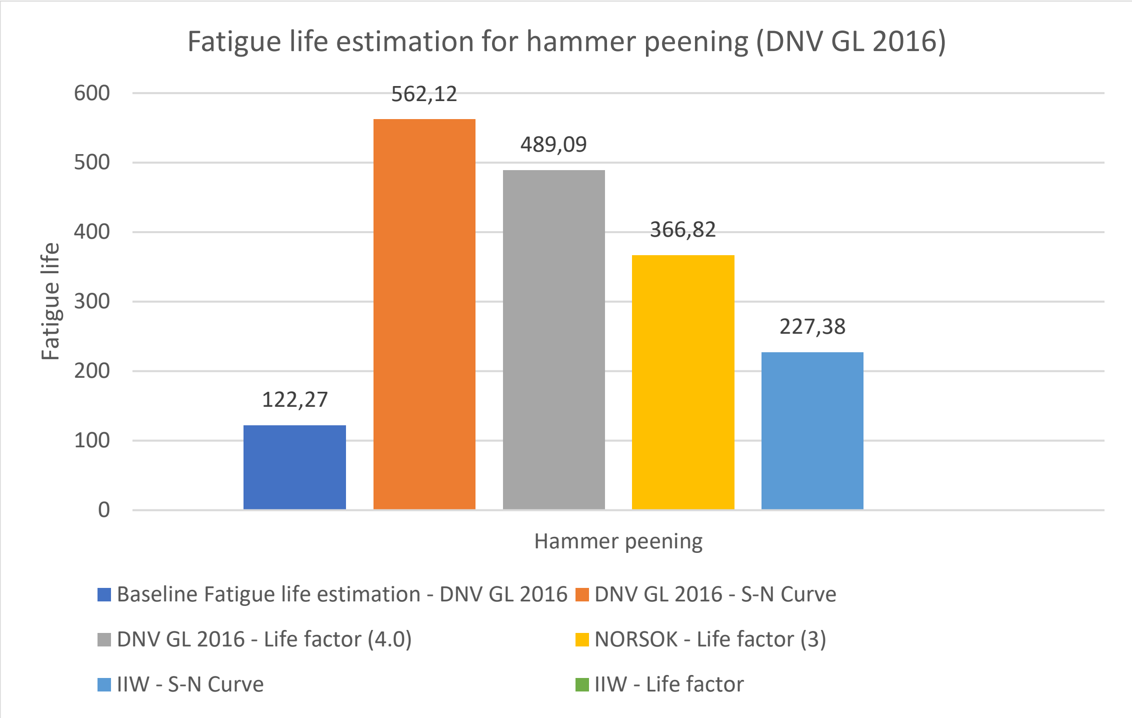


Figure 6.52: Bar graph of fatigue life estimation for hammer peening (DNV GL 2016)

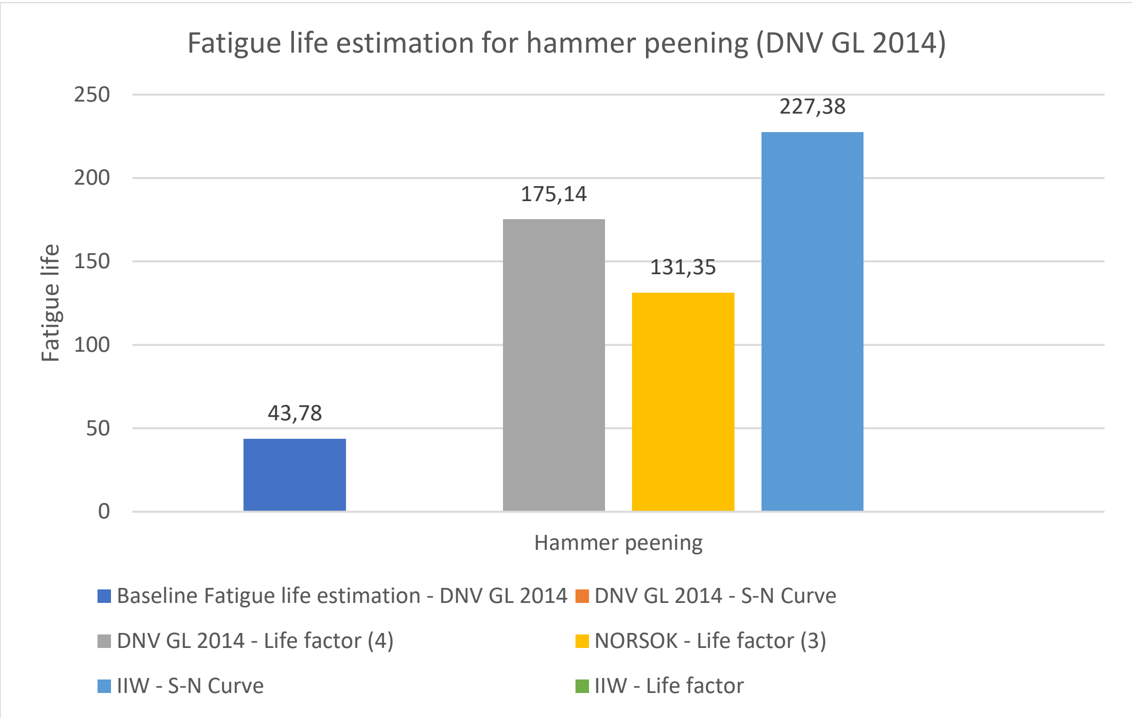


Figure 6.53: Bar graph of fatigue life estimation for hammer peening (DNV GL 2014)

Figure 6.52 and Figure 6.53 show that the baseline fatigue life have had significant improvement with the use of hammer peening. The 2016 version (Figure 6.52) shows a bigger jump in improvement due to different life factors used.

6.8.2.2 Grinding

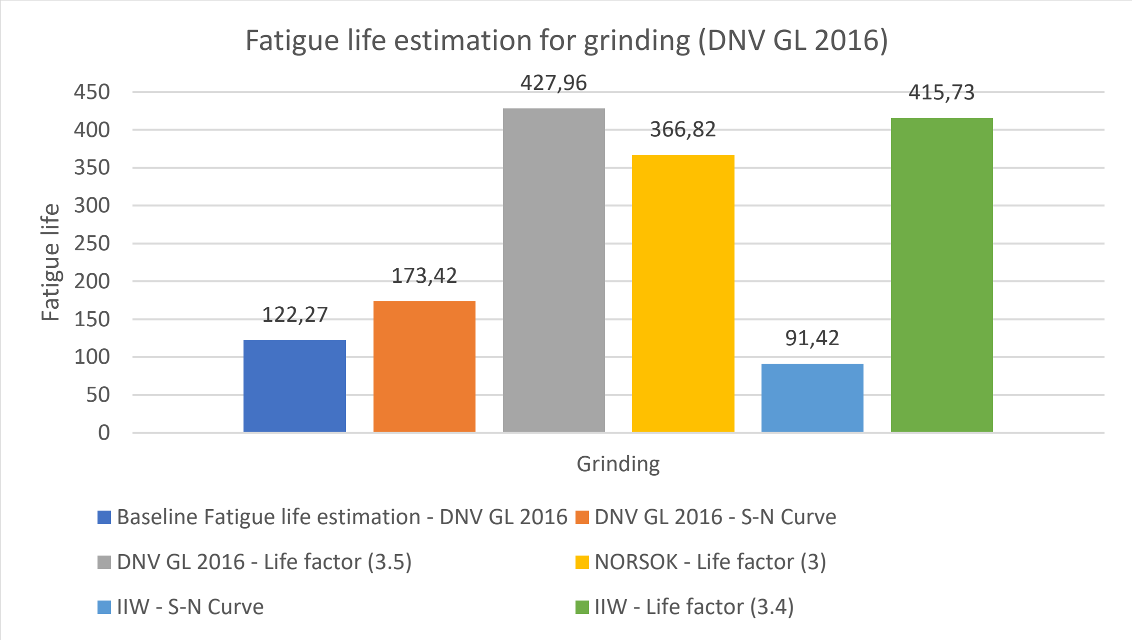


Figure 6.54: Bar graph of fatigue life estimation for grinding (DNV GL 2016)

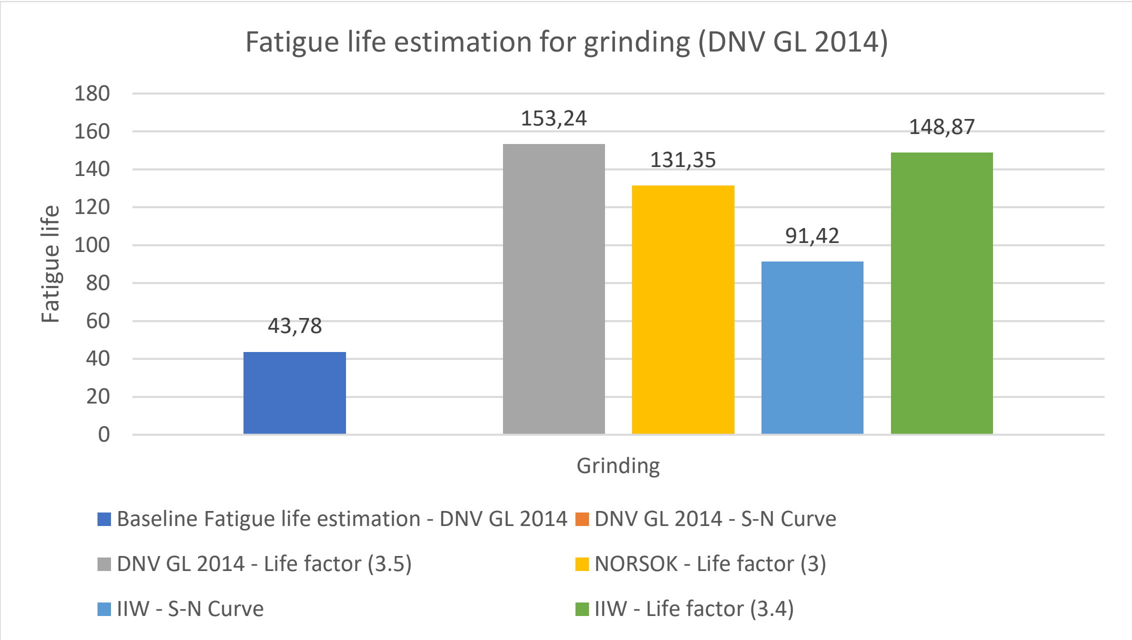


Figure 6.55: Bar graph of fatigue life estimation for grinding (DNV GL 2014)

The fatigue life improve thanks to grinding is also good, though not quite as high as hammer peening. From Figure 6.54 which shows the 2016 graph, the IIW – S-N curve is from 2014 version of DNV GL-RP-C203. Therefore, the improved fatigue life is still “lower” than the baseline which can be seen on the graph. As of today, IIW has not updated their post-weld improvement data and S-N curves. From Figure 6.55 which shows the 2014 graph, the improvement on the baseline is lower, but they all show a clear jump in increased fatigue life. Here, the IIW – S-N curve makes more sense and shows how the fatigue life has improved thanks to grinding.

6.8.2.3 TIG Dressing

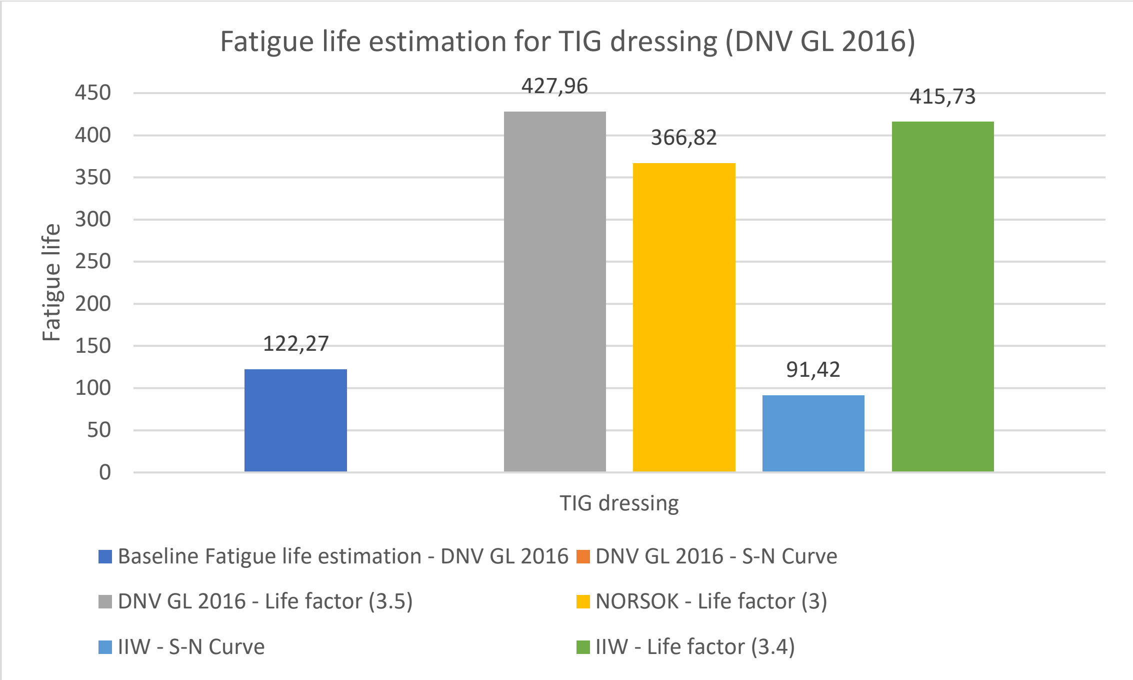


Figure 6.56: Bar graph of fatigue life estimation for TIG dressing (DNV GL 2016)

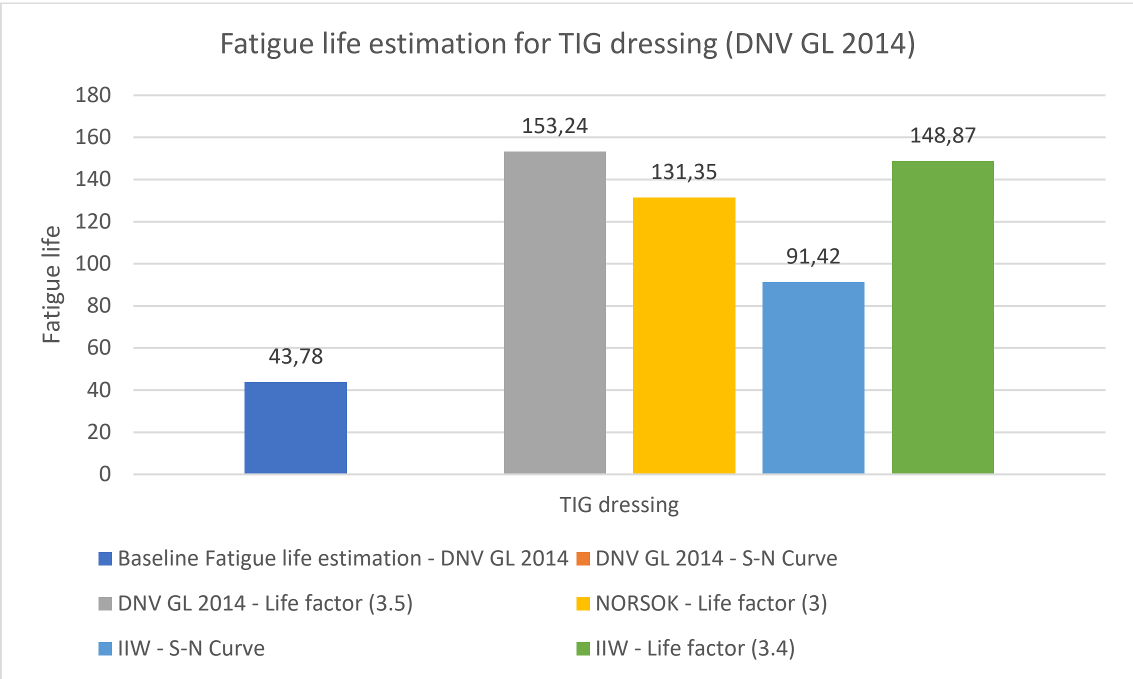


Figure 6.57: Bar graph of fatigue life estimation for TIG dressing (DNV GL 2014)

From Figure 6.56 and Figure 6.57 it is shown that the data and S-N curves from the different guidelines for TIG dressing is almost identical with the data and S-N curves provided for grinding. Similar to the graph for the grinding, in the 2016 graph (Figure 6.56), the improved fatigue life for TIG dressing according to IIW – S-N curve is still "lower" than the baseline fatigue life estimation. The improvement in the 2014 version (Figure 6.57), is the same as for the grinding.

6.8.3 Summary of Post-weld Mitigation Methods

Figure 6.58 and 6.59 show the best post-weld mitigation methods per DNV GL 2016 and DNV GL 2014.

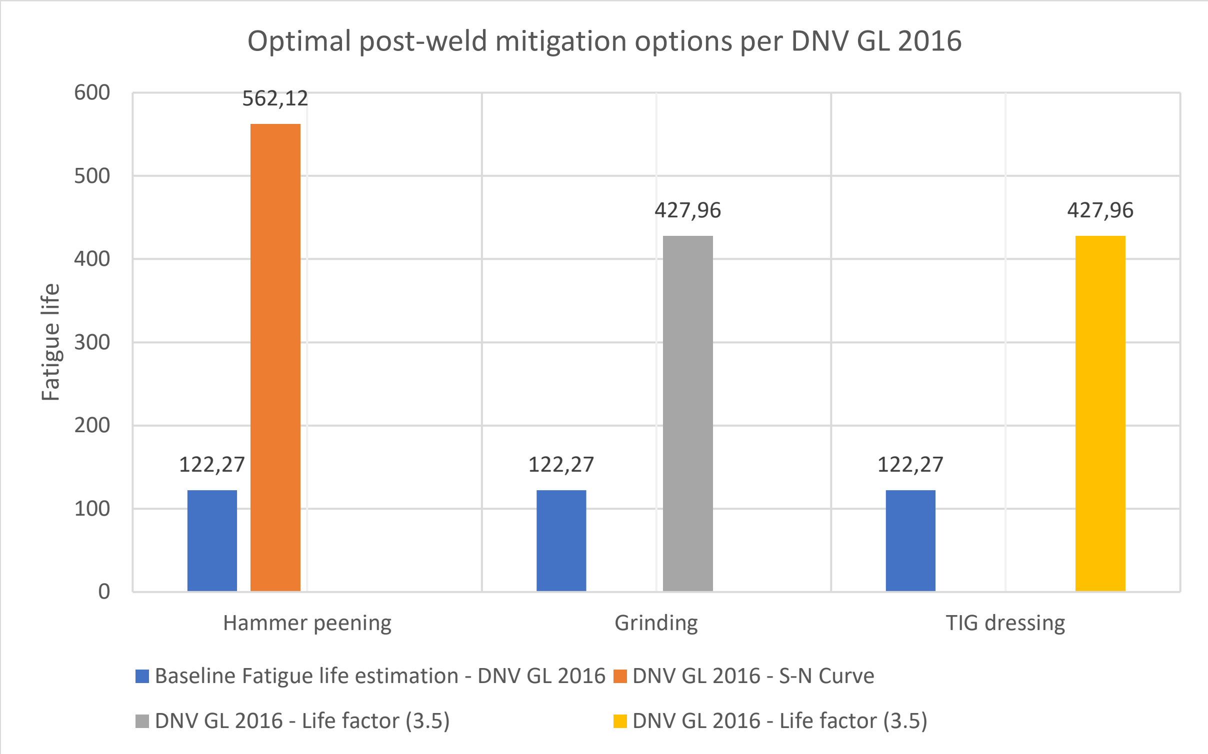


Figure 6.58: Bar graph of the best post-weld mitigation method per DNV GL 2016

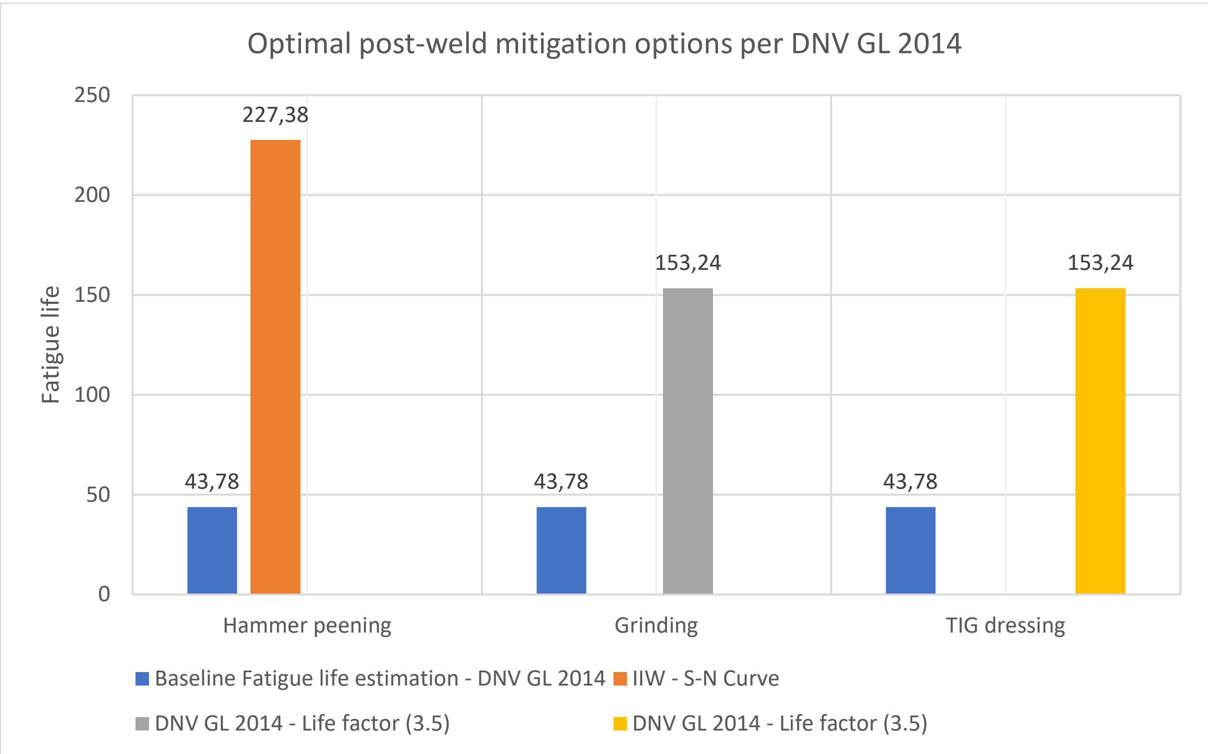


Figure 6.59: Bar graph of the best post-weld mitigation method per DNV GL 2014

The data from Figure 6.58 shows that the three mitigation options have increased the fatigue life from the baseline with quite a margin. The hammer peening option is clearly the optimal choice according to the data, as per S-N curves from DNV GL 2016. Followed by grinding/TIG dressing using life factor estimation from the same standard.

The results are similar for the three mitigation options using data from DNV GL 2014 in Figure 6.59, though the numbers are lower due to the relatively short baseline fatigue life estimation in comparison to numbers from DNV GL 2016. Again, hammer peening is the best post-weld option followed by grinding/TIG dressing. However, hammer peening is the best option in regard to S-N curves from the IIW, while the life factor from DNV GL 2014 is the best source of higher fatigue life for grinding/TIG dressing.

6.9 Summary of the Case Study

The jacket platform was strengthened with major and minor strengthening techniques. The data from the analysis of the jacket structure show how the UC values decrease thanks to the various mitigation methods. The various graphs/tables show how the different mitigation options have improved the structure from unstable to stable, fit for continued operation.

For the member failure in the leg, all the chosen mitigation methods improved the structure. The grouting of the members are the best choice in terms of pure improvement numbers due to grouting being much better at handling increased loading/weight on the legs. However, for total structural stability, the T-sections are a better choice due to the less added weight on to the members compared to the grouting. For mitigating the braces, the results were similar. Grouting and the T-sections showed good improvement values.

The wastage model provided a way to reduce the thickness of the members, to stimulate uniform corrosion damage. The steel caps and coating showed good improvement on the reduced members. The grouting presented the lowest UC values.

For the welding in the joint regarding fatigue damage, the data shows how the three mitigation options improve the fatigue life of the welded tubular joints. The results show a clear improvement on the fatigue life estimation using the three post-weld mitigation options. All the three methods improve the baseline fatigue life with quite a margin. There is a difference between life factor numbers and S-N curves from the 2016 version of DNV GL-RP-C203 and the 2014 version, which shows how standards can give large variances in design decisions. Hammer peening according to DNV GL data from 2016 improve the baseline fatigue life with 78%. While the baseline fatigue life improvement according to DNV GL data from 2014 is 81%.

The case study on the jacket structure show how the choice of mitigation options are much easier to pick and implement thanks to the proposed framework. After damage scenarios are identified, picking mitigation methods from the framework and applying them to the structure becomes much more straightforward than going through several standards and codes. The proposed framework is applicable for the majority of damages for offshore jacket structures.

7 Discussion and Conclusions

7.1 Discussion

The main objectives of this thesis were to do a general review/summary of standards and published data about mitigation methods for offshore steel jacket platforms, propose a mitigation framework to follow regarding common ageing damages, and finally do a case study to prove the applicability of it.

The standards from NORSOK, DNV GL, API and HSE provide necessary guidelines, codes, and recommendations for the design of offshore floating platforms, offshore fixed platforms, and other types of offshore facilities. The main emphasis of these standards is to provide a safe and reliable framework for the design, construction, maintenance, and assessment of said facilities. However, in terms of life extension and mitigation methods for the continued operation of offshore platforms such as steel jacket platforms, there is a clear lack of necessary framework to follow. The standards do not provide a step-by-step mitigation guideline to be referred to for the most common ageing and operation related damages for offshore jacket platforms. Simply put, there is no framework to follow for mitigating an offshore jacket structure in a precise manner. This has been a major reason for developing this framework.

Similar to the standards, the published data follow the same pattern. Numerous scientific articles were examined, some were included, and some were not due to lack of information or were deemed to unrelated to the main objectives of this thesis. The published material provides the newest and up-to-date information regarding general life extension of platforms, assessment for life extension, fatigue analysis, and many other topics which are relevant and useful for the offshore oil and gas industry. Still, the published articles are lacking in size, details, and/or experimental results to show for. Many of the articles provide numerical data or FE models, but without real experimental data to prove the application of said data/models, they are impractical. The information regarding life extension and mitigation methods is often undetailed. None of the published data provided a clear-cut mitigation framework to follow. For the articles that included some kind of case study, it was either too small in scope or limited in replicating said results in a grander scale. This was the second major reason for the proposed mitigation framework. After going through the standards and published data, the lack of mitigation framework for an offshore platform was highlighted in this thesis.

The framework that is proposed takes scattered information from the standards and published data. It combines relevant and up-to-date life extension data into a straightforward graphic to refer to regarding the most common damages for an offshore steel jacket platform. The framework proposes mitigation methods for major damages such as fatigue damage in the weld, corrosion damage, buckling/denting of members/braces and damages related to the total structural integrity of the facility. The case study exhibited good agreement with the theory, and the mitigation methods provided the necessary measures for the safe and continued operation of the facility. Design checks were performed per NORSOK N-004. It showed that the mitigation methods are effective, furthermore, it showed that the mitigation methods recommend for each damage-type were the correct choice of action. A damage in the legs can have many mitigation measures, selecting the right type of measure saves time, repairing costs, and provides optimal life extension.

7.2 Conclusions

Based on the work accomplished throughout the thesis, the following conclusions are drawn:

1. Most of the offshore jacket structures in the North Sea are operating beyond their design life and need to be reassessed/strengthened for possible life extension. Based on the literature survey done it is concluded that there is a need for more standard strengthening mitigations in the currently existing codes and guidelines.

2. Literature review of the standards from NORSOK, DNV GL, API and HSE was done. All standards do provide essential strategies and procedures for several offshore sectors in terms of design, construction and continued operation of offshore facilities. They provide necessary data for life assessment, design choices/specifications for the construction/maintenance of offshore facilities, fatigue calculation parameters etc. Mitigation methods are also mentioned in some of the standards. However, there is no guideline provided for the application of said methods. It is concluded that there is a necessity for a framework that encapsulates mitigation methods for offshore jacket structures in a more systematic way and shows how the implementation of said methods regarding what kind of damages are identified on the structure. A literature review of all recently published articles was also done, and a similar conclusion is drawn. Mitigation methods have been discussed in several research articles. However, the implementation of these methods through any case study is not shown. Few articles have included some case studies or experimental testing but in a very small scale with limited parameters. These results cannot be used for larger, complete structures such as offshore jacket platforms. It is therefore concluded that there is also not enough literature available on strengthening mitigations including any such framework. In addition, all available information regarding strengthening mitigations from the standards and published articles were evaluated, organised and presented in this thesis. It can also be concluded that the presented work can be used to get a complete overview of all strengthening mitigations/guidelines that exists in current codes/standards as well as published literature.

3. To address the mentioned lacks from above, a new framework is proposed for strengthening mitigations of offshore jacket structures. The framework associates common damages to offshore jacket structures with the most appropriate mitigation options for stated damages. The proposed framework is an attempt to streamline all available scattered information on strengthening mitigation at one place. It is concluded that the proposed framework can be used for assessing existing ageing jacket structures for determining suitable strengthening mitigations. Such a framework will not only make the strengthening mitigations a more standard practice for typical jacket structures but can also optimise the otherwise customised strengthening solutions. It is concluded that the proposed framework can make strengthening mitigation projects across various organisations more uniform and standardised.

4. The application of the proposed framework is also shown through a case study on an existing offshore jacket structure. Various failure modes such as leg failure, brace failure, material degradation (corrosion) are simulated and suitable strengthening mitigations are adopted as per the proposed framework. Mitigation methods such as reinforcement of member sections, addition of new members, grouting, steel caps etc. are applied to

considered failure cases and results are compared and discussed. Based on the results from the case study, it is concluded that the mitigation methods proposed in the framework provide an effective solution to the strengthening problems. It is also concluded that for minor strengthening works especially in cases of corrosion damages where member strength has reduced to critical level but not failed, grouting is the best suited option offshore. However, for major strengthening works as in cases of major modifications to the topsides that can cause jacket member failures, it is concluded that reinforcement of jacket legs is more effective solution compared to grouting. Various reinforcement options are tried during this thesis and it is concluded that reinforcement of jacket legs using T/Channel sections is the most effective method. For the jacket braces, it is concluded that grouting is a more suitable option due to accessibility and construction issues offshore.

5. The proposed framework is also applied to one of the welded tubular joints of the considered jacket structure. The base fatigue life estimation is made using the T curve from DNV GL 2014 and DNV GL 2016. Based on the results, it is concluded that there is a significant difference in these two curves and thereby a significant variation in the fatigue life obtained using these. The baseline fatigue life obtained using DNV GL 2016 T curve is almost three times of that obtained using DNV GL 2014 T curve. It is therefore concluded that firstly selection of correct S-N curve is of utmost importance while doing any fatigue life estimations. In order to improve above obtained baseline fatigue life, various post-weld improvement techniques are applied as per the framework and possible extended fatigue life results are compared. Comparison is also made for the estimated fatigue life using various standards, codes and guidelines. Based on the results, it is concluded that among the various life improvement techniques, hammer peening technique improves the fatigue life the most. All the standard codes/guidelines could not be compared for all the weld improvement techniques. This is because some codes do not provide any guideline for some of the improvement techniques. It is therefore concluded that the most conservative or the least conservative standard code cannot be ascertained based on the presented results due to the lack of information in the codes.

6. As a final conclusion, the proposed framework can be easily applied for many different steel jacket platforms in the NCS and possibly other offshore environments. This can be applied by practicing engineers in the offshore industry without needing to have comprehensive knowledge about life extension methods, since the proposed framework provides essential strengthening mitigations compiled from several standards/guidelines and published data in an orderly manner. Hence, the significance and applicability of the proposed framework is highlighted in this thesis.

7.3 Limitations

Some of the limitations about the thesis and the framework are presented below:

- The verification and application of the framework was completed using SAP2000, the programme has certain limitations in terms of correct modelling of corrosion damage. If the framework is applied with a different analytical tool, it might give slightly different results then those that were presented.

- ULS was the key limit state that was paid attention to during the case study. Limit states such as SLS, FLS and ALS should also be used in future case studies.
- The corrosion of the member should also be checked for patch corrosion, since it has a more severe effect in real life conditions.

7.4 Further Research

Further research and work is recommended for the following points:

- Do an even broader literature examination, to make sure every vital information about life extension and mitigation methods are collected and see if they comply with the proposed framework.
- Apply the framework for different jacket type structures with different height, weight, legs, and located in different environments to show the usefulness of the proposed framework in diverse scenarios.
- Verify the framework through several case studies by using different loading conditions than those that were used in this thesis.
- Expand the framework to include more age and operation related damages such as different types of corrosion damage, major ship impacts and pile/foundation problems.

References

[1] – A. Aeran and O. T. Gudmestad, “Guidelines for Estimating Remaining Fatigue Life of Ageing Offshore Jacket Structures,” Proceedings of the 36th International Conference on Ocean, Offshore and Artic Engineering, Trondheim, June 2017.

[2] – Herman Vestli, “Structural Health Monitoring of Offshore Jackets”, Master thesis, Stavanger, spring 2016.

[3] – A. Aearn, Sudath C. Siriwardane, Ove Mikkelsen and Ivar Langen, “A framework to assess structural integrity of ageing offshore jacket structures for life extension”, University of Stavanger, 2017.

[4] – G. Ersdal, “Assessment of Offshore Structures for Life Extension”, conference paper, University of Stavanger, June 2008.

[5] – I. Animah, M. Shafiee, N. Simms, A. Tiwari, “A multi-stage remanufacturing approach for life extension of safety critical systems”, The 5th International Conference on Through-life Engineering Services, 2016.

[6] – A. Nezamlan, R. J. Nicolson, D. Iosif, “State of the Art in Life Extension of Existing Offshore Structures”, Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering, Rio de Janeiro, Brazil, July 2012.

[7] – E. M. Soom, M. K. Abu Husain, N. I. Mohd Zaki, N. U. Azman and G. Najafian, “Reliability-based Design and Assessment for Lifetime Extension of Ageing Offshore Structures”, Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering, Busan, South-Korea, June 2016.

[8] – G. Ersdal, J. Sharp and D. Galbraith, “Ageing accidents – suggestion for a definition and examples from damaged platforms”, Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, California, USA, June 2014.

[9] – G. Solland, G. Sigurdsson, A. Ghosal and Det Norske Veritas, “Life Extension and Assessment of Existing Offshore Structures”, SPE projects and Facilities Challenges Conference, Doha, Qatar, February 2011.

[10] – Shell, 2018, [Online]. Available: http://twistedsifter.com/2016/03/base-of-bullwinkle-oil-platform-being-towed-to-sea/ [Accessed May 2018].

[11] – HSE Information Sheet, “Guidance on management of ageing and thorough reviews of ageing installations”, Offshore Information Sheet No. 4, 2009.

[12] – HSE, “Managing Ageing Plant - A Summary Guide”, 2010.

[13] – Tyra gas field, 2018, [Online]. Available: https://www.offshore-technology.com/projects/tyra-gas-field-redevelopment/ [Accessed April 2018].

[14] – H. Ahmadi and E. Zavvar, “Stress Concentration Factors in Uniplanar Tubular KT-Joints of Jacket Structures Subjected to In-Plane Bending Loads”, Thin-Walled Structures, 91. 10.1016.

[15] – F. H. Øyasæter, “Effect of corrosion on the buckling capacity of tubular members”, Master thesis, Stavanger, spring 2017.

[16] – Bathtub curve, 2018, [Online]. Available: https://en.wikipedia.org/wiki/Bathtub_curve [Accessed March 2018].

[17] – R. Kajolli, “A new approach for estimating fatigue life in offshore steel structures”, Master thesis, Stavanger, spring 2013.

[18] – Askale Wendimu, “Fatigue life estimation of existing steel structures under time-dependent structural degradation”, Master thesis, Stavanger, spring 2014.

[19] - Milana Giulia, Banisoleiman Kian and González Arturo, “Fatigue Life Assessment Methods: The Case of Ship Unloaders”, International Conference on Natural Hazards & Infrastructure, Chania, Greece, 28-30 June 2016.

[20] – A. Keprate and R. M. Chandima Ratnayke, “Fatigue and Fracture Degradation Inspection of Offshore Structures and Mechanical Items: The State of The Art”, conference paper, June 2015.

[21] – Belzona, 2018, [Online]. Available: https://khia.belzona.com/en/view.aspx?id=1591 [Accessed June 2018].

[22] – HSE, “Structural integrity management framework for fixed jacket structures”, RR684 – Research report, 2009.

[23] – Istvan Szarka, “Structural Integrity Management ensuring robustness and barriers”, Master thesis, Stavanger, spring 2015.

[24] – NORSOK, N-001 – “Integrity of offshore structures”, 2010.

[25] – NORSOK, N-003 – “Actions and Effects”, 2007.

[26] – NORSOK, N-004 – “Design of steel structures”, 2013.

[27] – NORSOK N-005 – “Condition monitoring of loadbearing structures,” 1997.

[28] – NORSOK N-006 – “Assessment of structural integrity for existing offshore load-bearing structures”, 2015.

[29] – API, RP 2SIM: “Structural Integrity Management of Fixed Offshore Structures”, 2014.

[30] – DNV GL, RP-C210: “Probabilistic methods for planning of inspection for fatigue cracks in offshore structures”, 2015.

[31] – DNV GL, RP-C203: “Fatigue design of offshore steel structures”, 2016.

[32] – HSE, Key Programme 4 (KP4), “Ageing and life extension programme”, 2013.

[33] – Pitting corrosion, TechnipFMC, 2018, [Online]. Available: https://www.technipfmc.com/ [Accessed June 2018].

[34] - Mohamed A. El-Reedy, «Offshore Structures: Design, Construction and Maintenance”, hardcover edition, published 2012.

[35] – P. J. Haagensen, J. E. Larsen and O. T. Vårdal, “Long term effectiveness of life extension methodologies applied to offshore structures” 20th European Conference on Fracture, 2014.

[36] – SINTEF, “Ageing and life extension for offshore facilities in general and for specific systems”, SINTEF report for PSA, 2010.

[37] - Eeva Mikkola, Yukitaka Murakami and Gary Marquis, “Fatigue life assessment of welded joints by the equivalent crack length method”, 20th European Conference on Fracture, 2014.

[38] - Riaz Khan, Ivana Kraincanic, Kenneth Smith and M. J. Gunn MA, “The Role of Joint Flexibility in the Structural Assessments of Ageing Offshore Structures”, ISOPE Proceedings, 2016.

[39] – A. Stacey et al., “LIFE EXTENSION ISSUES FOR AGEING OFFSHORE INSTALLATIONS”, 27th International Conference on Offshore Mechanics and Arctic Engineering, Estoril, Portugal, 15-20 June 2018.

[41] – John Wintle and John Sharp, “Requirements for Life Extension of Ageing Offshore Production Installations”, report for PSA, January 2008.

[42] - J.W. Turner et al., “A Review of Operations and Mitigation Methods for Offshore Platforms”, the 26th Annual OTC, Houston, Texas, 2-5 May 1994.

[43] - Ingar Scherf, Birger Etterdal and Trond Monshaugen, “Cost-Efficient Structural Upgrade and Life Extension of North Sea Jacket Platforms with Use of Modern Reassessment Techniques”, Offshore Technology Conference, Houston, Texas, 3-6 May 1999.

[44] – Dr. A. F. Dier, MSL Engineering Limited, “Assessment of Repair Techniques for Ageing Damaged Structures - Project #502”, November 2004.

[45] - T. S. Thandavamoorthy, A. G. Madhava Rao and A. R. Santhakumar, “Behaviour of Internally Ring-Stiffened Joints of Offshore Platforms”, Journal of Structural Engineering, 1999.

[46] - Gary B. Marquis, Eeva Mikkola, Halid Can Yildirim and Zuheir Barsoum, “Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed fatigue assessment guidelines”, research paper, IIW, 2013.

[47] - Fidelis R. Mashiri, “Recent Research on Fatigue of Tubular Joints”, Sydney University, Sydney, Australia, 2017.

[48] - Xiaoye Yu et al., “Relationships between internal forces, bracing patterns and lateral stiffnesses of a simple frame” 2015.

[49] - Abe Nezamian et al., “STATE OF ART IN LIFE EXTENSION OF EXISTING OFFSHORE STRUCTURES”, proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, Brazil, Rio de Janeiro, July 1-6, 2012.

[50] - Birger Etterdal, Dag Askheim, Henrik Grigorian and Rune Gladsø, “Strengthening of Offshore Steel Components Using High-Strength Grout: Component Testing and Analytical Methods”, Offshore Technology Conference, Houston, Texas, 30 April – 3 May 2001.

[51] - V. Schulze, F. Bleicher, P. Groche, Y.B. Guo and Y.S. Pyun, “Surface modification by machine hammer peening and burnishing”, CIRP Annals - Manufacturing Technology, 2016.

[52] - Sang Eui Lee, Anil Kumar Thayamballi and Jeom Kee Paik, “Ultimate strength of steel brackets in ships”, ocean engineering, April 2015.

[53] - M. M. Pedersen et al., “Comparison of Post Weld Treatment of High Strength Steel Welded Joints in Medium Cycle Fatigue”, Aalborg University, 2010.

[54] – Kulin Yuan, “Residual Stress Analysis and Fatigue Strength Assessment of Welded Joints with Ultrasonic Impact Treatment (UIT)”, Doctor thesis, Graduate school of Engineering, Yokohama National University, September 2015.

[55] - Masnaji R. Nukulwar and Shailesh S. Pimpale, “Fatigue Analysis of Welded Joint with and without Shot Peening”, research article Vol. 6 Issue no. 6, 2016.

[56] - S.H.J. van Esa, M. H. Kolsteina, R. J. M. Pijpers, F. S. K. Bijlaard, “TIG-dressing of high strength steel butt welded connections – Part 1: weld toe geometry and local hardness”, 5th Fatigue Design Conference, Fatigue Design, 2013.

[57] - Fikri Bashar Yalchiner and Zuheir Barsouma, “Life Extension of Welded Structures Using HFMI Techniques – Potential application to offshore structures”, 2nd International Conference on Structural Integrity, Funchal, Madeira, Portugal, 4-7 September 2017.

[58] - S.H.J. van Es, “Effect of TIG-dressing on fatigue strength and weld toe geometry of butt welded connections in high strength steel”, Master thesis, Delft University of Technology, 2012.

[59] – Hans-Peter Gunther, Ulrike Kuhlmann and Andre Durr, “Rehabilitation of Welded Joints by Ultrasonic Impact Treatment (UIT)”, 2005.

[60] – Y. Morikage et al., “Effect of compressive residual stress on fatigue crack propagation”, 14th International Conference on Pressure Vessel Technology, 2015.

[61] - Guenhael Le Quilliec, Henri-Paul Lieurade, Marc Bousseau, Monssef Drissi-Habti, Genevieve Inglebert, Pascal Macquet and Laurent Jubin, “Fatigue Behaviour of Welded Joints Treated by High Frequency Hammer Peening: Part I, Experimental Study”, 64th Annual Assembly & International Conference of the International Institute of Welding (IIW 2011), Chennai, India, July 2011.

[62] - R. Baptista, V. Infante and C. Branco, “Fully Dynamic Numerical Simulation of the Hammer Peening Fatigue Life Improvement Technique”, 2011.

[63] - F. Lefebvre, C. Revilla-Gomez, J-Y, Buffiere, C. Verdu and C. Peyrac, “Understanding the mechanisms responsible for the beneficial effect of hammer peening in welded structure under fatigue loading”, Advanced Materials Research Vol. 996, 2014.

[64] - Kengo Anami, Chitoshi Miki, Hideki Tani and Haruhito Yamamoto, “Improving fatigue strength of welded joints by hammer peening and TIG-dressing”, 2000.

[65] – IIW, “Recommendations for fatigue design of welded joints and components”, December 2008.

[66] - H. Gao, R. K. Dutta, R. M. Huizenga, M. Amirthalingam, M. J. M. Hermans, T. Buslaps and I. M. Richardson, “Stress relaxation due to ultrasonic impact treatment on multi-pass welds, Science and Technology of Welding and Joining”, 2014.

[67] – Jamie Goggins, B. M. Broderick and Brian Michael, “Behaviour of tubular steel members under cyclic axial loading”, Journal Of Constructional Steel Research, 2006.

[68] - K. H. Nip et al., “Cyclic testing and numerical modelling of carbon steel and stainless-steel tubular bracing members”, 2010.

[69] – R. Tremblay et al., “Inelastic cyclic testing of large size steel bracing members”, the 14th World Conference on Earthquake Engineering”, Beijing, China, October 12-17, 2008.

[70] - Sang-Rai Cho, Din Ngoc Can Le and Byeong-Soo Seo, “Response of tubular structures under dynamic impact loadings”, 2015.

[71] - Zhaolong Yu and Jørgen Amdahl, “Analysis and design of offshore tubular members against ship impacts”, 2016.

[72] – F. H. Øyasæter, A. Aeran, S. C. Siriwardane and O. Mikkelsen, “Effect of corrosion on the buckling capacity of tubular members”, First Conference of Computational Methods in Offshore Technology, 2017.

[73] - Tohid Ghanbari Ghazijahani, Hui Jiao and Damien Holloway, “Experiments on Dented Steel Tubes under Bending”, 2014.

[74] – H. Ahmadi, M. A. Lotfollahi-Yaghin and A. Aminfar, “Parametric Study of outer-brace SCFS in right-angle two-planar tubular DKT-joints of Offshore Jacket Structures”, Journal of Engineering Science and Technology, 2015.

[75] - Tae-Won Kim, Sang-Sub Lim, Ho-Hyun Seok and Chung-Gil Kang, “Concurrent engineering solution for the design of ship and offshore bracket parts and fabrication process”, 2013.

[76] - Y. Garbatov, M. Tekgoz & C. Guedes Soares, “Experimental and numerical strength assessment of stiffened plates subjected to severe non-uniform corrosion degradation and compressive load, Ships and Offshore Structures”, 2016.

[77] - P. Gandhi, G. Raghava, and D. S. Ramachandra Murthy, “Fatigue behaviour of internally rign-stiffened welded steel tubular joints”, JULY 2000.

[78] - Liam Gannon, Yi Liu, Neil Pegg & Malcolm J. Smith, “Nonlinear collapse analysis of stiffened plates considering welding-induced residual stress and distortion, Ships and Offshore Structures”, 2015.

[79] - Heba Wael Leheta, Sherif Farouk Badran and Ahmed Shawki Elhanafi, “Ship structural integrity using new stiffened plates”, 2015.

[80] - Jung Min Sohn, Sang Jin Kim, Jung Kwan Seo, Bong Ju Kim and Jeom Kee Paik, “Strength assessment of stiffened blast walls in offshore installations under explosions”, 2014.

[81] - Marcus M. K. Lee and Arwel Llewelyn-Parry, “Strength prediction for ring-stiffened DT-joints in offshore jacket structures”, 2005.

[82] - David Igoe, Giovanni Spagnoli, Paul Doherty and Leonhard Weixler, “Design of a novel drilled-and-grouted pile in sand for offshore Oil & Gas structures”, 2014.

[83] - Paul Dallyn, Ashraf El-Hamalawi, Alessandro Palmeri and Robert Knight, “Experimental testing of grouted connections for offshore substructures: A critical review”, Structures, 2015.

[84] – Peter Scahumann, Alexander Raba and Anne Bechtel, “Fatigue behaviour of grouted connections at different ambient conditions and loading scenarios”, 14th Deep Sea Offshore Wind R&D Conference, Trondheim, Norway, 2017.

[85] – G. E. Beyg and A. Taheri, “Investigation of the Pile Aging Effect of a Fixed Offshore Platform Located in Persian Gulf using Nonlinear Soil-Pile Interactions”, INTERNATIONAL JOURNAL OF MARITIME TECHNOLOGY, 2017.

[86] – Julio Alberto Méndez Romero, “Experimental and numerical study of needle peening effects in aluminium alloy 2024-T3 sheets”, Doctor Thesis, University of Montreal, 2016.

[87] – Uniform corrosion, 2016, [Online]. Available: https://piletechscrewfiles.blogspot.com/2016/05/stripping-down-corrosion.html [Accessed June 2018]

[88] – Standard Norge, NORSOK, 2018, [Online]. Available:
https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standards/#.Wu2PFX--mUk [Accessed June 2018]

[89] - M. Tekgoz, Y. Garbatov and C. Guedes Soares, "Ultimate strength assessment of welded stiffened plates", Engineering Structures, 2014.

[90] – Eivend Steen, Tom K. Østvold and Sverre Valsgård, "A new design model for ultimate and buckling strength assessment of Stiffened plates", 2001.

[91] - Roberto Taier, "Analysis of fatigue in the weld of the joints in the fixed offshore platforms", American Journal of Engineering Research, 2013.

[92] - Marcus Klose, Torsten Faber, Peter Schaumann and Stephan Lochte-Holtgreven, "Grouted Connections for Offshore Wind Turbines", Proceedings of the 18th International Offshore and Polar Engineering Conference, Vancouver, BC, Canada, July 6-11, 2008.

[93] - Masnaji R. Nukulwar and Shailesh S. Pimpale, "Fatigue Analysis of Welded Joint with and without Shot Peening", Pune, India, 2016.

[94] - Epoxy Coating, Corrosionpedia, 2018, [Online]. Available:
https://www.corrosionpedia.com/definition/463/epoxy-coating [Accessed May 2018].

[95] - Coatings for Marine Applications & Offshore Platforms, Corrosionpedia, 2018, [Online]. Available: https://www.corrosionpedia.com/2/1790/industries/coatings-for-marine-applications-offshore-platforms [Accessed June 2018].

[96] – R. Baxter and J. Britton, "Offshore Cathodic Protection 101", 2007.

[97] – Martin Linge Platform, Norsk Petrolem, 2018, [Online]. Available:
https://www.norskpetroleum.no/en/facts/field/martin-linge/ [Accessed May 2018].

[98] - E. Niemi et al., "Structural Hot-Spot Stress Approach to Fatigue Analysis of Welded Components", IIW Collection, Springer Nature Singapore, 2018.

[99] – M. M. Pedersen, O. Ø. Mouritsen, M. R. Hansen, and J. G. Andersen, "Experience with the Notch Stress Approach for Fatigue Assessment of Welded Joints", Proceedings of Swedish Conference on Lightweight Optimised Welded Structures, 2010.

[100] – Tord Slåke, "Analysis of Jacket type fixed platforms – Effect of various mass modelling approaches for Topsides on structural response", Master thesis, University of Stavanger, spring 2016.

[101] – Densit, "Technical data sheet – Ducorit", 2017, [Online]. Available:
http://densit.com/products/renewable-energy-foundation-solutions/ducorit-offshore/ [Accessed May 2018].

[102] – Polypropylene, Creative Minds, "Everything You Need To Know About Polypropylene (PP) Plastic", 2016, [Online]. Available: https://www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic [Accessed May 2018].

[103] – Polypropylene, British Plastic Federation, "Polypropylene (PP)", [Online]. Available: http://www.bpf.co.uk/plastipedia/polymers/PP.aspx [Accessed May 2018].

[104] – WS Hampshire Inc., "Material data sheet - Polyethylene", 2018.

Appendix A – Matlab Code for the Fatigue Life Estimation using Miner's Rule

The Matlab code that was used to estimate the fatigue life for the baseline and the three post-weld mitigation methods are posted below. The code was the same for all of them. Parameters that were changed is the fatigue life limit, loga and logb, and m1 and m2.

```
%-------------------------------Import data- mention the path where files
are located--------------------------------
filedir='\\uis.no\open\home\student01\220437\My
Documents\MATLAB\VAL2_1HOUR';
datfiles=dir(fullfile(filedir,'*.dat'));
nfiles=length(datfiles);


for k=1:length(datfiles);
  newData1 = importdata(datfiles(k).name);


    A=newData1.data; %Create matrix A, with all data from the file
    if k==1
        B=zeros(size(A));
        B=vertcat(B,A);
    else
        B=vertcat(B,A);  %vertically concatenates matrix A to B
    end
end
   B(all(B==0,2),:)=[];   %Delete all the zero lines
  % load('B.mat');

%----------------------------------------------------------------------------
Bnew=[];
Bc=B(:,1);
Bnew = repmat(Bc,1);
sizeB=size(Bnew,1);


% CONVERTING STRAIN HISTORY TO STRESS HISTORY (play with E to get decent
% life)

microstrain=Bnew(:,1);
E = ;
stress=microstrain*E*10^(-6)*10;
x=1:1:sizeB;
h1=plot(x,stress);
xlabel('Time,s','fontsize',12);ylabel('Stress,MPa','fontsize',12);

%---------------------rainflow counting---------------------------------


tp=sig2ext(stress);

rf=rainflow(tp);

rf=rf';
```

```
%-------------------- MEAN STRESS CORRECTION----------------------------

sigmaUTS = 460; %check for your material

lengthRf=length(rf);
sigmaAmpall=zeros(lengthRf,1);
    for i=1:lengthRf
        sigmaAmpall(i)=rf(i,1)/(1-(rf(i,2)/sigmaUTS));
    end

ncumm=zeros(lengthRf,1);
n=zeros(lengthRf,1);
ncumm(1)=rf(1,3);
 for i=2:1:lengthRf

    ncumm(i)=ncumm(i-1)+rf(i,3);
    n(i)=rf(i,3);
 end
 Ampn=[];
 Ampn=sigmaAmpall;
 Ampn(:,2)=n;
 Endu=0; %put endurance limit based on your SN curve
 Ampn(Ampn(:, 1)<Endu, :)= [];
 sigmaAmp=[];
 n=[];

 sigmaAmp=Ampn(:,1);
 n=Ampn(:,2);



% --------------------SN CURVE DEFINITION (defined as per Eurocode (not
% DNV)--- can be defined similarly for DNV as well using below formula

%    N(i)=10^(loga-m*log10((sigeff(i))));

fatiguelimit = 52.63;

m1=3;
m2=5;
loga1=12.164;
loga2=15.606;

l=length(sigmaAmp);
for i=1:l

    if sigmaAmp(i)>=fatiguelimit
        value(i) = 10^(loga1-m1*log10((sigmaAmp(i))));
    else
        value(i) = 10^(loga2-m2*log10((sigmaAmp(i))));;
    end
    N(i)=value(i);

    end

N=N';
```

```
% MINER'S DAMAGE

damageminer=zeros(l,1);

for i=1:l
        damageminer(i)=n(i)/N(i);
end

x=1:1:l;
%plot(x,damageminer);

damageminercumm=zeros(l,1);
damageminercumm(1)=damageminer(1);

for i=2:1:l

    damageminercumm(i)=damageminercumm(i-1)+damageminer(i);
end

% plot(x,damageminercumm);

DamageMiner_hourly=damageminercumm(l,1)   % total damage Miner's

% x=1:1:l;
%
% ncumm=zeros(l,1);
% ncumm(1)=n(1);
%
% for i=2:1:l
%
%     ncumm(i)=ncumm(i-1)+n(i);
% end

yearlydamage=DamageMiner_hourly*365*24

fatigue_life=1/yearlydamage
```

Appendix B – Comparison of Cross Sectional Properties of Strengthened Tubular Sections from SAP and using Analytical Formulas

The properties of the cross section of the additional T-sections and channels sections are compared from SAP2000 and analytical/manual formulas from Excel to show if there are any major differences.

1. Tubular member

Part 1 of Leg A with the dimension 1800x100 [mm] was compared from SAP2000 and analytical formulas.

SAP2000:

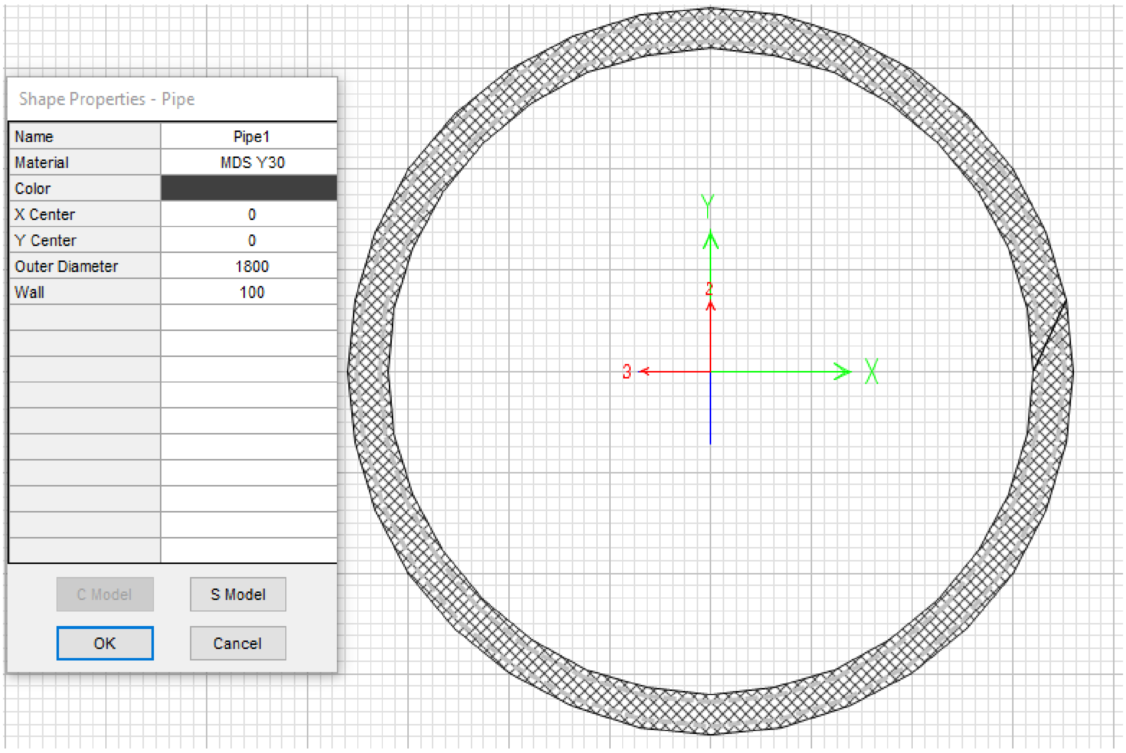


Figure B1: Tubular member from SAP2000

Properties

Cross-section (axial) area	534070,8	Section modulus about 3 axis	2,151E+08
Moment of Inertia about 3 axis	1,936E+11	Section modulus about 2 axis	2,151E+08
Moment of Inertia about 2 axis	1,936E+11	Plastic modulus about 3 axis	2,866E+08
Product of Inertia about 2-3	0,	Plastic modulus about 2 axis	2,866E+08
Shear area in 2 direction	357805,2	Radius of Gyration about 3 axis	602,0797
Shear area in 3 direction	357805,2	Radius of Gyration about 2 axis	602,0797
Torsional constant	3,818E+11	Shear Center Eccentricity (x3)	0,

OK

Figure B2: Properties of tubular member from SAP2000

Excel spreadsheet:

Table B1: Properties of tubular member from Excel spreadsheets

Outer diameter of pipe		1800,00	mm
Thickness of wall		100,00	mm
AREA	Cross section area	534071	mm^2
IX	Torsional moment of inertia about shear centre	387201294555	mm^4
IY	Moment of inertia about Y-axis	193600647277	mm^4
IZ	Moment of inertia about Z-axis	193600647277	mm^4

Comparison:

Table B2: Comparison of properties for tubular member from SAP2000 and Excel spreadsheets

Properties	**SAP2000**	**Excel**	**Difference [%]**
Cross-sectional area	534070,08	534071	0,000126
Torsional moment	3,872E+11	3,818E+11	0,000334
Moment of inertia about Y-axis	1,936E+11	1,936E+11	0
Moment of inertia about X-axis	1,936E+11	1,936E+11	0

2. T-sections added to tubular member

The T-sections that were added to the circular hollow tubular sections is compared below.

SAP2000:

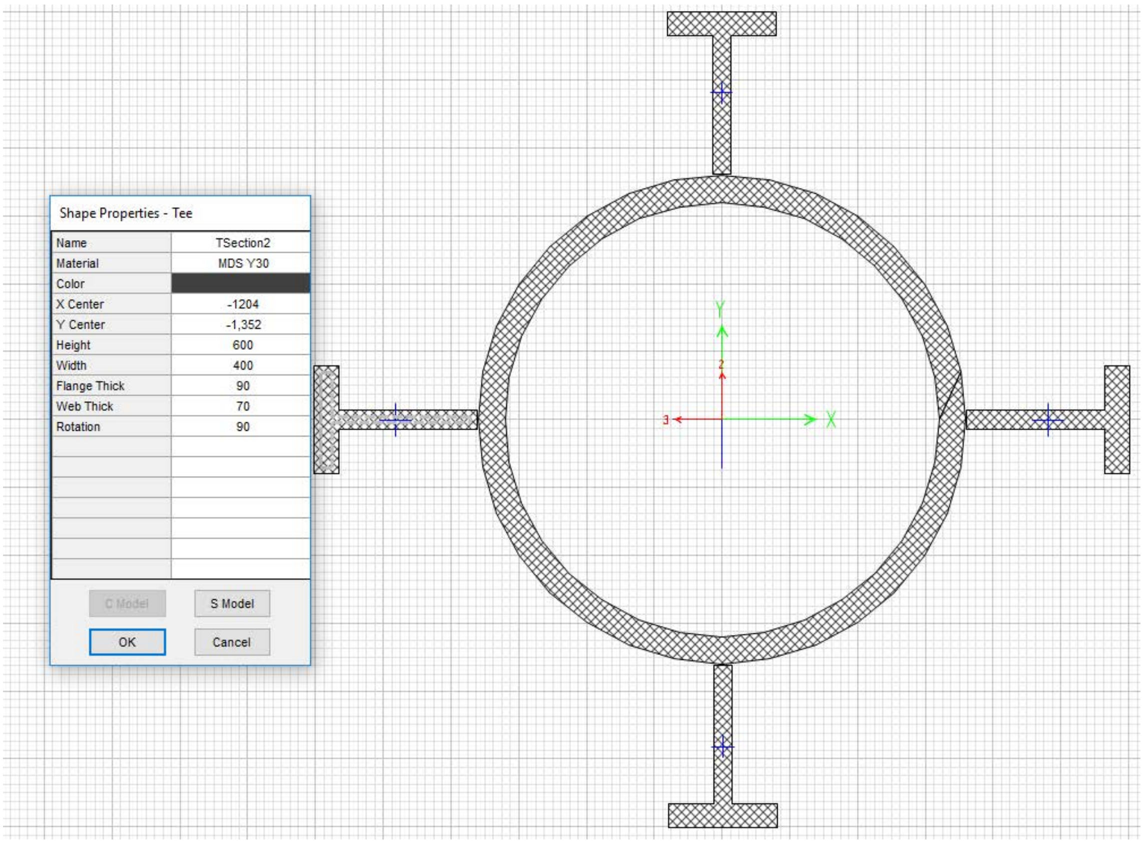


Figure B3: Additional T-sections added to the tubular member from SAP2000

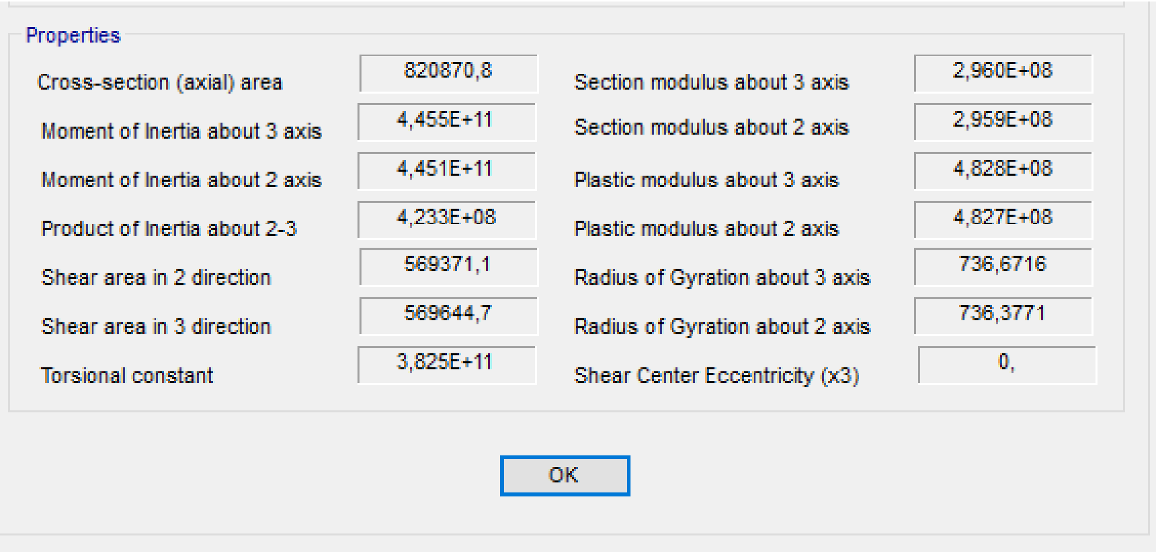


Figure B4: Properties of T-sections from SAP2000

Excel spreadsheet:

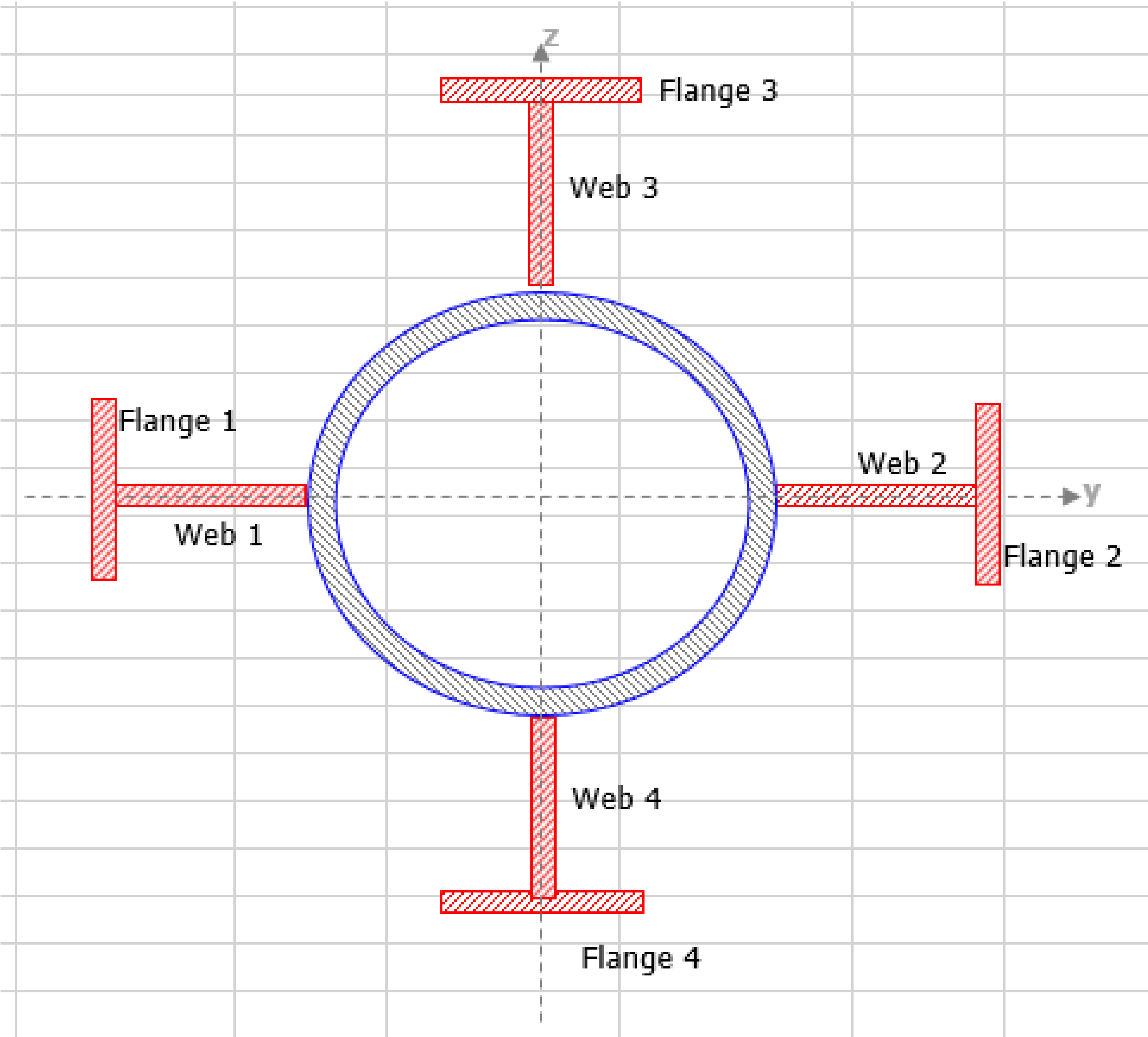


Figure B5: Added T-section to tubular member from Excel spreadsheets

Table B3: Dimensions of added T-section on tubular member from the Excel spreadsheets

Outer diameter of pipe	1800,00	mm
Thickness of wall	100,00	mm
Height of web 1	600,00	mm
Thickness of web 1	70,00	mm
Width of flange 1	400,00	mm
Thickness of flange 1	90,00	mm
Height of web 2	600,00	mm
Thickness of web 2	70,00	mm
Width of flange 2	400,00	mm
Thickness of flange 2	90,00	mm
Height of web 3	600,00	mm
Thickness of web 3	70,00	mm
Width of flange 3	400,00	mm
Thickness of flange 3	90,00	mm
Height of web 4	600,00	mm
Thickness of web 4	70,00	mm
Width of flange 4	400,00	mm
Thickness of flange 4	90,00	mm

Table B4: Calculated properties from the Excel spreadsheets

AREA	Cross section area	846071
IX	Torsional moment of inertia about shear centre	387201294555
IY	Moment of inertia about Y-axis	489989347277
IZ	Moment of inertia about Z-axis	489989347277

Comparison:

Table B5: Comparison of properties for additional T-sections from SAP2000 and Excel spreadsheets

Properties	SAP2000	Excel	Difference [%]
Cross-sectional area	820870,08	846071	2,978
Torsional moment	3,825E+11	3,872E+11	1,214
Moment of inertia about Y-axis	4,455E+11	4,899E+11	9,079
Moment of inertia about X-axis	4,451E+11	4,899E+11	9,079

3. Channel sections added to tubular member

The channel sections that were added in Y-direction is compared below.

SAP2000:

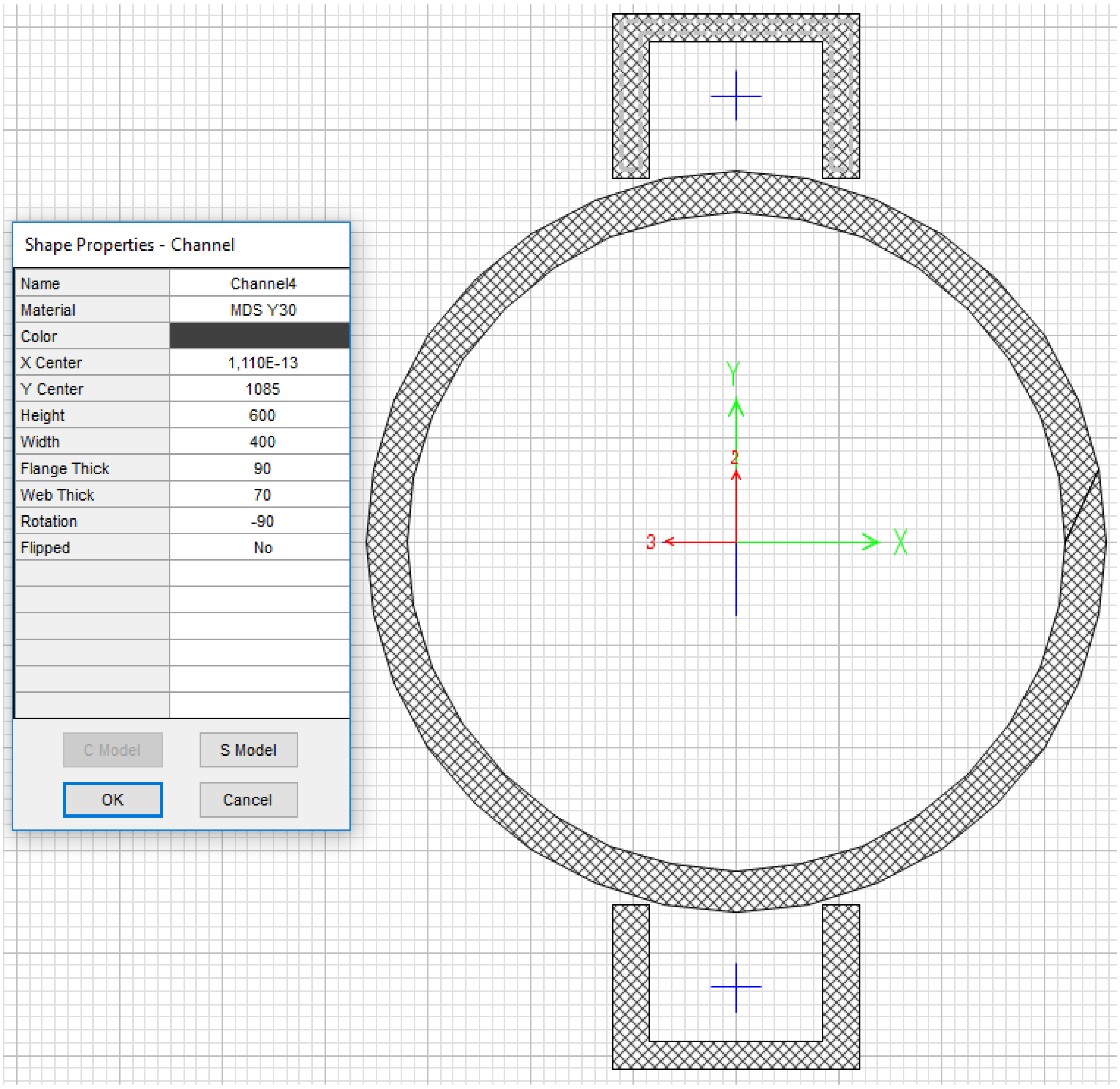


Figure B6: Channel sections added to tubular member from SAP2000

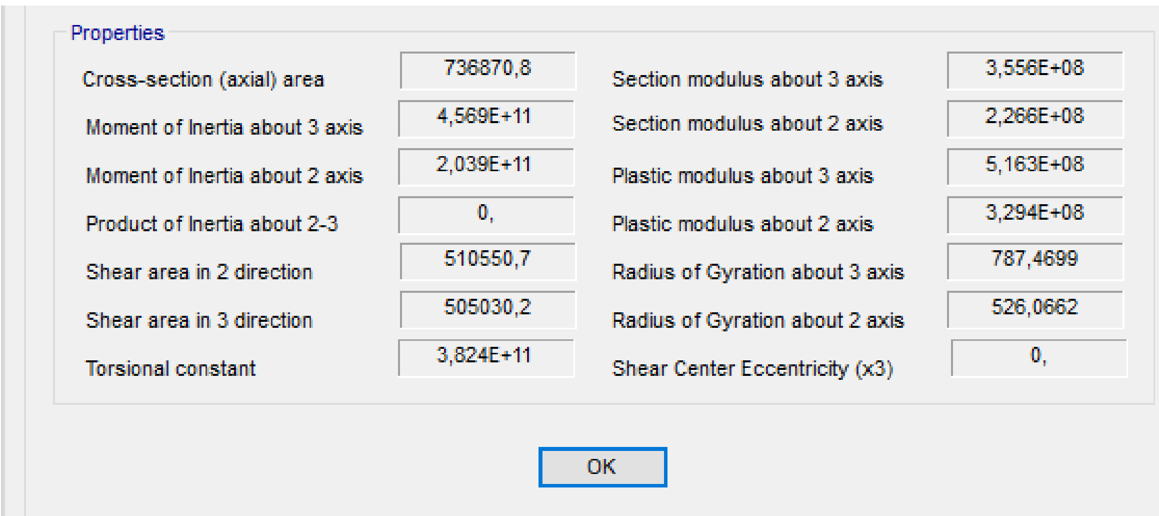


Figure B7: Properties of added channel sections in Y-direction to tubular member from SAP2000

Excel spreadsheet:

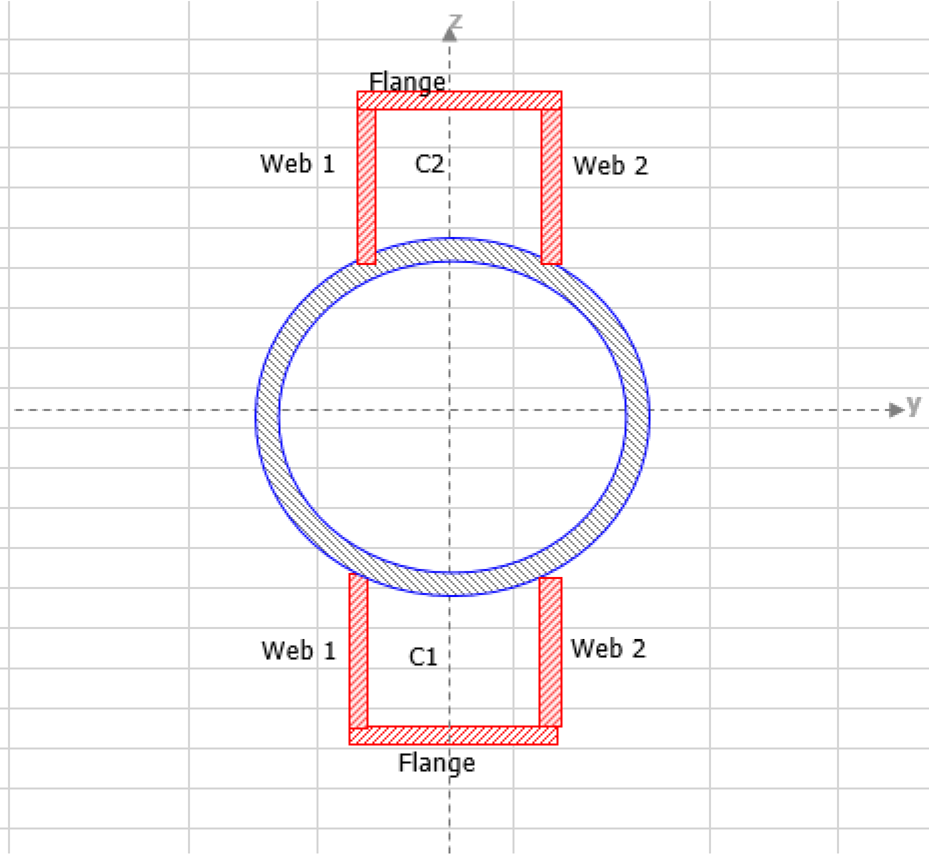


Figure B8: Channel sections added to tubular member from Excel

Table B6: Dimensions of channel section from Excel spreadsheets

Outer diameter of pipe	1800,00	mm
Thickness of wall	100,00	mm
		mm
		mm
		mm
		mm
C2-Height of web 1	400,00	mm
C2-Height of web 2	400,00	mm
C2-Thickness of web 1	90,00	mm
C2-Thickness of web 2	90,00	mm
C2-Width of flange	600,00	mm
C2-Thickness of flange	70,00	mm
C1-Height of web 1	300,00	mm
C1-Height of web 2	300,00	mm
C1-Thickness of web 1	90,00	mm
C1-Thickness of web 2	90,00	mm
C1-Width of flange	300,00	mm
C1-Thickness of flange	70,00	mm

Table B7: Properties of added channel sections from Excel

AREA	Cross section area	723071	mm^2
IX	Torsional moment of inertia about shear centre	387201294555	mm^4
IY	Moment of inertia about Y-axis	447395168872	mm^4
IZ	Moment of inertia about Z-axis	207217715611	mm^4

Comparison:

Table B8: Comparison of properties for channel sections from SAP2000 and Excel spreadsheets

Properties	**SAP2000**	**Excel**	**Difference [%]**
Cross-sectional area	736870,8	723071	-1,908
Torsional moment	3,824E+11	3,872E+11	1,240
Moment of inertia about Y-axis	4,569E+11	4,474E+11	-2,125
Moment of inertia about X-axis	2,039E+11	2,072E+11	1,601