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Abstract

In the last two decades, the number of floating, production, storage, and offloading units (FPSOs) deployed internationally has increased rapidly. Many of them are still young but have already started ageing. The objective of this thesis is to investigate life extension of ship-shaped floating production units in the petroleum activity. This will include an assessment of relevant ageing mechanisms for FPSOs, such as cracks, corrosion, load changes, deflection, and dents in the hull girder. In addition, two literature studies have been performed, one on hull structural integrity management and one on life extension practices for FPSOs.

This project investigates the operator experiences on managing actual ageing mechanisms on their FPSOs. This has been supported by interviews with representatives of the operators on how these are maintained during the operation. In addition, this project reviews actual ageing mechanism data (cracks) on two FPSOs (Balder and Jotun A) operated by Vår Energi. The data has been collected and analyzed with respect to the annual number of cracks as a function of severity and time in operation, cracks in terms of structural details, cracks in terms of crack length, and distribution of cause of failure. The results show that the annual number of cracks partitioned on the two units is very uneven, were for Balder, there have been found 333 cracks, and for Jotun A, there have only been found 12 cracks. Investigations have shown that the majority of the cracks have an insignificant severity classification on both FPSOs. For Balder, most of the cracks are found in ballast tanks in the way of longitudinal side shell stiffeners connection to transverse frames and bulkheads and in the form of the weld between the side shell and the longitudinals. These cracks seem to be caused by unfavorable design of details and fatigue failure. For Jotun A, most of the cracks were found in void spaces at door frames. These cracks seem to be caused by unfavorable design of details.

The review on the operator's life extension practices of ship-shaped units addresses the extent to which the operating companies have performed life extension assessment of their FPSOs in accordance with Norwegian regulation and the standard NORSOK N-006. Results show that the companies are following this regulation and standard. The project closes with a discussion regarding suggestions for improvements in the standard NORSOK N-006 for assessments of FPSOs.

Preface

This thesis concludes a Master of Science degree at the University of Stavanger (UiS), Department of Mechanical and Structural Engineering and Materials Science, Norway. The master's thesis is an obligatory part of the study program, worth 30 credit points (ECTS), to obtain a Master of Science degree in Engineering Structures and Materials. The problem in question has been prepared in collaboration with Vår Energi AS and my supervisor at UiS.

I would like to thank my supervisors at Vår Energi AS Andreas Hordvik, Jarle Husebø, and Ove Stapnes. They have provided me with information and necessary data regarding the offshore installations of interest. I would like to acknowledge the support they have given me by regular conversations and the time they have spent to find the necessary data for this project.

A special thanks to Narve Oma from the Petroleum Safety Authority Norway (PSA) for sharing his experiences and expert knowledge. He has provided valuable help and advice throughout the project. I would also like to thank Østen Jensen from Equinor for a useful and interesting discussion and sheared information regarding the relevant topic. This has contributed to helpful information used in this project.

Last but not least, I want to give a big thanks to my supervisor, Professor Gerhard Ersdal, from UiS. I am genuinely grateful for the unlimited assist and guidance throughout the whole writing process. His exceptional expertise in life extension of existing structures and the desire to contribute to such a case were essential in making the project a success. The regular meetings ensured progress in the work with the thesis.

Finally, I would like to thank my family and friends for supporting me in this work.

Stavanger, June 2020

Iselin Violet Kjelland Schøn

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Nomenclature

A	parameters of the $S-N$ curve
A_c	cross-sectional area involved in cracking damage
A_o	cross-sectional area of uncracked original plating
A_{pi}	surface area of the ith pit
a	plate length
a_c	random variable describing the uncertainty with the critical crack size
a_f	final or critical crack size
a_i	initial crack size
b	plate breadth
C	material constant
D	accumulated damage
D_t	total cumulative damage
f_X	joint probability density function
g	limit state function
h	parameters of a Weibull distribution function
K_{cr}	stress intensity factor attains a critical level
m	parameters of the $S-N$ curve
N	random variable describing the number of cycles experienced
N_c	random variable describing the critical number of cycles defined by fracture mechanics
N_i	total number of cycles to failure under constant amplitude stress ranges $\Delta\sigma_i$
n	number of pits
n_i	number of cycles of constant amplitude stress ranges $\Delta\sigma_i$
P_f	failure probability
R	random variable describing the uncertainty in strength
R_c	characteristic strength
R_d	design value for resistance
$R_{\tau c}$	factor of the ultimate shear strength reduction due to cracking damage
R_{xc}	factor of the ultimate tensile or compressive strength reduction due to cracking damage
S	random variable describing the uncertainty in the loading on the structure
S_c	characteristic value
S_d	design value for load

S_{hot}	hot-spot stress
S_{max}	maximum stress range
S_{nom}	nominal stress
S_{notch}	notch stress
V_{pi}	volume of the ith pit
X_n	variable
δa	crack growth with time
ΔK	stress intensity factor
ΔK_{th}	threshold stress intensity factor range
q	parameters of a Weibull distribution function
τ_u	ultimate shear strength for a plate with premised cracks
τ_{uo}	ultimate shear strength of uncracked plating.
σ_{xu}	ultimate axial strength of cracked plating
σ_{xuo}	ultimate axial strength of uncracked plating
γ_i	load factor
ϕ	strength factor
Δ	random variable describing the uncertainty with the fatigue accumulation

Abbreviations

ACFM	alternating current field measurement
AFOSM	advanced first order second moment
ALE	ageing and life extension
ALS	accidental limit states
CODAM	PSA corrosion and damage database
CP	cathodic protection
CVI	close visual inspection
DFF	design fatigue factor
DNV GL	class society
DP	dynamic positioning
EC	eddy current inspection
FLS	fatigue limit states
FORM	first order reliability method
FOSM	first order second moment
FPSO	floating, production, storage and offloading unit
GRP	glass-reinforced plastic
GVI	general visual inspection
ICCP	impressed current cathodic protection
LP	liquid penetrant testing
LRFD	load and resistance factor design
MCS	monte carlo simulation
MIC	microbiologically induced corrosion
MPI	magnetic particle inspection
NCS	Norwegian Continental Shelf
NDE	non-destructive examination
NPD	Norwegian Petroleum Directorate
PSA	Petroleum Safety Authority Norway
POB	personnel on board
POD	probability of detection
ROV	remote operated vehicle
SAI	special areas of interest
SCC	stress corrosion cracking

SCF	stress concentration factor
SCIP	structural critical inspection point
SIM	structural integrity management
SORM	second order reliability method
SRA	structural reliability analysis
SRB	sulfate reducing bacteria
SSC	sulfide stress cracking
ULS	ultimate limit states

Terms and definitions

The terms and definitions given below apply to how these are used in this thesis.

Accidental limit state (ALS): A check of the collapse of the structure due to the same reasons as described for the ultimate limit state but exposed to abnormal and accidental loading situations.

Ageing: A process in which the integrity (i.e., safety) of a structure or component changes with time or use.

Barrier: A measure intended to identify conditions that may lead to failure, hazardous and accidental situations, prevent an actual sequence of events occurring or developing, influence a series of events in a deliberate way, or limit damage and/or loss.

Design service life: Assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair from ageing processes being necessary.

Fatigue limit state (FLS): A check of the cumulative fatigue damage due to cyclic loads or the fatigue crack growth capacity of the structure.

Floating systems integrity management (FSIM): A process for demonstrating a floating system's fitness-for-service over its entire service life.

Hazard: Potential for human injury, damage to the environment, damage to property, or a combination of these.

Life extension: When a structure is used beyond its originally defined design life.

Limit state: A state beyond which the structure no longer fulfills the relevant design criteria.

Microbiologically induced cracking (MIC): A form of degradation that can occur as a result of the metabolic activities of bacteria in the environment.

Partial safety factor: For materials: This takes into account unfavorable deviation of strength from the characteristic value and any inaccuracies in determining the actual strength of the material. For loads: This takes into account the possible deviation of the actual loads from the characteristic value and inaccuracies in the load determination.

Primary structure: All main structural components that provide the structure's main strength and stiffness.

Redundancy: The ability of a structure to find alternative load paths following failure of one or more components, thus limiting the consequences of failures.

Residual strength: Ultimate strength of an offshore structure in a damaged condition.

Robustness: This reflects the ability of the structure to be damaged tolerant and to sustain deviations from the assumptions for which the structure was originally designed.

Secondary structure: Structural components that, when removed, do not significantly alter the overall strength and stiffness of the global structure.

$S - N$ curve: A relationship between the applied stress range (S) and the number of cycles (N) to fatigue failure.

Stress concentration factor (SCF): Factor relating nominal stress to the local structural stress at a detail.

Structural integrity: The state of the structure and conditions that influence its safety

Structural integrity management (SIM): A means of demonstrating that the people, systems, processes, and resources that deliver structural integrity are in place, in use, and will perform when required for the whole life cycle of the structure to provide an acceptable safety level.

Structural reliability analysis (SRA): Used to analyze the probability of limit state failure of structures.

Ultimate limit state (ULS): A check of failure if the structure if one or more of its members due to fracture, rupture, instability, excessive inelastic deformation, etc.

Wave in deck: Waves that impact the deck of a structure, which dramatically increase the wave loading on the structure.

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1. Introduction

1.1 Floating production, storage, and offloading units

Floating production, storage, and offloading units, referred to as FPSOs, are hybrid structures in the sense that these vessels are ships operating as offshore facilities. These ship-shaped offshore installations are either purpose-built vessels or tanker conversions. They constitute an efficient solution for remote oil field locations due to their storage capacity of crude oil (Ayala-Uraga, 2009). As illustrated in Figure 1, FPSOs receives fluids from subsea production wells or other installations, which is transmitted through flowlines on the seabed to flexible risers transporting the fluid to the vessel. The fluid separates into crude oil, natural gas, water, and impurities at the topside production facilities. Crude oil is stored in the storage tanks of the FPSO and offloaded onto shuttle tankers, which transport the crude oil to onshore refineries. Gas is transferred to shore via pipelines or re-injected into the field to boost production. Mooring lines are typically used to anchor the vessel from various locations on the seafloor, which allows the FPSO to rotate freely around the turret to respond to weather conditions (weather vaning).

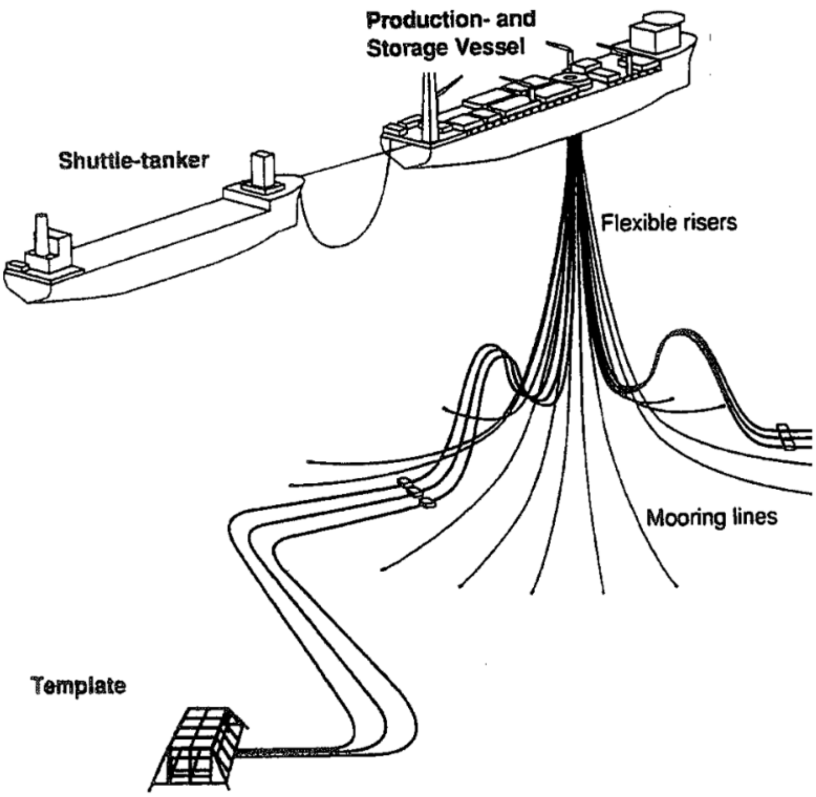


Figure 1: An FPSO system (Moan et al., 2002).

Ship-shaped offshore installations are some of the more economical systems for the development of offshore oil and gas fields and are often preferred in marginal fields. FPSOs are especially attractive for oil and gas fields in deep- and ultradeep-water locations and areas remote from existing pipeline infrastructures. Recently, FPSOs have also been considered for application to near-shore oil and gas terminals. It is proven over the last 30 years that FPSOs are reasonable, reliable, cost-effective solutions for the development of offshore fields in harsh environments and deep waters worldwide. Ship-shaped offshore units have opened the possibilities for the development of offshore oil and gas resources that would be otherwise impossible or uneconomical to perform. This innovative technology enables the production of oil and gas fields far beyond the water depths of fixed type offshore platforms. FPSOs also provides flexible solutions for developing short-lived fields with marginal reserves and fields in remote locations (Paik & Thayamballi, 2007).

1.2 Background and motivation for the present work

In the last two decades, the number of floating, production, storage, and offloading units (FPSOs) deployed internationally has increased rapidly (Cohrs et al., 2020). Many of them are still young but have already started ageing. Life extension of FPSO has getting more attention lately, especially in recent years, when the oil price has proven significant fluctuations, which leads to reassessing of expenditure in many oil and gas companies. During these years, a considerable amount of experiences has been gathered. In Norway, operating companies and shipowners are obliged to report incidents and damages to the Petroleum Safety Authority Norway (PSA), which are a useful source of experience. Ageing and life extension (ALE) present key challenges for the offshore oil and gas industry. This involves that the specifications and design of most FPSOs originates from conventional trading tankers where there is a normal routine of dry-docking events enabling significant recourse level to address all the essential repairs, inspections, and maintenance activities every 5th year of operation. While the integrity challenges for FPSOs and trading tankers are similar due to shared design and specifications, an alternative approach is necessary to address the effects of asset ageing on situ. This is a result of the routine for which FPSOs usually do not go into dry-docking every 5 years, which is the norm for trading tankers. If the ALE management work gets comprehensive, an off-situ campaign that addresses all of the ALE issues should be considered (Stobo et al., 2014).

In addition, FPSOs operate in volatile environments, which can give extra stress, accelerating ageing mechanisms and compromise efficiency and availability. A detailed understanding of safety factors and original design intent is an essential component of any FPSO integrity management strategy, which in turn will result in decisions regarding life extension. Technical justification is required in integrity management supported by advanced analysis. Cost-efficient and practical solutions are also necessary to maintain sufficient levels of safety when anomalies are detected. This means that operating companies should consult with expert technicians to get an assessment of individual FPSO components that are fit for service. The decisions to repair may influence a possible life extension for the FPSO due to integrity issues and economic issue. However, a high number of experienced cracks needing repairs is the most significant issue regarding a possible life extension (Cohrs et al., 2020).

Life extension of offshore fields does not only bring economic savings and risk profile benefits. Cohrs from the Oil and Gas Authority UK (Cohrs et al., 2020) believes that people employed in companies opt to extend the life of their FPSO have much to gain, and that life extension will provide continued employment. “Late-life” provides a different set of skills, where people within the organization and supply chain have the opportunities to develop their skills in inspection and maintenance. Further, the opportunities which come with better technology are fewer people and less intrusion, but improved technology gives, in turn, great opportunities for technical development. Overall, life extension across the board increases the need for specialized services, adds economic value, boosts people’s skillsets, and employee development. When thinking of life extension in particular, the number of eligible FPSOs in the NCS is increasing, where the majority of the vessels have reached 90 % of their design or field life (Cohrs et al., 2020).

1.3 Problem objective and scope of work

The objective of this thesis is to investigate life extension of ship-shaped floating production units in the petroleum activity (FPSOs, FPUs, and FSOs). This will include an assessment of relevant ageing mechanisms for FPSOs, such as cracks, corrosion, load changes, deflection, and dents in the hull girder. In addition, two literature studies will be performed. The first literature study will be on hull structural integrity management and investigate factors of keeping the structure sufficiently safe during operation and use. The second literature study will be on life extension practices for FPSOs and investigate factors that are necessary to keep the structure acceptable for further use, taking into account varieties that have arisen and other factors that may undermine confidence in its integrity.

This thesis will further investigate the management of actual ageing mechanisms with the emphasis on cracks at two operator companies. Further, ageing mechanism data with the emphasis on cracks will be collected and analyzed for two FPSOs at one operator company. The cracks on the two FPSOs will be collected and analyzed with respect to the following:

- The annual number of cracks as a function of severity and time in operation;
- Cracks in terms of structural details;
- Cracks in terms of crack length;
- Distribution of cause of failure.

In this thesis, investigation of the practices for life extension at two operator companies will be performed. This investigation addresses the extent to which the operating companies have performed life extension assessment of their FPSOs in accordance with Norwegian regulation and the standard NORSOK N-006. Results show that the companies are following this regulation and standard. The project closes with a discussion regarding suggestions for improvements in the standard NORSOK N-006 for assessments of FPSOs.

1.4 Thesis overview

To accomplish the problem objective and scope of work, the approach shown in Figure 2 was undertaken:

Chapter 1: Introduction

Chapter 2: Ageing mechanisms relevant for FPSOs

Chapter 3: Hull Structural Integrity Management. A literature study including:
The process of floating structural integrity management.
SIM in Life extension.
Implementation of SIM for the hull structure.
Cathodic protection system.
Inspection practices for FPSOs.
Methods for damage examination of FPSOs.
Risk-Based Inspection.
Evaluation of inspection findings.
Maintenance practices for FPSOs.

Chapter 4: Life extension assessment practices for FPSOs. A literature study including:
Design life and life extension in relation to the Bathtub Curve.
Assessment versus Design.
Assessment Procedures.
Assessment of Ageing Materials.
Strength analysis.
Fatigue analysis and the $S-N$ approach.
Fracture mechanics assessment.
Probabilistic strength, fatigue and fracture mechanics.
Regulatory practices in Norway regarding ageing and life extension.
NORSOK N-006 standard
DNV GL offshore standards and class guidance

Chapter 5: Ageing mechanisms at the operator companies.
Management of ageing mechanisms at the operator companies
Collection of crack data for Balder and Jotun A
Results and discussion of crack findings at Balder and Jotun A

Chapter 6: Life extension practices at the operator companies
Life extension practices at Vår Energi
Life extension practices at Equinor
Results and discussion of life extension practices at the operator companies
Suggestions for improvements in the NORSOK N-006 standard for assessment of FPSOs

Chapter 7: Concluding remarks

Figure 2: Thesis overview.

1.5 Limitations

Several ageing mechanisms are essential for FPSOs, as described in chapter 2. However, this project has placed emphasis on cracks. Classifications of cracks have been performed according to the PSA classification with some limitations of available information about the FPSOs of interest. In addition, investigations of actual ageing mechanisms with the emphasis on cracks have only been performed on two FPSOs from one operator company, Vår Energi. Hence, the crack analysis does not provide a complete overview on a general basis of cracking on FPSOs. Studying a higher number of FPSO will give more accurate and credible information that may be useful as guidance for FPSOs in the future. Such information could further be implemented in the NORSOK N-006 standard used on assessment for life extension of FPSOs.

2. Ageing mechanisms relevant for FPSOs

2.1 Introduction

Structures will start to change at the moment they are created, and these changes have to be managed to ensure that structures remain sufficiently safe. Some ageing mechanisms can influence the safety of the structure directly, such as fatigue, corrosion, material degradation, changes in loads, and weight on the structure and the application of the structure. The use of the structures, load, and the environment they are exposed to will change over time. In addition, the information and knowledge about the structure may change over time, e.g., design and inspection documentation. In addition, the physical theories and engineering methods used to analyze the structures may change as a result of new phenomena discovered. Lastly, the assessment of offshore structures is dependent on technological development and societal changes, which can lead to changes in the requirements used for offshore structures, taking into consideration the availability of spare parts for old equipment, obsolescence and lack of competence. These changes may be divided into four groups, as follows:

- Technological changes
- Physical changes
- Changes to knowledge and safety requirements
- Structural information changes

Figure 3 shows these four groups of ageing changes to a structure. The two upper boxes, technological and physical changes, will change the safety and the functionality of the structure directly. The two lower boxes, knowledge and requirements, and structural information changes primary will improve the understanding of safety and functionality of the structure. Groups can also be made from the two right boxes, where information gathered from physical and structural information changes applies to one specific structure. The two left boxes, technological changes, and changes to knowledge and safety requirements are applicable for all structures and are a result of social and technical developments.

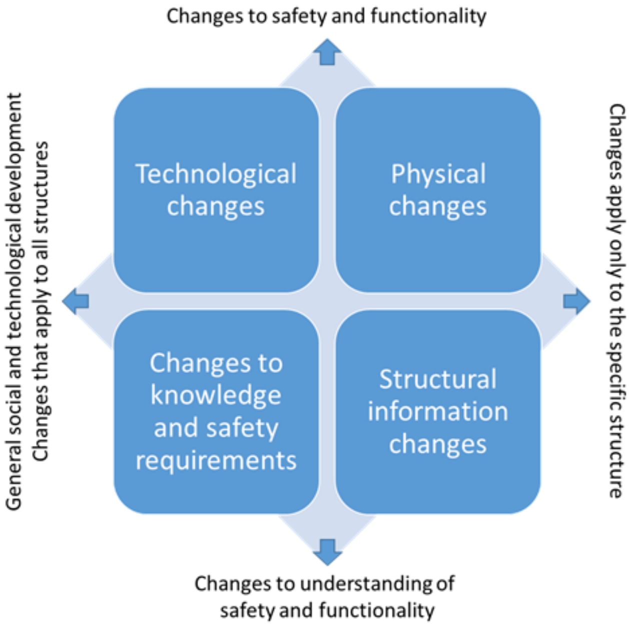


Figure 3: The four main elements of ageing of a structure (Ersdal et al., 2019).

Technological changes are a result of general technological development in society. Technological changes can appear if equipment or control systems applied in the original structure are outdated, spare parts are unavailable, or the compatibility between existing and new systems and equipment is challenging. Improved technology is developed as a result of industry needs and research, and as the improved technology will accumulate when the gap between original and new technology increases.

For floating structures, this may include a significant impact, as they do have computers and other equipment that can obsolete. For example, FPSOs rely on ballasting systems with computers, pumps and vents, hatches, and watertight doors that clearly could experience technological changes and obsolescence (Ersdal et al., 2019).

Physical changes lead to changes in the condition, configuration, loading, and hazards on the structure. These are changes that most people will first think of as the structure gets deteriorated over time, most likely because these are changes that are visible on a structure and easiest to detect. Physical changes are related to the structure and the system itself, their use, and the environment the structure is exposed to. An example of this may be fatigue cracking between the topside support structure and the main deck on an FPSO. Another example is changing to the hazards and loads to a structure. Any such physical changes may lead to a new assessment and analysis of loads, strength, and safety of the structure.

Changes to knowledge and safety requirements are associated with the increased understanding of the methods and models used when analyzing a structure, in addition to the level of safety that is required to the structure. Offshore installations have experienced significant development over several decades since the first installations were deployed in the sea. This development and the continuous research have increased the understanding of both structural performance and loading. Areas that have been improved is, for example, the understanding of materials and their performance, fabrication techniques, and inspection and maintenance methods. Further, steel quality has improved, particularly in through-thickness properties and weld techniques are better established.

In addition, knowledge of the criteria applied in the original design of older structures has changed with time. When performing life extension of structures, such changes need to be considered, and the newest knowledge, and hence often the latest standards, need to be used in an evaluation of an ageing structure for life extension (Ersdal et al., 2019).

Structural information changes can be loss of information from design, fabrication, installation, and use, or it can be the gathering of more information about the structure and its state from inspections. The information about the actual structure, the hazards that the structure may have been exposed to, the loads on the structure, and the strength will change over time. Even though this information does not modify the structure directly, this information will be relevant to the way the structure safety is preserved. To maintain the integrity of a structure, it is vital to know about the design, fabrication and installation, and operation of the structure. It will, for example, be essential to know the following:

- The design weight of loads on the structure
- Designed marine growth on the structure
- Material selection
- Inspection of parts
- Findings of corrosion and fatigue cracking
- Damaged members
- Repairs to the structure
- Documentation of repair welds in the fabrication

For life extension, an important consideration is adequate information and knowledge of the structure, both from its current state and of the original design criteria. Structural and material data from the design, fabrication, and operation of the structure is essential in the management of structures. If these data are available and in use, they will provide the necessary information for good decisions on how to manage the structure. In addition, these data will be of great benefit to the understanding of the structure. However, partly or totally loss of structural information data will lead to a lesser degree of understanding of the safety of the structure, and this will, in turn, affect decisions on how to inspect, modify and repair the structure.

The availability of structural information data gives increased confidence of the structure, its strength, and hence its safety. For life extension, such information provides principal value in assessment and analysis of the safety of the structure. Lack of these data will result in uncertainty and decreased confidence in structural safety.

Information about the structure is missing for various reasons. For older structures, a lot of information is, to a large extent, in the memory of individuals. Even if data is archived, the information may exist in a format that is no longer available. Over time, it will naturally take place changes in staffing within the workplace. Hence, persons responsible for managing the integrity of the structure may be replaced with less knowledge of the given structure. Therefore, it is crucial that information about the structure is well-kept in preferably a database gathering data from the design and fabrication phase, the inspection history, and repairs (including accidental damage). Operators must ensure continuity maintaining of experience and knowledge (Ersdal et al., 2019).

2.2 Physical degradation mechanisms

Degradation mechanism means the process of something being damaged or made worse, while deterioration is the fact or process of becoming progressively worse (Ersdal et al., 2019). Several age-related degradation mechanisms may result in changes to the material properties, cracking, or metal loss as a localized or uniform attack. Further, high loads from temperature expansion or contraction, damage from dropped objects or impacts, and quick pressure changes may influence the material capacity of a structure. Geometrical changes of a structure or structural elements may also occur. Table 1 gives examples of age-related degradation mechanisms occurring in ship-shaped offshore structures while in service.

Table 1: Degradation issues in ship-shaped offshore structures (Ersdal et al., 2019).

Floating structure elements	Typical degradation specific for these elements
Hull structural integrity	Fatigue is the most important issue for the main load-bearing structure as it has to withstand the cyclic loading, particularly from waves Corrosion will be a typically problem for the ballast and cargo tanks and external surfaces, usually involving cathodic protection and coating Ship collisions Dropped objects
Watertight integrity Doors, hatches, dampers, etc.	Wear and tear and corrosion
Marine system Ballast, control and cargo system, inert gas system, and marine utilities (pumps, generators, etc.)	Wear and tear and corrosion
Station keeping integrity	Fatigue Wear and tear Corrosion

Corrosion can be of various types, such as localized corrosion or uniform corrosion. Cracking may be caused by fatigue due to dynamic actions arising from environmental phenomena, operation, and other causes, such as high local stress and hard spots. Deck plates of offshore structures may be subjected to impacts due to objects dropped from cranes. Such mechanical damage can result in denting, rupture, and residual stresses or strains due to plastic deformation. In addition, the coating may be damaged, which may lead to corrosion. Mechanical damage may also increase the likelihood of crack initiation. The durability of the protective coating is affected by various parameters (Paik & Thayamballi, 2007).

Ship-shaped structures are especially exposed to fatigue cracks due to cyclic loading and, in some cases, enhanced by residual stresses and fabrication dents. This is caused by the thousands of local details in the hull girder as slots, scallops, lugs, cut-outs, air-holes, penetrations, doubling plates, and bracket toes. Further, traditional double-hull tankers will have considerably more complex load situations when compared to, for example, fixed offshore structures. This is due to local loads on the bottom structure and side shell, such as large internal and external static differential pressure, slamming loads due to wave actions and external dynamic pressure, and variable internal dynamic pressure caused by the motion characteristics of the unit.

In addition, local loads on the transverse bulkheads, longitudinal bulkheads, and inner bottom will include static differential pressures, internal dynamic pressures due to the motion characteristics of the unit, and sloshing loads due to wave actions. Further, the global hull girder dynamic and static response will lead to alternate sagging and hogging condition in the hull girder due to the respective loading condition and wave action, typically in the main tank and bottom structure. Effects from whipping and springing are known to induce cracking and fatigue damage on e.g., bulk carriers. All these stated local and global loads would produce high dynamic stresses in the hotspots of the structural details mentioned above. Structural details that are common for the main loadbearing structure in cargo and ballast tanks that are susceptible to high stresses are often upper- and lower hopper knuckle areas, transverse girder bracket toes, crosstie end connections, stringer bracket toes, and corresponding heel connections. In aggressive weather conditions, even the bulkheads and adjacent plates, bilge keel, deck longitudinal- and side longitudinal connections to transverse frames may be susceptible to fatigue cracks (Halsne et al., 2020).

The larges differences between FPSOs and conventional trading tankers are that FPSOs usually:

- are continuously loading and discharging in a various sea state
- have more global load cycles
- have no possibilities to avoid hostile weather conditions
- the bow of the ship is continually pointing towards the dominating weather
- have a discontinuity on the bottom and/or the main deck due to a moonpool
- have a substantial load that is transferred from the topside, the mooring system, cranes and flare to the hull girder
- repair works are done on situ with unfavorable work conditions, such as poor access and with humid conditions

A conventional trading tanker is traditionally designed for wave statistics based on a 25-year return period, while FPSOs usually are designed for a 100-year return period based on site-specific wave statistics. These differences may give rise to cracks at different locations for FPSOs and trading tankers. Despite that, since the hull structural details are similar, apart from discontinuities in terms of moonpools, cracks are usually expected to arise for the same structural details with some deviations due to the mentioned variations above (Halsne et al., 2020).

2.3 Fatigue

2.3.1 Introduction

Fatigue can be described as cumulative material damage resulting from numerous loading cycles during the service life, causing crack initiation and propagation (Ersdal et al., 2019). Fatigue cracks tend to occur from defects and discontinuities in areas with high stress. A typical example is welded joints with high-stress concentrations. Fatigue failure is usually considered to occur when a through-thickness crack forms.

Fatigue failure is a significant hazard to FPSOs, which is exposed to cyclic loading such as wind and wave loading in harsh environmental conditions.

The primary methods for evaluating fatigue life are the fracture mechanics approach and the $S - N$ approach. These methods used for assessing the fatigue life have considerably developed over the last decades. The $S - N$ approach is an empirical method based on laboratory tests to establish characteristic design curves for the assessment of fatigue life. These design curves have a safety margin to allow for the inherent uncertainty in the test data. Therefore, the design curve is usually derived by the logarithmic mean curve minus two standard deviations (Ersdal et al., 2019). The methods and models used to assess the fatigue stress ranges are also empirical and bring up additional uncertainty into the fatigue assessment.

It is required to have reliable fatigue assessment procedures for the evaluation of the likelihood of fatigue failure. The fatigue assessment should be performed to enable the implementation of suitable control measures. Fatigue safety within the required design life is considered to be reached by:

- Designing structural components with fatigue life's meeting the planned life and allowing for the required design fatigue factor (DFF).
- Fabricating structures with a minimum of defects and discontinuities.
- Having the ability to inspect where and when necessary.
- Having the ability to repair propagated cracks that could affect the overall structural integrity.

In the structural integrity assessment of ageing and life extension of structures, detailed information on the structural condition is a requirement. During the operation of offshore structures, inspections are performed to identify any damage, for example cracking. Negligence in the detection of fatigue damage has caused enormous structural failures. An example of fatigue cracking in a ship is the severe accident in 2002 of MV Prestige, which first was reported as a crack in the side shell and eventually lead to collapse of the structure. This has resulted in a significant effort to develop appropriate fatigue design and assessment methods in the 1980s and 1990s, and this has led to a considerable reduction in the amount of fatigue damage being found. Thus, fatigue failure is an essential consideration throughout the lifecycle of the structure, i.e., during design, fabrication, and service life and hence the integrity management of ageing structures. Application of new methods for the fatigue assessment of existing ageing offshore structures has, in some cases, led to a reduced calculated fatigue life compared to what was initially considered for the structure. However, in many of these cases, there are no indications of early fatigue cracking as predicted by the improved methods. This emphasizes that the methodology of fatigue analysis is not intended to predict precise fatigue life. Still, rather it is intended to ensure that the likelihood of cracks in the design life is reduced to an acceptable level (Ersdal et al., 2019).

2.3.2 Factors influencing fatigue

The key factors influencing fatigue are the following:

- Discontinuities and defects in the material.
- The presence of cyclic loading.
- The operating environment.

Fatigue damage has proven to take place as a result of fabrication defects being present, normally at welds and areas experiencing high-stress concentrations, for example, at geometrical discontinuities. Defects are inherent to the welding process, and thus the crack initiation stage may become shorter in welded connections compared to that in non-welded elements. Welded elements can experience stress concentrations many times greater than the nominal stress, which will lead to cracking in these areas. A high-stress concentration factor (SCF) is particularly occurring in areas such as joints, transitions, supports, connections, and built-in discontinuities (e.g., thickness changes). The fatigue life is also significantly influenced by the operating environment where the material is used. Testing has shown that the fatigue life can be reduced by a factor of at least two unless coating or cathodic protection (CP) as anodes and impressed current cathodic protection (ICCP) is present.

Another important effect is the so-called thickness effect. Increasing the size of a given type of fatigue specimen while maintaining all other parameters will, in general, cause a decrease in fatigue strength (Morgan, 1983). This thickness effect has been quantified as a result of testing large specimens and is now included in the design requirements. It is also vital to notice that the cyclic stress range influences fatigue damage, and fatigue damage is proportional to the cyclic stress range to the third power (Ersdal et al., 2019).

2.3.3 Implications of fatigue damage

The primary consequences of fatigue damage are increased fatigue crack growth, reduced structural strength, increased chance of brittle or ductile fracture, and that water ingress may occur to structural members. As an example, for tubular members, a through-thickness crack can reduce the static strength by 40 % (Stacey et al., 1996). It is particularly important in the management of ageing structures to understand the implications of fatigue failure.

A through-thickness crack may be followed by the severance of structural members and loss of stiffness in the local structure. This will result in load redistribution, which in turn will cause other elements to be more heavily loaded, and fatigue cracking is possible to occur in other locations. Thus, several cracks can occur and, depending on the level of redundancy; the structure may eventually fail.

Hence, as both component strength and fatigue life predictions are affected by the load redistribution (Noordhoek et al., 1987), due consideration must be given in the development of the structural integrity management plan. This due to the possibility of total member failure occurring after penetration of the wall and to its consequences.

The effect of load distribution of fatigue life may cause unexpected failures as the fatigue of intact structures does not account for this load redistribution after fatigue failure. Furthermore, fatigue cracks may also possibly start to initiate and propagate at fabrication defects, which are not necessarily in the assumed areas identified from the structural analysis as being critical. A lack of data on such defects can give an incorrect view of the structural integrity of the installation. This places additional emphasis on the need for an understanding of the system performance.

Structural member failure may not only occur as a result of a fatigue crack but also as a consequence of reduced capacity due to a fatigue crack being subjected to a level of loading, for example, due to ship impact or wave loading. These loads may also result in a local collapse of greater consequence in areas with significant amounts of fatigue cracking. It should be noted that this incident of multiple cracking might occur towards the end of life of a floating structure, and its impact on structural integrity is not usually a part of the assessment of the integrity management of ageing installations (Ersdal et al., 2019). This is an exclusion that can have significant consequences. Fatigue is not restricted to the hull of a floating structure. Essential structural details in ship-shaped structures that are susceptible to fatigue are structural connections with high-stress concentrations placed in areas with localized high dynamic pressures. Relevant details where cracking has been localized are specified in the NORSOK N-005 standard (Standard Norge, 2017), including among others upper and lower hopper knuckles, portions of bulkheads, and frames subjected to concentrated loads, stiffened plates in the side shell, etc.

2.4 Corrosion

2.4.1 Introduction

Ship-shaped units are typically built without a corrosion allowance. Also, a corrosion protection system is usually included in addition to the net scantlings, according to the classification rules from DNV GL (DNV GL, 2019).

Cathodic protection as anodes and impressed currents, in addition to coatings, is used for protection against corrosion. For structural elements, the concern is thickness diminution due to uniform and localized corrosion affecting both fatigue resistance, strength, and buckling. Marine systems are also exposed to galvanic corrosion, which may lead to leakage (Halsne et al., 2020).

A typical strength degradation phenomenon on offshore installations is corrosion, generally accounted for as uniform corrosion wastage. Studies conducted by (Paik & Thayamballi, 2007) show corrosion rates ranging from 0.01 mm/year to 0.3 mm/year for general corrosion dependent on location in tanks, temperature, and fluid medium. Corrosion wastage increases nominal stresses and hence, induces earlier fatigue failure, as well as reduces ultimate strength capacity. Corrosion damage is not commonly treated as a failure criterion in itself, but if corrosion allowance is exceeded, the component is to be replaced. During the design stage, the effect of corrosion is dealt with by specifying a coating, cathodic protection, and a corrosion allowance on the plate thickness. FPSOs follow usual ship practice and receive a given corrosion supplement on the plate thickness. However, during the service life of FPSOs, the corrosion protection system is prone to fail after some time in operation. Hence, its adverse effects on the ship's hull strength are to be explicitly considered, especially if its service life is extended.

Corrosion is defined as a chemical or electrochemical reaction between a metal and its environment, which may lead to deterioration of materials and its properties. There are some underlying conditions needed to be fulfilled to corrosion to occur:

- The potential damaging environment acts on a metal surface (e.g., bare steel in physical contact with the environment)
- An oxidant available to cause corrosion (e.g., oxygen, CO_2)
- A suitable electrolyte available to conduct an electrical current (e.g., seawater containing ions)

However, no corrosion can occur if some of these conditions are not present. show corrosion rates ranging from 0.01 mm/year to 0.3 mm/year for general corrosion dependent on location in tanks, temperature, and fluid medium. Corrosion wastage increases nominal stresses and hence, induces earlier fatigue failure, as well as reduces ultimate strength capacity. Corrosion damage is not commonly treated as a failure criterion in itself, but if corrosion allowance is exceeded, the component is to be replaced. During the design stage, the effect of corrosion is dealt with by specifying a coating, cathodic protection, and a corrosion allowance on the plate thickness. FPSOs follow usual ship practice and receive a given corrosion supplement on the plate thickness. However, during the service life of FPSOs, the corrosion protection system is prone to fail after some time in operation. Hence, its adverse effects on the ship's hull strength are to be explicitly considered, especially if its service life is extended.

summarizes the main corrosion mechanisms present in an offshore environment on structures, elements, and equipment subsea (Ersdal et al., 2019).

Table 2: Main corrosion mechanisms present in an offshore environment (Ersdal et al., 2019).

Corrosion mechanism	Chemical environment
O_2 corrosion	$2FE + H_2O + \frac{3}{2}O_2 = 2FeO(OH)$ (rust)
CO_2 corrosion	$Fe + H_2O + CO_2 = FeCO_3 + H_2$
Microbiologically induced corrosion (MIC)	$Fe + (\text{bacteria related oxidant}) \rightarrow Fe^{2+}$

2.4.2 External Corrosion

External corrosion of, for example, steels may occur in seawater, where absorbed oxygen results in loss of material and reduced load-carrying capacity. The rate of corrosion is influenced by the temperature of the seawater and the level of oxygen. The seawater in the North Sea is usually saturated with oxygen at a level of approximately 6 ml l^{-1}. External corrosion can be potentially be mitigated by using a corrosion protection system and, in some cases, by the use of corrosion coatings. The design life of the equipment is dependent on the design life of the CP system and the type of quality of the external coating system. Levels of CP is recommended to be around -850 mV Ag/AgCl (DNV GL, 2015). If the level of protection becomes more negative, then the overprotection may result in initiation and propagation of hydrogen with adverse effects on the steels. It can be seen that high strength steels are more susceptible to this overprotection, and more stringent requirements are recommended for the level of CP (HSE, 2003). Furthermore, shielding can lead to limitations in the efficiency of the CP system, for example, in areas where anode placement is difficult. Although the assumption that CP protection is effective, there should be limited loss of material due to external corrosion. However, the CP system is not effective in the splash zone, and alternative protection is required in these areas, such as coatings, plus a corrosion allowance. A variety of coating systems have been used offshore, and epoxy-based systems have become more widely used (Ersdal et al., 2019).

2.4.3 Different types of corrosion

*2.4.3.*1 CO_2 *Corrosion*

$\mathrm{CO_2}$ corrosion is a type of corrosion that may arise in carbon steels. The rate of which corrosion develops is dependent on factors as temperature, flow regime, the partial pressure of $\mathrm{CO_2}$ and the pH of the water in the field. Corrosion is a time-dependent degradation mechanism and is this type of corrosion is usually localized as pitting, and it can be managed by the use of inhibitors and by pH stabilization of the pressure field. This is generally applied to pipelines.

2.4.3.2 Environmental Cracking due to H_2S

Environmental cracking due to H_2S is generally caused by the presence of bacteria activity or by drill cuttings, and this is associated with sulfide stress cracking (SSC). Carbon steel is susceptible to SSC. The presence of SSC is influenced by several factors such as the total tensile stress, the partial pressure of H_2S, chloride ion concentration, and the presence of another oxidant. There is a critical partial pressure of H_2S, and SSC is not expected to occur below this limit. Although, for partial pressures above this limit, there is an increasing likelihood for SSC and the environmental condition in this situation is called "sour". The resulting failure mode of SSC is cracking and may be abrupt. Materials that are susceptible to SSC have a higher chance of experiencing environmental cracking in the production stage, and it is controlled by the specification of the material properties (particularly hardness) and the manufacturing process. Further, ageing installations have a higher likelihood of souring of the wells (the produced amount of H_2S increases), and the production environment is then changing from sweet to sour. This may, in turn, lead to a higher probability for environmental cracking, which is influenced by the material properties and the ability to change service conditions.

2.4.3.3 Microbiologically Induced Corrosion

Microbiologically induced corrosion (MIC) is a type of degradation that may occur in environments with metabolic activities of bacteria. These types of bacteria are called sulfate-reducing bacteria (SRB), and it has turned out as the most aggressive microorganisms that intensify the corrosion of steel. It can accumulate the corrosion process due to the conditions that apply, already have elements of corrosion cells. SRB live in oxygen-free environments, making use of sulfate ions in the seawater as a source of oxygen. Further, H_2S is produced as a waste product from the SRB, creating a local corrosive environment in connection with the bacteria. MIC has been observed on steel buried with seabed sediments. The likelihood of MIC occurring is difficult to predict as it depends on the availability of nutrients, local flow conditions, and water temperature (Ersdal et al., 2019).

2.4.4 Corrosion in the hull structure

The integrity of floating offshore structures is dependent on the intact hull, and ballast tanks and corrosion are one of the main concerns regarding this. Ballast tanks are especially susceptible to corrosion as seawater is used for ballast purposes. Corrosion protection systems are generally used to limit extent of corrosion, either by CP or by coatings or by a combination of both. Relevant survey requirements are listed in "DNV GL Fleet in Service" (DNV GL, 2018). Also, systematic thickness measurements need to be carried out at renewal surveys and inspection of the corrosion protection system to establish its effectiveness. For critical areas, a detection system is recommended to establish any water ingress as a result of corrosion or cracking.

Further, both design and survey requirements for corrosion protection systems are listed in "DNV GL Corrosion protection of floating production and storage units" (DNV GL, 2015). Also, the document states that it is a challenge to provide more than 10 years' service life for the corrosion protection of an FPSO. While more traditional vessels dock every five years for detailed inspection and repair, an FPSO will be in continuous operation for its service life. Hence, it is needed to develop an improved specification for the corrosion protection of an FPSO with a service life of 10 years or longer. This should be based on experience for the corrosion protection of fixed offshore structures with design life's exceeding 25 years. A case for life extension would need evidence of the continuing performance of relevant CP systems and coatings protecting against corrosion, as well as evidence of thickness measurements of critical areas.

Ballast tanks are significantly susceptible to corrosion, particularly at locations where the use of anodes cannot provide the required protection. Oil tanks are also vulnerable to corrosion, particularly if the oil has a low pH value. This tends to form pitting corrosion at the bottom of a tank. If inert gas from oil production is used (with potential sulfide content), corrosion may also be a problem for the deck level. Hence, corrosion protection in the form of anodes and coating is crucial in such areas (Ersdal et al., 2019).

2.5 Load changes

A physical ageing mechanism affecting the safety of the structure directly are changes in loads on the structure. The addition of modules and modifications and more equipment are typical examples of such load changes. Further, the wind and wave loading on structures also change and need to be considered in structural integrity management and particularly in life extension assessments. The wind loading will typically change as a result of a change in wind area, for example, as modules are added. Wave loads will vary due to increased marine growth with time, and as a result of the addition of structural parts, conductors, risers, and caissons in the wave affected zone. Wave in deck will dramatically increase the wave loading on the structure. Changes to wave loading have also increased due to new knowledge in wave height statistics, updated understanding of slamming pressures from waves, and new knowledge about wave kinematics. Global warming may influence the wind and wave climate and hence influence the loading on the structures (Ersdal et al., 2019). The loading of the ship may be controlled by an inclining experiment to determine the stability and coordinates of its center of gravity. Such an experiment is applied to vessels altered in ways that could affect stability.

2.6 Deflection, dents, and other geometrical changes

Structures are susceptible to damage during service, mainly from dropped objects, ship collisions, or extreme weather. Impact from swinging loads or dropped objects during lifts by cranes and similar devices also constitutes a hazard scenario for floating structures. These damages are in the form of bows or dents, and sometimes these are associated with cracks. Such dents have a significant influence on member buckling capacity and the static capacity of beams, tubular joints, and stiffened plates.

A periodic inspection will identify some of this damage, and some of these will be repaired. However, it has been shown that a significant amount of the damage will remain either undiscovered or unrepaired. During the structure’s lifetime, multiple damage sites could build up to an extent where collectively, they may weaken a structural member.

Surveys of data on bows and dents have shown, as indicated in (HSE, 1999) that dents found during inspection are up to 300 mm in depth, but more typically dents are in the range of 10 mm to 60 mm in depth. Some of these are associated with bows, which can be quite large, up to 500 mm in magnitude. More serious bows and dents may be related to cracking dependent on the local stress magnitude, which can result in fatigue cracking. This will, in turn, require specific monitoring and possible repair.

The structural effect of bows and dents on strength has been investigated both through modeling and physical tests. ISO 19902 (ISO 2007) contains a section of the effect of dents and tubular members. Equations are given for the effect on strength and stability for dented members subjected independently to axial compression, axial tension, shear or bending. (HSE, 1999) identified threshold levels of bow and dent damage as follows:

- Dent damage of 12.5 mm when an incident that is likely to cause damage is known to have taken place.
- Dent damage of 38 mm in the absence of an alert of an incident. Such damage could be detected by a general visual inspection (GVI) survey provided that marine growth has not occurred to be obscure the dent.
- Bow damage of 130 mm following an immediate response to a known incident.
- Bow damage of 350 mm when a routine inspection is being carried out.

For floating skip-shaped offshore structures, longitudinals in side shells can be twisted or bent as a result of local impact leading to local reduced structural capacity. A twisted or bent ring stiffener or girder will reduce the global buckling capacity of the column.

In ageing structures, accidental damage can accumulate, and the combined effect of multiple bows and dents can reduce the resistance of the structure significantly (Ersdal et al., 2019). Table 3 shows the reasons for structural damage in FPSO structures.

Table 3: Causes of structural damages in FPSO structures (Paik & Thayamballi, 2007).

Damage	Cause
Bow damage	Inadequate structural design and inadequate consideration of environmental loadings
Caisson damage	Improper material selection
Flare damage	Inadequate structural design and inadequate consideration of environmental loadings
Tank damage	Inadequate consideration of environmental loadings or errors in design process; unsatisfactory construction techniques; site-specific loadings not anticipated in design process
Breakdown of coating systems	Poor surface preparation, application, and/or selection
Swivel damage	Use of new technology

3. Hull Structural Integrity Management

3.1 Introduction

In engineering terms, integrity is defined as the state of being whole and undivided, the condition of being unified or sound in construction. Structural Integrity Management (SIM) is a key process in ensuring the safety of offshore structures. The purpose of SIM is to identify changes, evaluate the impact of these changes, mitigate the impact of these changes found necessary with the aim of keeping the structure sufficiently safe during operation and use (Ersdal et al., 2019).

A successful way of managing ageing and life extension requires that competent personnel with an understanding of the issues take effective actions to enable the FPSO to continue to function safely for its required service life. It is essential that personnel, which is substantial for management, operation, inspection, maintenance, and ensuring the integrity of plant and equipment should have a demonstrable understanding of the systems, their ageing mechanisms and mitigation measures. Basic system training of technical and professional qualifications should be supplemented when necessary to ensure a detailed understanding of how the distinct systems work, and to be able to identify critical elements and ageing mechanisms.

The operating companies of the FPSOs should:

- Identify the systems which contribute to the continuing operation of the asset
- Understand the failure modes of each system and its components
- Regularly review failure modes and consequence analysis to identify changes and refresh understanding within the organization
- Create operational procedures and maintenance strategies which can prevent or reduce the risk of failure
- Identify and have in place contingency plans which can limit the consequence of failure

The first step to get an understanding of the ALE of systems and components is the original design specification, the operating procedures, and management of change. Safety regulations require that safety-critical elements are initially suitable and remain suitable throughout the entire life of the FPSO regardless of any life extension requirements. Actions taken in the early stages of the life cycle of the systems will have a large impact on the feasibility of life extension. Also, these actions will have a huge impact on the understanding of how the systems will deteriorate over time, the use of the systems, and how to mitigate the risks. Frequent record keeping will help ensure that knowledge can be assessed by studies or assessments required to support life extension strategies. Examination of inspection, maintenance, and operation records will provide an understanding of the rate of deterioration and the level of intervention that has historically been necessary to maintain operations. It is known that knowledge of the personnel should also be gathered. Often local knowledge is only used on a daily basis to maintain operations. This is an unfavorable practice when knowing that fully documented knowledge may be essential in understanding the vulnerabilities of systems.

The importance of having a clear understanding of the likelihood of deterioration and its consequences is large, as typical shipbuilding techniques result in the same details being repaired in hundreds of locations. Even though issues identified in inspections may be minor, the cumulative effect of a large number of these observations may be that it is difficult to manage, monitor, and remedy the total number of these.

3.2 The process of floating systems integrity management

The purpose of floating systems integrity management (FSIM) is to ensure a proactive process for demonstrating the integrity of an FPSO throughout its life on a fitness-for-service basis. This involves the collection of information of the FPSO, periodically evaluating the data, and using the evaluation to set a strategy for subsequent inspection and maintenance plans. FSIM consists of the continuous process, as illustrated in Figure 4.

DATA	EVALUATION	STRATEGY	PROGRAM
Managed system for the archival and retrieval of IM data and other pertinent records	Evaluation of the mechanical integrity and fitness for service; development of remedial actions	Overall inspection philosophy, strategy, and criteria for in-service inspection	Detailed work scope for inspection activities and offshore execution

Figure 4: FSIM process (API, 2019).

The FSIM process is intended to be applied from the installation phase through to decommissioning to:

- understand, communicate, and manage the in-service structural risk;
- manage the effects of deterioration, damage, changes in loading and accidental overloading;
- establish the framework for inspection planning, maintenance, and/or repair; and
- demonstrate that the FPSO is fit-for-service.

The implementation of the FSIM process provides a method for managing the ageing mechanisms, which may reduce the intended function or capacity of an FPSO. The FSIM process is based on risk principles. It provides owners a framework for developing, implementing, and using engineering, inspection, maintenance, monitoring, and remediation activities to validate the fitness-for-service of an FPSO for its intended application throughout its service life. The FSIM approach varies depending on factors as field life, type of FPSO, and the sophistication of regional infrastructure in which the FPSO is located. These factors will, in turn, influence the philosophical approach to FSIM, which varies from one involving an emphasis on the use of monitoring equipment to one with a preference for the extensive use of inspections. The implementation of the FSIM process demonstrates that the system risk of the ship is understood and that this FSIM process is used to prevent and/or mitigate incidents that could result in safety, economic, or environmental consequences to the operator company of the ship.

Choices made in the design phase as the selection of materials, design margins, new or proven technology, condition monitoring systems, redundancy, the robustness of design, and fabrication/installation methods, will have influence FSIM activities during the operations period. Implementation of an FSIM process may also benefit from design decisions, such as providing access for inspection and maintenance. Initial FSIM development begins as part of the FPSO design or convention, ideally during the concept and select stages.

The FSIM process is intended to be used for the development of an inspection and monitoring program, including scope and frequency, that can provide additional data on the condition of the FPSO. The collected data can be applied to understand present and emerging risks from operating the ship and may also provide data for determining the ongoing strategy for mitigating emerging risks. A well-implemented FSIM process can provide evidence that the FPSO remains fit- for-service for the operational life of the ship and through to decommissioning.

The FPSOs operating team managing the implementation of the FSIM strategies and maintaining the FSIM information should confirm that the FPSO project team has provided the design and commissioning information. Also, the FPSO operating team should confirm that the project developed FSIM strategies can be implemented. This means that the risks are identified, tools/equipment and resources are available, and that regional regulations have been adhered to. Throughout the service life of the FPSO, new data are collected through scheduled maintenance, monitoring activities, results of accidental events, surveys planned. Planned changes, for example, modifications or additions, may also appear to the floating system. As new data are obtained, the data are subject to engineering assessment to validate fitness-for-service. Based on the assessment, adjustments to the strategy plans and program work scopes can be required to confirm fitness-for-service and maintain the floating system's integrity.

3.3 SIM in Life Extension

Historically, SIM in life extension has been handled as a part of the ongoing maintenance routine for operational installations without formal recognition as an explicit activity. However, after initiatives from regulators such as PSA, more attention has been placed on structures in life extension. It usually is a requirement in regulations and standards that foreseeable structural damage, escalation potentials, and all likely scenarios have to be considered. This would include the identification of degradation and deterioration to be a part of the SIM system and associated strategy.

An essential requirement in the assessment of structural integrity of ageing offshore structures and life extension is the availability of detailed information from inspections. It is necessary to get information from both the fabrication stage as well as during the operational phase. Unfortunately, the entire inspection history is not always possible to obtain.

Structural assessment is an ongoing process to ensure that the basis for demonstrating the integrity of the structure and for confirming that the associated risk level is still valid. The outcome of this evaluation and possibly additional assessments, and the effects of the subsequent control measures, have to be taken into consideration and further applied in updating the SIM strategy. The process of SIM requires that a large amount of information is collected and stored. To this association, operators usually have computerized systems in place. Although, in some cases, information on older structures has disappeared, e.g., following changes in ownerships. This lack of information needs to be carefully treated at the assessment stage and possibly the use of higher safety factors in the analysis. A modern SIM strategy relating to life extension is presented in Table 4.

Table 4: SIM processes and issues relating to life extension of structures (Ersdal et al., 2019).

SIM process	Primary issues relating to life extension
SIM strategy	The strategy should include managing the approach to assessing ageing processes and the need to link surveillance and inspection requirements to these
Surveillance program	More detailed surveillance and inspection may be required if a period of life extension is to be justified
Structural evaluation	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)
Information management	This may be influenced by loss of key data from original design, construction, installation and early operational inspections

3.4 Implementation of SIM for the hull structure

3.4.1 Internal hull

Inspection frequencies and examination methods should be based on component criticality. GVI should be performed in the following areas (API, 2019):

- machinery spaces, such as a pump or engine rooms
- tank spaces, inner shell, life-saving equipment

A more detailed survey of the internal hull structure may be carried out on a specified periodic cycle or on a continuous cycle where a particular percentage of the components in the hull is inspected annually such that over a specified period, all compartments are inspected.

Specific locations and examination methods should be based on the developed inspection plan. Typical structures and systems that should be included in a more detailed internal hull survey are as follows (API, 2019):

- special areas (i.e., structural critical inspection point [SCIP] and special areas of interest [SAI]);
- manway hatches, bolts, and coamings;
- interior walkways, stairs, and handrails;
- interior surfaces of primary load-bearing structures, including hull plating, transverse and radial frames, and longitudinal and vertical stiffeners;
- internal backup structure (e.g., fairlead, riser porches, caisson supports);
- condition of coatings and anodes;
- equipment function testing (e.g., ballast pumps, leak detection systems);
- piping, valves, and conduit and associated supports and compartment penetrations;
- pump and engine foundations.

3.4.2 External hull above water

The external hull structure and systems above the waterline should be inspected to provide information on possible gross damage or deterioration that may have influence the intended function of the systems or the ship. This survey normally includes the above water external structures and systems, including the hull, moorings attachments, and appurtenances. The method of inspection usually consists of GVI and function checks, etc.

Typical activities included for the above water external hull is as follows (API, 2019):

- hull deck exterior;
- inspection of walkways, ladders, stairs, and handrails to confirm items provide adequate support and protective barriers to personnel;
- inspection of hull penetrations, including hatches, manholes, vent pipes, and sounding tubes on deck and in the deck box (if applicable) to confirm watertight/weathertight integrity of hull;
- condition of external coatings;
- inspection of on-vessel mooring components (e.g., chain jacks, chain stoppers, mooring lines) above the waterline, if visible;
- hull outer shell (above water);
- inspection of the external hull above the waterline, looking for signs of coating deterioration, corrosion, or damage;
- inspection of mooring system support structures;
- inspection of hull appurtenances (e.g., hard pipes, caissons, and associated connections above the waterline on the hull exterior);
- inspection of walkways, ladders, stairs, handrails, and boat landings to confirm items provide adequate support and protective barriers to personnel;
- confirm hull markings (e.g., draft markings) that are visible.

3.4.3 External hull below water

External hull surveys below the water should be performed on the submerged areas of the hull. The surveys should include below water structures and any SCIPs and SAIs. Also, external marine systems components and the mooring system hull attachments or tendon system should be included within the survey. This should consist of steering, propulsion, and sea chests, as applicable. External hull surveys are executed to assess the extent of marine growth and to confirm that the corrosion protection system on the external hull is functioning adequately.

The external hull surveys may be performed on a continuous cycle where a particular percentage of the hull is inspected at a time such that all accessible structures are inspected over a specified period. Another option is to inspect the entire hull on a specified periodic cycle. Additionally, inspection cycles may incorporate different examination methods and techniques. For example, a GVI of the entire hull with ROV at a defined interval and more detailed inspection techniques of critical locations with diver and ROV on an alternating schedule.

Defined locations and examination methods should be based on the developed inspection plan. Typical structures and systems that should be included in the underwater survey are as follows:

- accessible hull exterior surfaces and appurtenances below the waterline (e.g., caissons, hard piping, and their associated external guards, clamps, and standoff supports);
- structural bracing and associated connections;
- external mooring/tendon system to hull connections (e.g., fairleads, tendon porches);
- riser and umbilical porch structures and I-tubes;
- sea chests and hull penetrations;
- special areas (i.e., SCIPs and SAIs);
- propulsion and steering, as applicable (e.g., rudder, propeller, thruster);
- corrosion protection system (e.g., coating, anode, and impressed current system);
- hull markings (API, 2019).

3.4.4 Requirements for hull structure

Table **5** specifies the minimum requirements for the type and frequency of inspection for the hull structural components of floating systems. The intervals and extent of weld inspections required for special areas should be established on the basis that there is adequate time to detect and repair any potentially critical structural defect allowing for the lead times inherent in detecting such defects and effecting their repair.

Table 5: Default Inspection Program: Minimum Inspection Requirements for Structural Components (API, 2019).

Component	Location	GVI		CV I		UTT		WI	
		I years	*E* %	*I* years	*E* %	*I* years	*E* %	*I* years	*E* %
Exterior structure [a]	Atmospheric	1	100	—	—	—	—	—	—
	Splash zone above water line	1	100	—	—	—	—	—	—
	Splash zone below water line and submerged	2.5	100	—	—	—	—	—	—
	Special areas	—	—	2.5	100	—	—	2.5	50
Interior structure [a]	Ballast tanks [b]	1	20	5	—	15 [c]	—	—	—
	Slop tanks	2.5	50	—	—	5	—	—	—
	Oil storage cargo tanks	2.5	50	2.5	50 [d]	5	—		—
	Storage tanks exterior (fuel oil, potable water, lubrication oil)	5	100	—	—	—	—	—	—
	Storage tanks interior (fuel oil, potable water, lubrication oil)	15	100	—	—	—	—	—	—
	Void spaces	5	100	—	—	5 [e]	—	—	—
	Machinery spaces	1	100	—	—	1 [e]	—	—	—
	Special areas	—	—	1	100	—	—	2.5	50
CP system	External	—	—	2.5	—	2.5 [f]	—	—	—
	Internal	—	—	5	—	—	—	—	—
Other	Showing substantial corrosion	To be determined by engineering assessment							

I: inspection interval (in years)

E: extent (percentage) of inspection

GVI: general visual inspection

CVI: close visual inspection

UTT: ultrasonic thickness testing

WI: weld inspection to include crack detection methods such as GVI, CVI, MT, PT, and UT

NOTE The extent applies to the total number of components, e.g. tanks.

[a] Including girders, stiffeners, plating, attachments, appurtenances, openings, penetrations, vents, and pipes.

[b] Ballast tanks are assumed to have a suitable hard coating.

[c] More frequent intervals can be required where the coating breakdown is found.

[d] One transverse section and adjacent frames (different ones at successive inspections) plus one transverse bulkhead together with adjacent transverse section and frame (opposite tank ends at successive inspections).

[e] At the discretion of owner.

[f] Measure cathodic potential readings and check for fouling/damage.

3.5 Cathodic protection system

Table 6 shows the cathodic protection systems, which is crucial to resist the constant threat of corrosion, leading to a reduction of structural strength. Experience has shown that typical and well-applied paint systems have a useful lifespan of 10-15 years.

When new FPSOs are to be built, the main decisions are taken, considering corrosion allowances needed to be carefully addressed and understood by the operating companies. For some elements, reduction in steel thickness can be made placing a more extensive reliance on the coating system to prevent corrosion, and in other cases, additional margins are applied to the steel at specified elements. It is essential to fully understand these historical specifications for corrosion allowance and coating in addition to actual data when assessing acceptable levels of corrosion. The building specification generally provides only limited generic information regarding standards of surface preparation and coating application standards for both the internal and external hull.

For the underwater external hull, sacrificial anodes and Impressed Current Cathodic Protection (ICCP) systems are used as a corrosion protection system. The examination method used in situ is typically visual inspection performed by ROV or divers to establish the condition of the external hull cathodic protection systems and coatings. However, the buildup of marine growth often disturbs the inspection process. The potential difference of the hull can successfully be established by undertaking “drop cell” surveys. It can be measured by a survey from onboard the FPSO. Survey findings of this type can effectively be developed into a numerical model where it is possible over time to monitor the effectiveness of the hull coatings, sacrificial anodes, and ICCP system. Further, it is recommended that the external cathodic protection systems and external hull coatings are a part of the hull structural integrity management program and detailed inspection scopes included for the external hull survey performed by either an ROV or a diver.

The internal hull is influenced by different factors and ageing mechanisms. Several operator companies have discovered issues with the failure of coatings in the way of erection joints, especially in the form of cargo tank boundaries when cargo has been stored at elevated temperatures $(> 60°C)$. It is recommended that clear criteria for reporting the condition of coatings and cathodic protection systems and coating inspection are incorporated into the hull structural integrity management strategy and inspections performed to gain a better understanding of the condition of hull coatings. To get an understanding of the efficiency of existing tank cathodic production systems, it is recommended that existing anode designs should be reviewed in compliance with the requirements of an established code. This is to identify if there are any deficiencies in the current distribution and sizing of anodes mounted in cargo and ballast tanks.

Table 6: Cathodic protection systems (Stobo et al., 2014).

Element	Ageing mechanisms	Controls	Life extension actions
External hull	Impact damage Marine Growth Anode depletion Structural behavior Coating disbondment	Anti-fouling Inspection and assessment ICCP testing Anode surveys	Corrosion threat assessment Anode renewal Evaluate ICCP system performance using inspection findings and review operating procedures
Internal hull	Traffic and impact damage Erosion Coating disbondment Change of tank service/maximum water levels Increase in service temperature Scale/sludge build up	Coating inspections Anode surveys Tank washing Demucking	Corrosion threat assessment Anode renewal Review coating suitability for current service, operating philosophy Coating repair/renewal procedures

Over time, maintenance and repair of the coating system will be needed for ageing hull structures. It will be beneficial for the operator companies if they have in place coating repair procedures and an understanding of the work scope required for safely executing such repairs. If considered necessary to perform a full coating replacement in a tank, then implications of such work have to be fully understood in regards to personnel on board (POB), access, ventilation, number of personnel working in a confined space, egress, deck space and supporting equipment specifications, etc. (Stobo et al., 2014).

3.6 Inspection practices for ageing ship-shaped offshore installations

3.6.1 Introduction

Inspection is an essential activity in maintaining the safety of structures in operation, both to detect any defects and in reducing uncertainty about their current state. The methods, acceptance criteria and frequencies applied when conducting inspection can have a large impact on the structural integrity of the offshore units. Inspection can be defined as an activity performed during the service life of a functioning structural unit to help detect and evaluate deterioration in the structural components or equipment by visual, electronic, or other means (Paik & Thayamballi, 2007).

It has been found that almost all notable and expensive failures on FPSOs can be attributed to various mostly addressable and detectable causes. Inspection of fatigue cracks is generally undertaken by visual inspection in the first instance. NDT methods as magnetic particle technique or ultrasonic inspection are useful for the focused examination of selected fatigue-prone and high-stressed areas and to better assess the size of defects. However, it is crucial to have in mind that no matter which method is applied, the probability of sizing or detection depends on the access, general visibility, crack size, inspector training, surface condition, and various other parameters. Inspection for corrosion, including pitting, is usually performed visually, followed by thickness measurements in selected areas using ultrasonic thickness gauging. In essence, destructive methods such as cutting and drilling may be used to get more accurate measurements, but this is not convenient except if studying of material which has been removed from the structure either by investigations or accidents.

3.6.2 The inspection process

Several inspection standards as ISO 2394 ISO 2394 (ISO, 1998) ISO 19901-9 (ISO, 2017) and ISO 19902 (ISO, 2007) specifies requirements for SIM, which involves a process cycle for inspections, as indicated in Figure 5.

The process in Figure 5 is a cycle for inspection planning, performance, reporting, and evaluation, including:

- Collection and retention of data from present and previous inspections, in addition to data from design, fabrication, and installation.
- Evaluation of findings and anomalies in the data (e.g., cracks, corrosion, changes in loading, standards, and knowledge, etc.).
- Update on the long-term inspection program based on the evaluation of the data, which contains an overall plan for what needs to be inspected, when, and how.
- The development of an inspection work scope which contains the detailed specification for inspection activities and the means of offshore execution and procedures for reporting data.

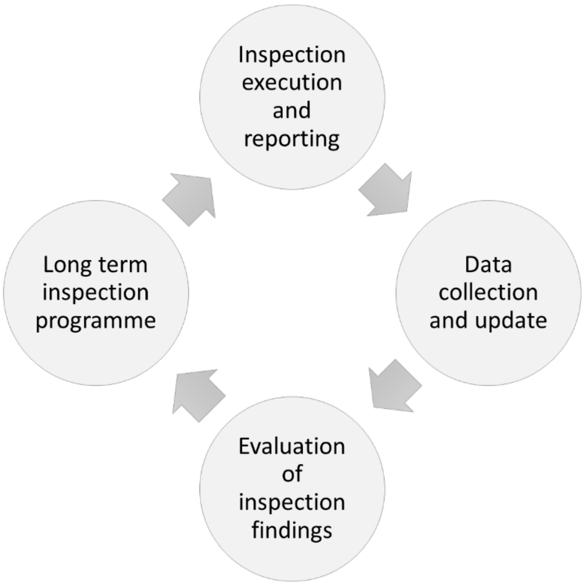


Figure 5: Inspection process cycle (ISO, 2007).

For ageing offshore installations, the periodic, special, and unscheduled inspections are dominant, with the expectation that the frequency of periodic inspection increases. Several standards provide relevant information about the inspection of floating structures. In particular, these are API RP 2FSIM (API, 2019) the NORSOK N-005 (Standard Norge, 2017) and NORSOK N-006 (Standard Norge, 2015).

3.6.3 Inspection

During the operation of offshore structures, inspection is performed to identify any damage and degradation, for example, cracking, particularly in welded joints. Several techniques are available for inspection of a structure. These techniques have been developed over many years. Inspecting plays an essential role in reducing uncertainty in the current state of the structure. An example of reducing uncertainty would be to use inspections to verify results from, for example, fatigue analysis of the structure. However, there are uncertainties associated with inspection results and fatigue analysis, which is vital in developing confidence in the actual structure. The identification of defects is reducing the uncertainty, and the resulting fatigue analysis taking determined from the inspection results will give more confidence in the actual structure.

Furthermore, it should be noted that there are also uncertainties associated with the inspection results, regarding the reliability of the inspection. An inspection will not identify cracks smaller than a certain length, dependent on the conditions in which the inspection is performed and the method used for inspection. The capacity of detection for different inspection methods is described as a function of the condition and the defect size and is illustrated by a probability of detection (POD) curve. As an example, DNV GL-RP-C210 (DNVGL, 2015) indicates that there is a 90 % probability of detecting a 12 mm deep crack underwater by magnetic particle inspection (MPI) and alternating current field measurement (ACFM). Also, there is a 90 % probability of detecting a 350-400 mm crack length by close visual inspection (CVI) under challenging conditions (underwater would typically fall into this category). These factors are influenced by the skill of the operator. The POD curves are developed from data based on information gathered from many operators.

Inspection is often employed in a broader sense than just control the condition of the structure. In ISO 19901-9 (ISO, 2017) inspection is defined as all survey activities with the purpose of collecting the necessary data required for evaluating the integrity of the structure. The inspection would then, in addition to surveying the actual condition of the structure, also include surveillance of configuration, information, loads, knowledge, regulation, standards, and other changes that affect the structure.

Regular inspections are a regulatory requirement in most countries with offshore structures. In Norway, the Norwegian Petroleum Directorate (NPD) issued guidelines for the inspection of primary and secondary structures in 1976. These required an initial inspection (first-year inspection) and subsequent annual inspections. Further, there was a four-yearly condition evaluation to procedure a summary of the results from inspections and potential analysis of findings from these to derive updates to the framework inspection program. Similar requirements have been maintained in the Norwegian regulations, both in the 1992 update of the NPD regulation and in the NORSOK N-005 standard that replaced this regulation in 1997. However, the requirement of a four-yearly update of the long-term framework inspection program was relaxed in NORSOK N-005, and the update of this program was left to the operator to perform inspections when necessary.

Structural inspection tasks for floating structures cover the inspection of the hull for cracks and corrosion concerning the watertight integrity and assessment of the integrity of the mooring system are also included. For the topside structural condition, inspection for cracks in support members and welded connections are required, as well as checking for corrosion, which may be difficult if cladding is present. Competence in both the management of inspections and understanding them in the field is essential to ensure the integrity of a structure (Ersdal et al., 2019).

The concept of inspection planning can be divided into either deterministic or probabilistic approaches. In both approaches, one determines the inspection interval so that the next inspection must be carried out before the largest undetected defect reaches a “critical” size. For the probable approach, explicit limitation of consequences to an allowable level of risk is part of the analysis. In the deterministic approach, lower bound capacity and upper bounded demand parameters are applied together with a deterministic safety factor to achieve a similar goal. However, it is usually more pessimistic due to the nature of the assumptions made. The explicit consideration of variability in parameters, including the probability of detection is what makes probabilistic approaches more powerful but flexible enough to be better tailored to the particular circumstances at hand. Both approaches will generally contain information about fracture mechanics analysis and crack growth calculations, for example, related to critical crack sizes.

Various inspection intervals can be set on different systems or components in question through such approaches. Risk-based inspection methods, involving reliability-based methods, permit one to determine cost-effective inspection alternatives better and, at the same time, keeping the risk below an acceptable level. Even though the risk-based inspection method is the most desirable to use, this method is challenging to use because the output of the risk-based approach is sensitive to the risk-assessment values that are quite subjective. However, the traditionally rule-based inspection approach is inflexible. For such situations, an intermediate strategy can be applied as follows:

- Initial examination and response to the developments of inspection schemes may be largely driven by generic recommendations, learning from a large fleet, and pooling experience, bringing in consistent practice from outside areas, it could be from trading tankers or FPSOs under varying circumstances, and in various regions.
- The subsequent particularization of strategies and tactics would be driven more directly by vessel-specific experience.
- Analysis and modeling would be aimed at identifying on a rational basis the required inspection and maintenance.

(Paik & Thayamballi, 2007).

3.7 Methods for damage examination on FPSOs

3.7.1 Introduction

Nondestructive examination (NDE) methods are typically used for the detection and measurements of defects and deterioration in marine structures; however, their actual application may depend on a surveyor's experience and motivation, vessel type, and condition, and the environment around the structure.

Table 7 describes several methods that can be used for age-related detection and measurements. In the following sections, various methods for detecting and measuring are presented (Paik & Thayamballi, 2007).

Table 7: Methods for examining defects and deterioration (Paik & Thayamballi, 2007).

	Type of defect/deterioration			
Method of examination	Corrosion	Cracks	Mechanical Damage	Remarks
Visual detection Close-up detection	√	√	√	Small equipment such as hammer, flash, caliper, and measuring tape are needed.
Leak or pressure tests	√	√		Pit corrosion and small cracks can be detected.
Dye-penetrants, chemical sensors		√		Affected by cleanliness.
Ultrasonic tests	√	√		Time consuming and requires operator skill like all other methods.
Magnetic particle		√		Only for magnetic materials; only (sub)surface defects are detected.
Electro-magnetic field techniques		√		Surface and subsurface cracks at weld seams, heat-treatment variations, steel thickness, coating thickness, crack depth
Radiometry (X-ray)		√		Danger of radiation; specialized expertise needed.

3.7.2 Corrosion Wastage Examination

In terms of evaluation of corrosion wastage, the following parameters are to be detected and measured: average remaining thickness, minimum thickness, and maximum pit depth or pit intensity as a percentage of the plate surface. Currently, the parameters considered as primary parameters are the average remaining thickness and maximum pit depth, while the trend is now towards a more quantitative definition of corrosion intensity. The examination methods, visual or close-up detection, is a primary method to detect corrosion wastage, but it is, to a large extent, influenced by the detector's experience, skills, and localized conditions. In the design phase, it is helpful to use light color paints to detect any coating breakdown and small rust spots. Photographic records are considered useful in all types of visual inspection for postinspection defect and damage assessment. Computer-aided digital-imaging methods using modern digital cameras, as an alternative to direct visual detection, can also be used to inspect for corrosion wastage, for example, to avoid having a person to enter a tank. The method ultrasonic sensors are also extensively employed. However, it is time consuming due to the need for surface preparation, point-to-point examination, and preparation of coupling medium as needed. For structures that have a lot of pit corrosion, it can be hard to remove the heavy rust and correct the thickness measurement because of the uneven surface formed after the rust is removed from the surface. More advanced methods like acoustic emission and natural frequency measurement are available. These methods are both cheap and reliable and suitable for both general corrosion and localized corrosion.

Radiographic methods are capable of detecting variations in the thickness of metallic components. Electrochemical impedance spectroscopy may be applied to measure the early phase of coating deterioration and substrate corrosion during a paint coating. However, chemical techniques are influenced by temperature and pH, among other factors. Eddy current arrays can provide high-resolution readings with fast response, although eddy current arrays may not always be easy to use on large and geometrically complex structures. In cases where corrosion proceeds with measurable evolution of hydrogen, hydrogen measurement probes can be applied. When measuring magnetic flux, a sensor is immersed in the sense of current between the anode and cathode regions. Then by measuring the metal loss, the corrosion wastage distribution can be achieved by computer-controlled data processing. However, the use of chemical sensors of certain types, especially those that rely on fluorescence and color change used for dye-penetrant testing, has not proved very effective because corrosion is typically widespread. Furthermore, methods that use strain gauges are also not very effective because they need calibration with the non-corroded elements and are generally influenced by the corrosive environment as strain gauges must be bonded to the structure in large quantities (Paik & Thayamballi, 2007).

3.7.3 Fatigue and Other types of Crack Examination

In practice, fatigue cracking is frequently observed in geometrically similar regions. Therefore, it will be wise to know critical locations prone to fatigue cracking in advance. This may be simpler for standard details, but more complicated in new types of structures, and can be reached by appropriately detailed stress and fatigue analysis. Visual inspection is a primary method for inspection of cracks where it is necessary to determine the type of crack in situ and examine whether cracks are expected to propagate. Magnetic particle and dye penetrant testing may follow after visual detection so that surface crack can be suitably measured. Still, it is usually complicated to measure the crack depth without removal of the material affected.

Various NDE methods are assessable for the detection and measurement of fatigue cracking (Paik & Thayamballi, 2007). Table 8 compares the applicability of NDE methods for cracks. More advanced NDE techniques are also available, such as infrared thermography, acoustic emission, potential drop test, laser shearography, crack propagation gauges, alternating current field measurement, and automated ball indentation. Ultrasonic, eddy current, and potential drop tests can characterize the crack dimensions and locations, but these tests are generally more accurate than visual inspection (Paik & Thayamballi, 2007).

Table 8: Comparison of nondestructive examination (NDE) methods for cracks (Paik & Thayamballi, 2007).

Item	Ultrasonic	X-rays	Eddy current	Magnetic particle	Liquid penetrant
Time of results	Immediate	Delayed	Immediate	Short delay	Short delay
Effect of geometry	Important	Important	Important	Less important	Less important
Type of defect	Internal	Most	External	External	Surface breaking
Relative sensitivity	High	Medium	High	Low	Low
Operator skill	High	High	Medium	Low	Low
Dependent on material composition	Very	Very	Very	Magnetic only	Little

3.7.4 Mechanical Damage Examination

For the detection of mechanical damage (e.g., local denting), a close-up visual inspection is usually considered, as long as deformations are within specified limits in terms of depth and extension of the dent so that the inspection can be performed safely. However, it essential to realize that such mechanical damage is typically accompanied by other types of deterioration, for example, coating damage and cracking, and that these must usually also be checked (Paik & Thayamballi, 2007).

3.7.5 Probability of detecting and sizing

Uncertainties related to the detection and measurement of deterioration originate from several sources, such as material properties, geometry, location of structural components, type of cargo, life of the coating, operational conditions, internal temperature, loading cycles, seawater, humidity, measuring sensors, environment, access, and lighting (Paik & Thayamballi, 2007). Manuals, standards, and guidelines for NDE techniques are focusing on the uncertainties of the methods and measuring sensors. Still, it is noted that a major source of data scatter is related to practical difficulties and operator skill rather than the measuring equipment. An example could be that gauging for remaining thickness measurements may have some errors mostly due to errors inherent in measuring a sensor's location, which is not easy to quantify at the post-inspection stages of damage evaluation.

Statistical distributions then characterize the uncertainties related to measurements and damage detection in terms of probability of detection (POD). Figure 6 shows examples of the POD curves for fatigue cracking in ship-shaped offshore structures as a function of crack size. The larger the crack size, the higher the probability of crack detection. The POD will be low also for cracks at structural details that are hard to detect.

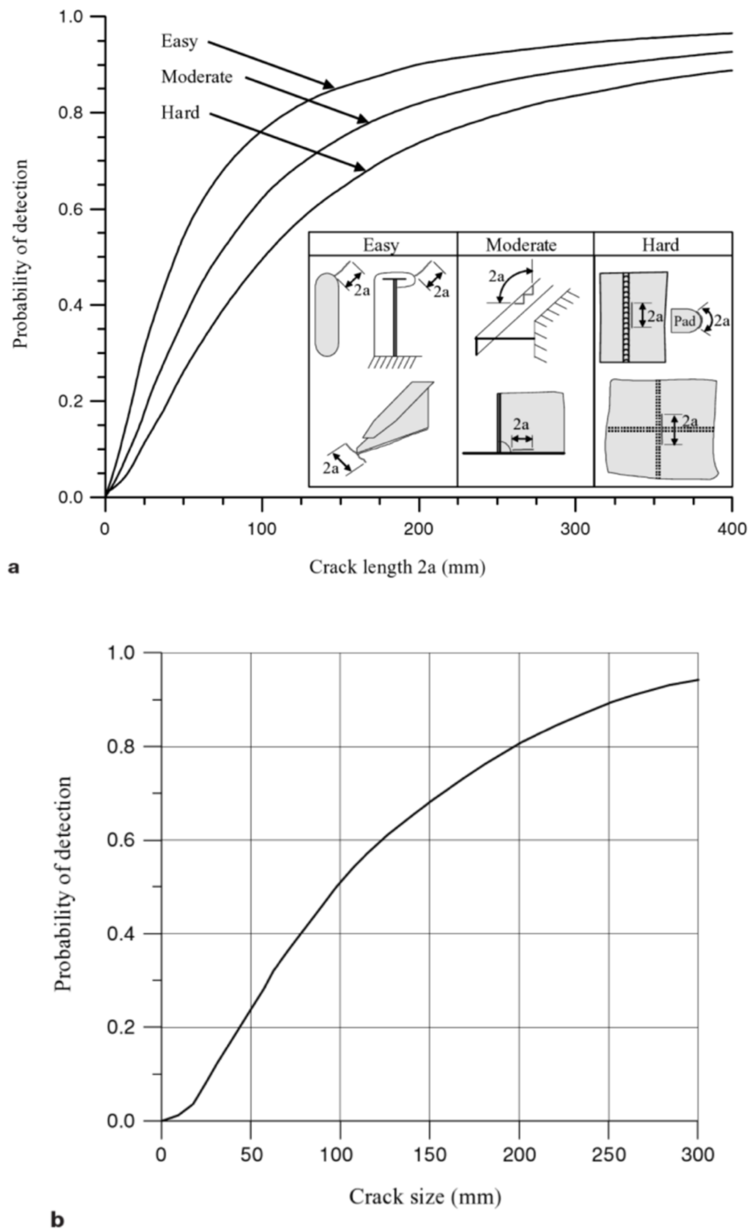


Figure 6: (a) An example of POD by visual inspection as a function of crack size in ship-shaped offshore structures, depending on the complexity of structural details. (b) An example of POD by visual inspection as a function of crack size in ship-shaped offshore structures (Paik & Thayamballi, 2007).

3.8 Risk-Based Inspection

3.8.1 Introduction

Inspection is conducted to detect deterioration on marine and offshore structures to prevent catastrophic failures to result. However, inspections cannot affect the likelihood of failures to occur in themselves. Still, any excessive deterioration can be found by relevant inspections, and the subsequent actions such as replacements, repairs, and adjustments can be performed. If potential issues are to be found in a timely manner, proper actions can be applied with corrective risk measures to reduce the likelihood of failure. Although the risk cannot be reduced to a likelihood of zero, it can be controlled and managed under an acceptable level (Paik & Thayamballi, 2007).

The purpose of risk-based inspection (RBI) is to prevent and significantly reduce failures of the FPSO employing knowledge of its safety, environment or economic viability, by the use of risk assessment and mitigation technology to make an inspection plan. It is essential to develop inspection programs, including practices that are specifically provided and identification of frequency of inspection. The RBI scheme addresses the application of risk assessment, considering both the likelihood and consequences of structural failures initiated from different types of deterioration and preexisting conditions and defects.

The main steps of developing an RBI program is shown in Figure 7. The first step is to establish an RBI team that will formulate the goals of the RBI program and decide on the overall RBI approach needed to reach an inspection plan that succeeds in achieving the desired goals.

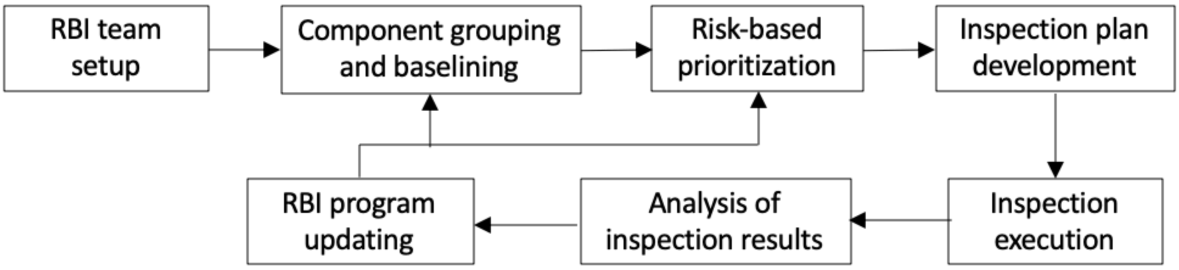


Figure 7: Main steps for developing risk-based inspection program (Paik & Thayamballi, 2007).

Moving to the second step about component grouping and baselining, where components that are subjected to the RBI program are identified and grouped. Design features of such components, as well as in-service data, are sought and collected for examination of this purpose. In the third step, a risk-based prioritization is performed following a risk assessment so that the components involved are ranked based on risk, from the highest risk to the lowest risk. The fourth step is then to develop an inspection plan based on the results of the risk prioritization so that the risk of failure is kept below an acceptable level. In the fifth step, the next necessary inspection is performed, and the inspection results are evaluated. The information gathered in this step is required by the RBI plan for the identification and implementation of measures important for the continuity of successful operation for FPSOs until the next inspection. The final conceptual step is about updating the RBI plan for the future based on inspection results, observed deterioration mechanisms, and other prior experience (Paik & Thayamballi, 2007).

3.8.2 RBI team setup

The setup of an RBI team depends on factors as the complexity of the project, the scope of work, type of installation, and applicable regulatory requirements that need to be satisfied. The RBI team will consist of experts who are familiar with risk assessment, including the identification of potential failure, their likelihood, and the determination of consequences. Usually, there are experts in the following disciplines:

- Risk assessment
- Inspection and maintenance
- Structural integrity and reliability
- Structural deterioration and related failure mechanisms
- Production processes and associated hazards
- Materials and their selection and application
- Operation and related hazards
- Health and safety

The individual experts in the RBI team are often staying involved in all tasks until the RBI plan has been fully developed (Paik & Thayamballi, 2007).

3.8.3 Component grouping and baselining

Information on various forms is required to perform this step in the relevant RBI scheme. These may cover design and construction data, inspection and maintenance records, subsequent structural modifications, and operational histories. In cases where the accuracy level is low, or information is lacking, some conservatism may result depending on the assumptions made. Data may be obtained from an initial condition survey, specific measurements, previous inspection records for the component concerned, or in some situations, data can be found from similar components. A thorough assessment is carried out of such data to identify, and various components are grouped. Further, the likelihood and consequences of possible hazards associated with deterioration in these groups have to be identified so that the risk assessment can be performed afterward. Based on the information found from the data, certain logical groupings of components will be defined as inspectable units. These inspectable units have to be large enough to have a consequence of deterioration. Still, it should also be small enough to have a similar load effect and deterioration-mechanisms exposures. Some examples of possible inspectable higher-level units for offshore installations are as follows:

- Cargo tanks
- Ballast tanks
- Watertight compartments
- Void spaces
- Pump rooms
- Spaces with through-hull connections

(Paik & Thayamballi, 2007).

3.8.4 Risk-based prioritization

A risk assessment is necessary to perform the risk prioritization. Once the risk assessment is carried out, the selected component groups to be subjected to the RBI inspection can be ranked on a risk basis, from components with the highest risk to the components with the lowest risk. Such prioritization may be influenced by additional factors such as anomalies, repairs, or scheduled shut down programs (Paik & Thayamballi, 2007).

3.8.5 Inspection plan development

When a risk-based prioritization of inspectable components is evolved, appropriate inspection strategies are selected to assess the damage detection methods, scope, and frequency.

The inspection strategy must focus on the following aspects:

- Location of the items and which of them is susceptible to deterioration
- Methods of inspection required to deliver the desired inspection results
- The efficiency of the selected inspection methods of detecting the possible deterioration mechanisms
- Amount of inspection needed to ensure the target inspection effectiveness
- Frequency of inspection required for each inspectable component

The scope of inspection must describe where to inspect and the amount of inspection in terms of sample size (number of test points), location, and extent of the inspection for purposes of measuring the level of activity of the deterioration process. The risk will, in general, increase as a function of deterioration of the inspectable components. If the number of units influenced by the same deterioration mechanisms increases, the associated likelihood of loss of integrity can increase as well. Most types of deterioration are time-variant, meaning that the risks are higher for older, more continuously used units. The sample size (number of test points) must be large enough to represent the entire deterioration mechanism collectively. For localized deterioration mechanisms, for example, cracking and pitting, a higher number of points must be inspected. Still, prioritization among them is possible if specific experience is available or certain types of structural analysis results. Another example, uniform corrosion wastage characteristics of an inspectable component must be measured at a sufficient amount of points spread evenly over the component when the corrosion rate is of concern. The locations of inspection should be selected so that features that are exposed to deterioration mechanisms can be taken into consideration within each inspectable component.

Examples of such inspection locations may include the following:

- Weld seams at heat affected zones
- Heat-affected zones from welds on component surfaces
- Hard spots and also complex connections involving structural components
- Process internals, phase boundaries
- Vapor spaces in the deckhead
- Areas subjected to impingement of water
- Difficult-to-inspect internal structural components

The extent of inspection of an inspectable unit or component must be decided based on the component size together with the likely uniformity of the deterioration environment. The whole unit may be more readily inspected if it is small enough. However, for units of large sizes, appropriately selected areas are required for inspecting considering economy and efficiency. The chosen areas of the unit for inspection must when put together, adequately represent the whole deterioration behavior of the structure during its entire service life. The frequency of inspection is about the time interval between planned inspections, which is regulated concerning the overall condition identified for a component at inspection and the expected deterioration rate. When characteristics of deterioration become sufficiently recognizable, through the first few inspections, the inspection frequency can then be optimized (Paik & Thayamballi, 2007).

3.8.6 Inspection execution

The developed inspection plan has to be correctly executed for an RBI to be successful. This is because the results from each inspection have a large impact on the understanding of the integrity of the ship, and the accuracy of the subsequent RBI program updates. Also, the inspections are the primary sources for the collection of deterioration data.

The prerequisites needed to be evaluated for a successful RBI execution are the following:

- Prior definition of clear and concise inspection work scope, including inspection control procedure
- Qualified inspectors
- Reporting format standardization
- Clear anomaly criteria and reporting process
- Clear management process for any possible change in the inspection procedure, allowing flexibility to respond to findings on a real-time basis
- Precision of equipment used for inspection
- Clear safety guidelines and policies

(Paik & Thayamballi, 2007).

3.8.7 Analysis of inspection results

When inspection activities are finished, the inspection results should be analyzed to make sure that important information for inspection plans for the future can be obtained. In some situations, anomalous data falling outside the acceptable level or the normal operational boundaries may be observed, and some corrective actions may be required as a matter of urgency. Examples of possible activities to resolve these types of issues are as follows:

- Reinspection to resolve data capture, measurement, or input errors.
- Additional inspections including broader coverage and possibly more invasive techniques to refine the extent of the abnormal condition.
- Technical analysis of the installation, unit, and its components to determine their fitness for purpose for continued service; for example, corrosion predictions using more accurate corrosion wastage models, refined fatigue analysis, fatigue-crack-growth analysis, and fracture mechanics analysis.
- Development of repairs and modifications to restore the structure or its components to a state that is suitable for safe operation.
- Modification of the RBI plan to increase and/or modify the inspection scope and frequency.

Further, an important intention of the analysis of inspection results is to develop trending information associated with the deterioration mechanisms. It is essential to identify whether the current deterioration trends are comparable to the expected trends generated from data and previous inspections and whether the trends are still suitable or have to be modified (Paik & Thayamballi, 2007).

3.8.8 RBI program updating

By continuous feedback and analysis of inspection data, the effectiveness of the RBI program can be improved. Most types of deterioration in FPSOs are time-variant so that the RBI program must be updated periodically and at significant stages during its service life. To improve the future accuracy of the RBI program, it will be important with real-time data, which applies to the deterioration mechanisms gathered from previous inspections. The program updating may lead to correction of the following:

- Risk ranking of components
- Inspection frequency and/or scope
- Inspection methods

(Paik & Thayamballi, 2007).

3.9 Evaluation of inspection findings

The inspection and other surveillance of the FPSO will produce new data about the current condition and configuration, loading on the structure, and trends in any degradation. Such new data make it necessary to undertake an evaluation of the structure to evaluate whether it is adequately safe and fit for the purpose up to the time of the next planned inspection, of if:

- There are trends in any degradation mode.
- Immediate actions are needed (if the data indicate that the structure is in immediate danger of failing).
- Further analysis (assessments) are needed.
- Mitigating measures are needed, such as repair, strengthening, or weld improvement.
- The existing surveillance programs are adequate and properly executed.
- Further inspections are needed.

The evaluation will often be performed by checking against predefined acceptance criteria for e.g., corrosion extent, crack size, acceptable loading on decks, etc. In this case, some simplified calculations may be performed, but if an analysis has to be performed, this is usually done as a part of an assessment. If an analysis like this is needed, accurate information about the anomalies must be communicated to engineers undertaking the assessment. The evaluation also has to cover the preparation of documentation, which is necessary for the execution of corrective actions and mitigations if needed.

Evaluation requires consideration of numerous factors influencing the structural performance and corrosion protection for different structural components. According to ISO 19902 (ISO, 2007), the following structural performance factors need to be considered:

- Age of the structure, its location, current condition, original design situations, and criteria and comparison with different design criteria.
- Analysis results and the assumptions for the original design and subsequent assessments.
- Structural reserve strength, structural redundancy, and fatigue sensitivity.
- Degree of conservatism or uncertainty in specified environmental conditions.
- Previous in-service inspection results and learnings from the performance of other structures.
- Modifications, additions, and repairs or other strengthening and presence of any debris.
- The occurrence of any accidental and severe environmental events.
- The criticality of the platform to other operations.

In terms of corrosion control, are the following aspects needed to be considered in the evaluation ISO 19902 (ISO, 2007):

- The assumptions and criteria used in the design.
- The details of the system (impressed current (ICCP system) and sacrificial anodes) and its past performance.
- CP readings from monitoring, compared with design criteria.
- State of the anodes from visual inspection (if a sacrificial system is used).

In cases where the criteria described above are not met, then further analysis may be required. As an alternative, mitigation measures that reduce the likelihood of structural failure can be implemented.

3.10 Maintenance Practices for FPSOs

For effective maintenance and repairs activities of FPSOs, the following factors must be achieved to the requisite degree of success:

- Repair in situ that is, without going off the field or dry-docking
- Repairs ideally affecting only the repair area, without functional stoppage or interruption including the production storage areas and offloading in other areas
- Repair, preferably without hot work such as cutting or welding
- Fast track and cost-effective repair
- Repair by easy-to-apply and readily or even locally available technologies and personnel
- Reliable repair methods backed up by a large amount of experience

Table 9 shows several operator's experiences regarding repairs and modifications of FPSOs. In addition to remedial actions for age-related deterioration, such as corrosion and fatigue cracks, it is also seen that several modifications required to improve the serviceability and operability of the units possibly arose because the original design may have been inadequate.

Indifference from trading tankers, dry-docking of FPSOs usually is not planned during the entire production life of the field, which could be around 20 years to even 30 years. Repairs of ship-shaped offshore units are performed in situ, using flame cutting or welding which is usually used for traditional tankers, could be concerns for high-fire or explosion risks. Therefore, large parts of the FPSO need to be closed during such activities, which is very expensive. For welding repairs of bigger areas, the offshore installation can expect production shutdown, dry-docking for repair, transit to repair yard, transit to the field, and recommissioning. The time estimated for such operation may be several months. Small area repairs by welding can be carried out on-site if the weather conditions are appropriate, and the time of production shutdown is limited. Even minor repairs can take up to several weeks to be performed.

Table 9: Selected experience related to repairs and modifications for FPSOs (Paik & Thayamballi, 2007).

Damage or inadequacy	Remedial actions
Fatigue cracks in water ballast tank frames	Fatigue cracks detected in lower fume openings after 2-3 years of operation as a converted FPSO after operation of about 15 years as a trading tanker. The cracks were drilled and ground. Modifications using rope access were made. These are now subjected to annual monitoring.
Defects in cargo oil tanks	Defects found in two starboard cargo tanks in way of transverse lower support brackets. Repaired using additional brackets and new inserts plates. A high level of nondestructive examination and strict welding control is required.
Breakdown of paint coating	Breakdown of paint coating in various areas of vessel hull structures was found. The cause is perhaps inadequate selection and application of coating. Recoating is necessary.
Corrosion in caissons	Extensive corrosion of seawater and firewater caissons in the water ballast tanks mainly caused by coating breakdown. Repairs by means of external plugs and recoating were partially successful. In some severe cases, repairs were attempted by recoating and by grouting a larger annular sleeve, but they are not successful. The cement leaked into and blocked base of caisson to a depth of 1-2 m.
Bow damage	Heavy weather damage to plating and internals of vessel's bow was found. Plating variously indented between stiffeners with internal brackets sprung. Repaired on location using heavier selection bulb bar and larger brackets with strict welding control. Tears in way of inner deck were faired and rewelded.
Green water impacts	Green water impacts effects were observed. Additional green-water protection added to protect the process equipment pallets aft of the forecastle.
Deformation on main deck foundations and supports	Process module main deck foundations and supports were found to be inadequate large after a structural motion analysis showing accelerations and forces attributable to the vessel movement to be in excess of the original design limits. Modifications would require substantial strengthening.
Excessive roll motions	Bilge keels added to alleviate the excessive roll of the vessel during heavy swells.

Various methods are used to limit repairs of ship-shaped units, for example, building the FPSO in additional structural design safety margins in the fabrication of the ship. These margins need to be higher than for traditional trading tankers, which is going in dry-docking every 5 years, which is usually the norm (Paik & Thayamballi, 2007).

4. Life Extension Assessment Practices for FPSOs

4.1 Introduction

The aim of performing assessment analysis on existing structures is to ensure that the structure is acceptable for further use, particularly for life extension, taking into account varieties that have arisen and other factors that may undermine confidence in its integrity. Typically, assessment of an existing structure is deployed when:

1. Variations have appeared to the condition of the structure. Such varieties could be:
    - Deterioration due to time-dependent processes such as corrosion and fatigue.
    - Structural damage by accidental loads or an extreme weather event.
2. Variations have arisen or are planned for the loading on the structure. Such varieties could be:
    - Increased loading from updated met ocean data, the addition of new modules and loading areas, an increased number of risers or conductors, increased wind loading areas, and wave in deck loads.
3. Changes to the use of the structure. Such changes could be:
    - Increased service life.
    - Accommodate modifications in the structures use (e.g., manning levels and operation).
    - Increased size of supply vessels.
    - Exceedance of original design life.
4. Changes have been made to the requirements of the structure. Such changes could be:
    - Requirements for increased safety (increased importance to the owner, public, or society).
    - Changes that have been implemented in standards and regulations (e.g., due to new knowledge about structural failures).
5. When there is doubt about whether the assumptions underlying its original design are fulfilled, such as:
    - The structure has not been inspected for an extended life extension.
    - Unexpected degradation has been observed.
    - The structure has been subject to accidental or otherwise unforeseen extreme loads (e.g., weather events).
    - Similar structures have shown unsatisfactory performance.
    - New knowledge and revised design codes.

To ensure sufficient safety in extended use of the structure, a method of evaluating the structure has been established. The primary way of evaluating the safety of a structure is by the use of design code checks (partial safety factor method for different limit states) using current standards and taking into account inspection and survey results. Other recognized methods for evaluating existing structures may be as follows:

- Non-linear ultimate capacity checks
- Comparison with other structures
- Proof-loading (not easily applicable for offshore jacket structures and other types of sub-structures)

Assessments and analysis of existing offshore structures should include evaluation of the effect of changed requirements for the use of the structure, validation of the design assumptions and assessing the effect of possible deviation from these on the structural performance, as well as assessment of the condition and residual capacity and service life of the structure. All components of the structure which cannot meet the assessment requirements have to be improved, strengthened, or replaced by new structural components.

Risk reduction to personnel from structural failure can be handled by introducing risk prevention and mitigation procedures. An example of risk prevention and mitigation procedure can be an evacuation procedure to use if the main hazard is caused by a predictable event such as wave in deck loading or excessive wave loading.

The requirements when assessing a structure is that the structure is sufficiently safe to use.

Certain information needs to be available when performing the assessment of existing structures:

- Correct drawings of the structure and marine systems to perform the right calculations.
- Degradation history of the structure, and prediction of further degradation.
- Inspectable and reliable areas on the structure.
- Regulations and standards which is updated for assessment of ageing structures for life extension.
- Relevant developments in technology.
- The procedure of how analysis for the assessment of ageing structures for life extension is conducted (which differs from the design of new structures).

(Ersdal et al., 2019).

4.2 Design life and life extension in relation to the Bathtub Curve

The "design life" is used as a term for ageing of an offshore facility used for practical purposes. It is described based on the definitions from ISO 2394 (ISO, 1998) and ISO 19902 (ISO, 2007) as the assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair from ageing processed being necessary (Ersdal et al., 2019).

The original design life is described as the assumed design working life of the installation at the time of design. Figure 8 shows the bathtub curve in a modified version, including the stages; initial, maturity, ageing, and terminal at the end of the curve. The maturity stage represents the useful life, and the ageing and terminal stages representing the first and second part of the end of life for the structure. A further description of the stages is as follows (HSE, 2006):

- Stage 1: "Initial"

  When systems, equipment, and structures are put into service, there can be a relatively higher rate of damage accumulation and issues requiring attention as a result of faults or inherent weakness in the design, materials, or fabrication – and bedding (coating?)– in defects.
- Stage 2: "Maturity"

  After the systems, equipment, and structures have passed through the early-life problems, they enter the second stage. The longer "maturity" stage is when equipment is predictable, reliable and is assumed to have a low and relatively stable rate of damage accumulation and few issues requiring attention. It is operating comfortably within its design limits.
- Stage 3: "Ageing"

  By this stage, the systems, equipment, and structures have accumulated some damage, and the rate of degradation is increasing. Signs of damage and other indicators of ageing are starting to appear. Further, it becomes more important to determine quantitively the extent and rate of damage and to make an estimate of remnant life. Design margins may be eroded, and the emphasis shifts towards fitness-for-service and remnant life assessment of specific damage areas.
- Stage 4: "Terminal"

  As accumulated damage to systems, equipment, and structures becomes increasingly severe, it becomes clear that the systems, equipment, and structures will ultimately need to be repaired, refurbished, decommissioned, or replaced. The rate of degradation is increasing rapidly and is not easy to predict. In this final "terminal" stage of the equipment's life, the main emphasis is on guaranteeing adequate safety between inspections while keeping the equipment in service as long as possible.

The concept of design life for a mobile installation that may operate in different parts of the world subjected to different environmental conditions, the interpretation of design life, and assessment of ageing becomes more undecided. The design life is assumed to be the period during which the structure can safely be used, and hence must be assumed to reach somewhat into the maturity phase, but not into the ageing phase. Life extension is assumed when the structure is beyond this originally defined design life. Complications can arise if there are dissimilarities between the:

- Design life as defined in design specifications
- Original calculated design life
- Updated calculations of life

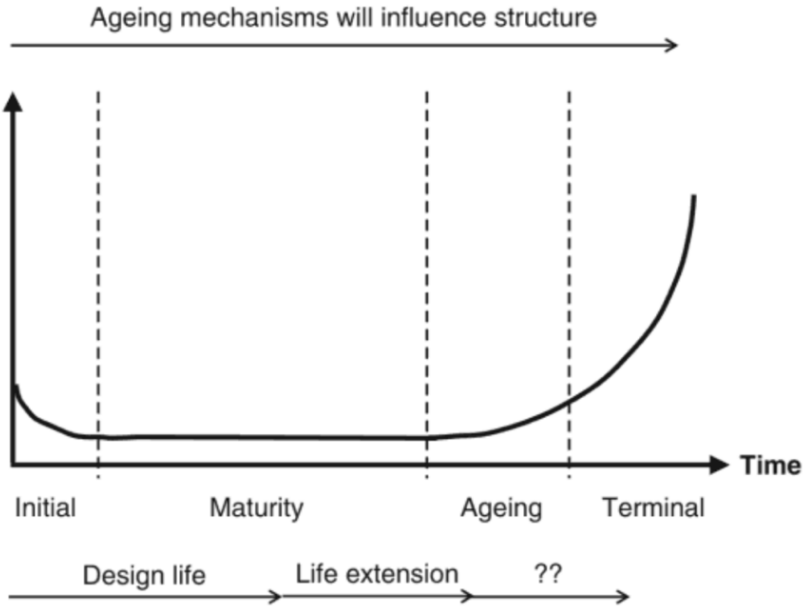


Figure 8: An ideally representation of design life and life extension in relation to the bathtub curve (HSE, 2006).

4.3 Assessment Versus Design Analysis

There are many differences between an existing structure subject to an assessment and a structure being designed. One important difference is the available information about the structure, which is information about the current condition of the structure and previous performance data. This information can be applied as a method for evaluating the future safety of the structure. Another important difference is the cost of assessing an existing structure compared to a structure in the design phase, where the cost is typically much higher for the assessment of existing structures. The reason for the big difference in costs has to do with, among other things, the analysis method needed to be used design analysis and assessment of existing structures. In the design of new structures, the cost of adding a little extra steel in the structure is limited and does not necessarily justify expensive advanced engineering analysis.

For design analysis, methods such as linear elastic analysis, standardized code checks of most members, nodes, and details, and stress concentration factors (SCFs) will often be taken from simplified standardized formulas. Further, when assessing existing structures, the cost of any modification to the structure is high, because of more advanced structural analysis methods needed. These could be analysis of, for example, members, nodes, and details modeled carefully in advanced finite analysis programs and the use of non-linear structural analysis and structural reliability analysis (SRA). New structures are designed according to design codes that take into account assumed uncertainties by characteristics of loads and strength and partial safety factors. On the other hand, an existing structure can be measured, inspected, tested, instrumented, and sometimes proof loaded. All information needed for assessing the condition and performance of an existing structure can be gathered. Although, in practical purposes, proof-loading is often unrealistic, and the collection of a large amount of data requires significant effort, and it is costly. However, the number of years of an existing structure in operation at given loads and exposures contains information of value in assessment of the structure. To establish adequate safety in the extended use of a structure, taking into account the above information, several methods have been developed for evaluating the structure. These procedures are, among others, ISO 19902 (ISO, 2017) and NORSOK N-006 standard (Standard Norge, 2015).

4.4 Assessment Procedures

The purpose of assessing an existing structure is to make sure that the integrity of the structure is sufficiently safe, even though it might be in a degraded state. Such procedures are proposed in standards and guidelines (e.g., ISO 19902, NORSOK N-006). A flow sheet of the assessment process for life extension is shown in Figure 9.

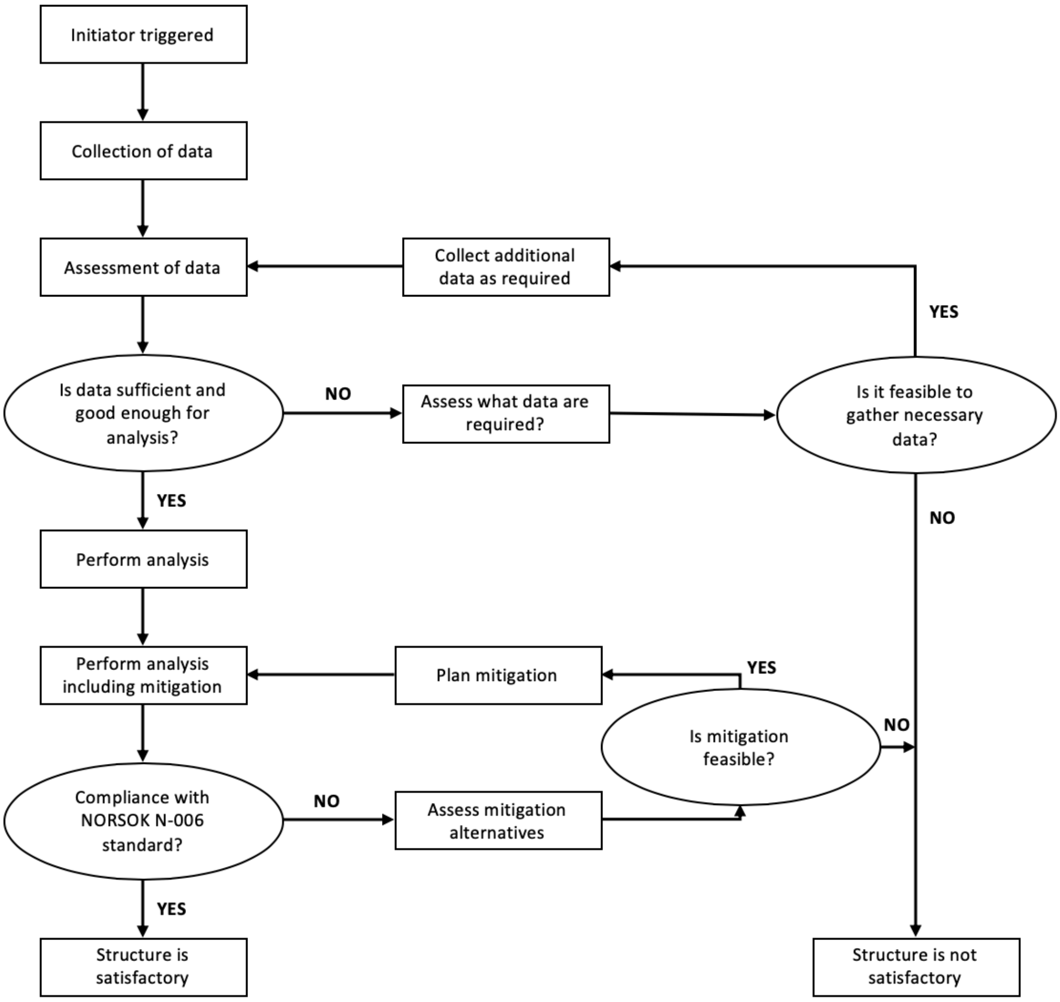


Figure 9: Flow sheet of the assessment process for life extension of FPSOs). Based on NORSOK N-006 standard.

When performing assessments of existing structures, the condition of the structure as it is at the current state has to be assessed, including deterioration mechanisms such as corrosion, cracks, and dents. Then, based on this assessment, existing computer models and drawings have to be updated to perform the necessary analysis. To ensure reliable results of the analysis, the load description has to be updated based on the changes in loads or load specification (e.g., due to weight increases, subsidence, or updated environmental criteria). Since the original design of the structure, engineering methods used for calculation of loads and strength of the structure may have changed. Therefore, the effects of these changes also need to be taken into consideration.

Degradation history data of the structure, such as the number of cracks and extent of corrosion, is important information when performing life extension of a structure. Such information can, among other uses, be applied to indicate trends in the degradation process. For example, if degradation has increased rapidly or has developed slowly over time. Other uses of degradation history data are to decide uncertainty about the structure. Incidents and accidents should be evaluated, along with their influence on aspects as the strength of the structure. Positive performance history data will also be necessary for reducing the uncertainty about the structure because, without performance history data of the structure, the uncertainty will be considered as large. If this increased uncertainty is to be taken into consideration when assessing life extension of the structure, the assessment should be based on significantly higher safety levels. However, at present, such increased safety levels are not required in standards and guidelines.

Future degradation of the structure may be developed based on historical data and the present condition of the structure. Looking ahead, the assessment should also cover risk analysis, including future operations which are updated with relevant incident and accident history data of the structure. Lastly, all planned modifications and changes to the structure during the life extension period have to be covered in the assessment. The information above should be used to evaluate the integrity of the structure. The assessment should be carried out to verify whether the structure is still acceptable in its present condition or whether it has to be decommissioned. Nevertheless, the cost of mitigation can lead to a more economical question rather than a structural safety question. If the conclusion is that the structure is still acceptable, and it is possible to continue to use the structure, it is also crucial to have an idea of how long the structure can be in use and still be sufficiently safe. Also, it is significant to find out which ageing mechanisms that will likely occur and the characteristics of these ageing mechanisms.

The assessment may be applied to identify possible monitoring or inspection activities to develop good warning signs of future deterioration. Planned mitigation actions to maintain a necessary level of safety, may or may not work as intended. Therefore, it is necessary to establish methods to assess the effect of these mitigations.

Life extension assessments are leading to an updating plan for structural integrity management, which takes into account the ageing mechanisms that the structure is assumed to be exposed to under given conditions. Further, a long-term inspection plan should be a part of the structural integrity management plan. The most used standards for life extension of existing offshore structures are among others, ISO 19900 (ISO, 2007), NORSOK N-006 (Standard Norge, 2015), API RP 2FSIM (API, 2019) and ISO/DIS 13822 (ISO, 2000).

4.5 Assessment of Ageing Materials

The most frequently used materials at FPSOs is steel, and for some special area's composite materials and Glass-Reinforced Plastic (GRP). In addition, aluminum is applied at living quarters and helideck. Ageing ship-shaped structures have a limited possibility for a new material selection process and material replacements when the structure is assessed for life extension. In general, the operators have to accept the original materials specified in the design stage. Several degradation mechanisms are influencing the materials, which is mentioned in chapter 2. All materials have a certain loss of performance when aging occurs, which may have an impact on structural safety. Ageing is caused due to environmental effects on the materials, recognizing that seawater is a particularly hazardous environment. The cyclic stresses that a material is exposed to may result in loss of performance, especially due to fatigue.

At the design and fabrication stage, data are required for the processes and materials applied. These include welding procedures, material certificates, results of non-destructive examination (NDE), etc. At the life extension stage, this data may no longer be accessible, which introduces significant uncertainties in the assessment.

Assessment of an existing FPSO for life extension includes a process where the operator needs to verify that the FPSO has the ability to operate safely at acceptable risk levels. In addition, degradation mechanisms and failure modes of the aged materials are essential to identify, control, and mitigate. The materials selected in design, have to be proved and documented, and their fabrication and quality need to be adequately robust to be fit for purpose also in the extended life.

Table 10: Traffic light scheme for the assessment of ageing materials (Ersdal et al., 2019).

Green	**Amber**	**Red**
Material certificates present and verified, or substantial material testing performed	Materials certificates present for most elements	Material certificates are lacking
Prediction of material degradation in whole life extension period is accepted with proven safety factors by corrosion and materials engineers	Limited evaluation of material degradation is performed, and it is assumed that material degradation is acceptable for whole life extension period	No prediction of material degradation in life extension period is performed
Low level of material degradation, or intensive condition monitoring to ensure operation within design limitations	Medium level of material degradation, or limited condition monitoring	High level of material degradation, i.e. corrosion beyond design limitations. Minimum condition monitoring undertaken
Active use of inspection records in life extension assessment and operation	Inspection records are documented and reviewed, but no fully utilized in life extension assessment	Inspection records poorly documented or not used in life extension assessment
Utilization of material information from testing and inspection of decommissioned installations. Lessons learned	Limited material inspection from testing and inspection of decommissioned installations	No assessment of external material data, particularly from decommissioned structures

The characteristic parameters of a material are significant in the design stage to allow for any different properties as, for example strength. Also, safety factors in the form of material factors are used to take uncertainty into account. Different materials have different safety factors, depending on the level of uncertainty in their properties. These are normally defined in standards and codes. Although, as a result of ageing, it may be necessary to reassess the characteristic properties of the material and these safety factors. An understanding of the processing of uncertainty relevant to life extension can be reviewed via a “traffic light” scheme as shown inTable 10. These three areas (green, amber, and red) can be summarized as follows:

- *Green*. If the result of the life extension assessment is all within the green area, the design of the FPSO is good. Proven test data exist, and the materials are fit for purpose for life extension.
- *Amber*. Some important data is missing, and caution must be exercised in determining the characteristics of the material and the safety factors used in the assessment.

- *Red*. Important data is missing, and considerable caution will be needed in determining the characteristics of the material and the safety factors used in the life extension assessment.

The processing of amber or red structural materials requires careful consideration of the safety factors during the assessment to ensure continued safety at life extension. For the red category, coupon testing in the field may be necessary to ensure continued performance as knowledge of the original material selection may be absent.

4.6 Safety Principles Applicable to Structural Integrity

4.6.1 Introduction

A safe structure that can withstand all situations load distributions and accidental events at all times is not a feasible structure. This has to do with the uncertainty and inherent randomness in the strength of the structure, the accidental events, and loads. Also, several aspects will not be foreseeable. The load situations of a structure, strength, and accidental events are not deterministic and predictable quantities. The strength of a structure varies with, among others, the strength of the material and the quantity of fabrication work, etc. In addition, load situations are unpredictable and have inherent randomness. Accidental situations may be predicted, but these situations are possible to occur differently compared to what is predicted or at a higher level of severity. In other words, it usually is not possible to foresee all accidental situations the structure will be exposed to. Errors from the design and fabrication phase, and the use of the structure is not possible to foresee. However, it has been shown that a few cases have led to a realization that the structure was not designed correctly and with an insufficient design after new knowledge has been obtained.

The traditional methods which may be applied to ensure that a structure is sufficiently safe (acknowledging that some structures may fail but with a very low probability) are to design them according to the following principles.

1. Strength, according to the partial safety factor limit state design method, also called load and resistance factor design, is based on the following:

- A characteristic value of material strength is used. This is a low value of strength, which is probabilistically defined – normally in the range 2-5%. The intension by using this characteristic value is to ensure that there is a low probability of the strength being lower than what is assumed in the calculation.
- Similarly, a characteristic high value is used for load – normally with an annual probability level of being exceeded of 10^{-2} for extreme loading situations and up to 10^{-4} for abnormal loading situations. The intension is to ensure a low probability of the load being higher than what is assumed in the calculation.
- A predefined safety factor reduces the characteristic strength into what is called design strength and individual/partial safety factors increase the various types of characteristic loads according to their assumed uncertainty. Higher safety factors are used for uncertain loads such as waves, and wind. Further, lower safety factors are used for less uncertain loads as structural weight into are used what is called design loads.
- The structure is checked for predefined limit states (ULS, ALS, FLS, and serviceability limit state [SLS]). Partial safety factors for strength and loads will vary for the different limit states. However, in general, a limit state check is used to ensure that the strengths are higher than the loads.

2. In addition to designing strength according to the partial safety method, a structure should also be sufficiently damage-tolerant in order to withstand local failure without collapsing. This is meant to ensure some robustness for unanticipated degradation, accidental events, unforeseen exceptional loads, and unknown phenomena.

3. Structures should be managed during operation to maintain the integrity for which they were designed.

4.6.2 Partial Factor and Limit State Design Method

The concept of partial factors and limit states as a design philosophy includes several independent safety factors. Each of these plays a specific role in ensuring the safety of the structure against the exceedance of a limit state. There are two main types of partial factors (Ersdal et al., 2019):

1. Partial safety factor for a material, which includes statistical variability of strength probabilities for materials, fabrication, and modeling of material parameters.
2. Partial safety factors for loads that include possibly deviation of actual loads from design values due to variability of loading and deviations from normal service conditions.

The limit states that a structure has to be able to withstand, due to applied actions during its life, are divided into two main groups (Ersdal et al., 2019):

- ULS, which is a failure check of the structure or one or more of its members due to fracture, rupture, instability, excessive inelastic deformation, etc.
- SLS, which is a check of deflections and vibrations, etc.

The structure may fail in a ULS as a result of a deterioration process followed by a milder load event or from a single extreme load event. Exceedance of a ULS is almost always irreversible and will cause deformation, permanent damage, or failure.

ULS can be divided into two main sub-groups:

- ALS, which is a check of the collapse of the structure due to the same reasons as described for the ULS but exposed to accidental and abnormal loading situations.
- FLS, which is a check of the crack growth capacity of the structure or the fatigue $S - N$ capacity.

In the ALS, the effect of possible accidental loads (e.g., explosions, collisions, and fires) on the structural behavior and abnormal loading (such as very low probability environmental events) is considered. ALS may also include a check of the post-accidental condition where, for example, the structure is checked for representative loading situations after an accident such as a fire or explosion. The purpose is to ensure that the structure will maintain its integrity to allow for escape and rescue before collapsing. This is, for example, the case in the NORSOK N-series of standards (Standard Norge 2012) and the Health and Safety Executive (HSE) safety case regulation (HSE 2015).

The partial factor and limit state method is a so-called semi-probabilistic method. The method includes that there is a chance for the structure to becomes unfit for use, which in this context means that a specific limit state condition is exceeded. Although there is no attempt to calculate the probability. The variable of any given parameter of the structural system (most generally strength and loads) is defined using statistics and a resulting characteristic value chosen for the design calculations. A characteristic load is defined as the load that has a certain chance of being exceeded at least once during the life of the structure (for example, a 10% characteristic dead load has a probability of 0.1 of being exceeded).

Having defined characteristic values of strength and loads, the design values for a specific limit state are the characteristic values of strength and load factored by the relevant individual partial safety factors. This strategy results in design values that have a very low but unknown probability of being exceeded. The partial safety factors thus serve to deal empirically with the uncertain and extremely low probabilities associated with the tails of the probability distribution functions (Ersdal et al., 2019).

The general form of the partial factor and limit state method can be expressed in Eq. (4.1):

$$\phi R_c \geq \sum_{i=1}^{m} \gamma_i \cdot S_c \tag{4.1}$$

where ϕ is the strength factor, R_c, is the characteristic strength, γ_i, is the load factor of the ith load components out of m load components, and S_c is the characteristic value of the ith load component out of m components.

Usually, this equation is written in the form of design value for load (S_d) and resistance (R_d) as in Eq. (4.2):

$$R_d \geq \sum_{i=1}^{m} S_d \tag{4.2}$$

Figure 10 illustrates concept of partial factors, known as load and resistance factor design (LRFD), based on simple distribution functions for load and resistance. The partial factor and limit state method are in various standards developed for the design of new structures. These standards may, to some extent by applied for existing and ageing structures, but this will often depend on careful comprehension of ageing effects. It has been shown that ageing mechanisms such as cracking, corrosion, load changes, deflection, and dents, etc., have not been included in the design formulae, and the engineer is often left to rely on other information such as research papers.

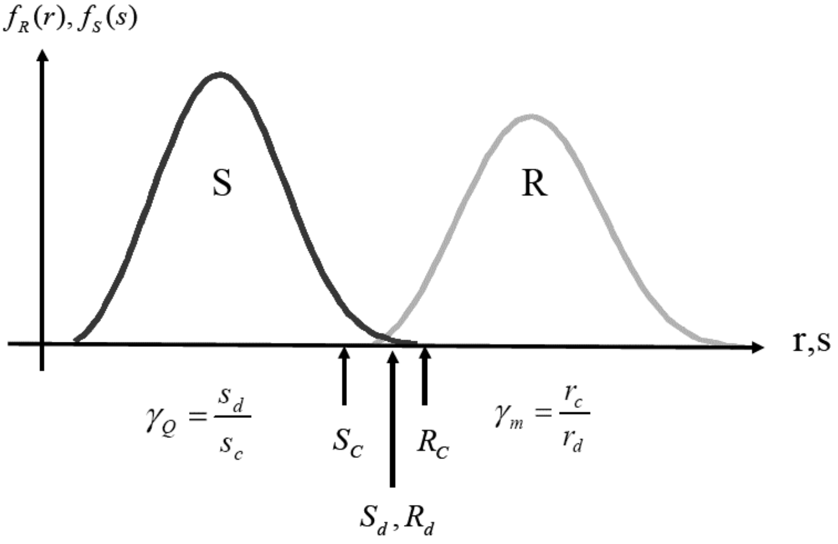


Figure 10: Concept of partial factors (Ersdal et al., 2019).

4.7 Strength Analysis

4.7.1 Introduction

The strength of a structure can be defined as the ability to withstand the applied load and load effects, such as stresses, and not causing any failure of the structure or causing a defined limit state to be exceeded. Usually, strength analysis of existing structures is performed as a part of a life extension process, or it can be carried out due to other triggers indicating that an assessment should be performed. Assessments are carried out partly due to degradation defects or possible damage that will reduce the load capacity of the structure. It is also performed to decide if loads are found to be higher than the acceptable level in the original design analysis or if regulatory requirements have become more stringent.

Analysis of the strength of degraded and damage structures and structural elements is the main challenge in the evaluation of ageing offshore structures. Different degradation and damage effects which may be applied to offshore structures are as follows:

- Cracks in members and joints
- Dents
- Corroded members
- Deflected members
- Tears
- Deformed shapes
- Holes
- Missing members
- Unusual deflections
- Hardening
- Wear

All of these degradation mechanisms affect the strength of the structure in various ways and should be assessed by suitable techniques. For instance, corrosion will first affect the thickness of a steel member, which can be included in calculations of section properties (e.g., area and moment of inertia) by taking into account the metal loss and hence wall thinning. Further, corrosion may lead to eccentricities in the member if the metal loss is unsymmetrical. This needs to be taken into consideration and can particularly have an impact on the buckling capacity of a member on the structure. Also, corrosion may cause extensive fatigue cracking, which also has to be taken into consideration in fatigue analysis.

Considering four major factors which may have an impact on the strength capacity of a structure due to the effects of degradation mechanisms:

- Cracking and partial removal of part of a section
- Metal loss and wall thinning
- Geometrical changes
- Changes to material properties

Table 11 indicates various degradation mechanisms and how these may be maintained when performing structural strength analysis. The evaluation of the capacity of members has to take these ageing mechanisms into consideration, as further described in this section.

Table 11: Ageing effects and the effect on the structures (Ersdal et al., 2019).

	Metal loss and wall thinning	**Cracking and removal of part of section**	**Changes to material properties**	**Geometric changes**
Corrosion	X	X	X	X
Cracking		X		X
Denting				X
Deformed shapes				X
Tears		X		
Holes		X		X
Wear	X			X
Hardening			X	

4.7.2 Strength and Capacity of Damaged Steel Structural Members

For offshore structures are the most likely degradation mechanisms fatigue cracks, corrosion, dents, wear, and buckling. This needs to be taken into consideration when performing calculations of the strength of the structure, the ULS, and ALS.

Common modes of failures of steel members are due to excessive stresses caused by bending, axial and shear loads (or a combination of these), bearing failure, and local and global buckling. The first four of these failure modes are mainly influenced by the fact that the section area and other section properties are reduced by the material loss caused by fatigue cracks, corrosion, and wear. Further, a reduction in yield stress will also influence these failure modes. Local and global buckling will also be affected by any eccentricity introduced by degradation or damage.

Effect of Metal Loss and Wall Thinning

The main effect of metal loss and wall thinning is the reduction of section properties such as area, the moment of inertia, and section modulus. The capacity of a steel beam is dependent on the axial, shear, and bearing capacities subjected to the section area. Hence, any reduction in the section area will lead to a reduction of the steel capacity. Moment and buckling capacity are also subjected to the section properties of the steel beam.

Unsymmetrical metal loss and wall thinning, locally or along the steel beam, may give rise to eccentricities, which will be discussed further as a geometric change.

An essential feature of the strength capacity of a steel member is its ability to deform elastically or plastically prior to local buckling. Steel beams can be classified into four classes depending on their failure modes. Class 1 is typically steel beams that can fully develop plastic hinges with the necessary rotation capacity without reducing the resistance prior to failure. Class 2 steel beams can form plastic moment resistance but have limited rotation capacity as they may experience local buckling. Class 3 steel beams will not buckle locally prior to yielding in the extreme compression fibre, and the capacity can be calculated by elastic methods. Lastly, Class 4 steel beams have slender cross sections that will experience local buckling prior to yielding in the extreme fibre.

If steel beams have experienced wall thinning due to corrosion or other degradation effects, they may have to be reclassified based on the new thickness of the section. This is important because even for small changes in the thickness of a steel member, a reclassification may result in a significant drop in the section's ability to withstand axial, shear, moment, and bearing loads.

Effect of Cracking and Removal of Part of Section

Usually, the effect of cracking and removal of part of the section (e.g., due to extensive damage, boreholes, etc.) will lead to a reduction of section properties as well as geometric changes by the introduction of eccentricities.

Effect of Changes to Material Properties

The effect of changes to material properties is affected by the hardening of materials, hydrogen embrittlement, and possibly by corrosion as well. The ability of various material properties, such as rupture stress, may need to be updated as a result of degradation to find strain and hardening by non-linear plastic analysis of the structure.

Effect of Geometric Changes

Geometric changes such as cracking, corrosion, and dents, are a result of most degradation mechanisms, typically introducing eccentricities to the structural member. These degradation mechanisms are disturbing the geometry and the centroid of the section and introduce eccentricities that will affect the buckling capacity of the structural member particularly.

4.7.3 Effect of Fatigue Cracking on Plate Ultimate Strength

Fatigue cracks may occur in stress concentration regions under the action of repeated loading of a region of the structure. Initial defects and cracks can also arise from inappropriate fabrication procedures and are likely to remain undetected over time. Another way of cracks to propagate, in addition to repeated cyclic loading, is by unstable crack growth under monotonically increasing extreme conditions. This circumstance eventually may lead to catastrophic failure of the structure. This possibility usually has to do with the ductility of the material and also the presence of reduced stress intensity regions in a complex structure that can serve as crack arresters even in an otherwise monolithic structure. To evaluate the residual strength of aging steel structures under extreme loads as well as under oscillating loads, it is often necessary to evaluate the effect of a known or assumed crack as a parameter for impact (Paik & Thayamballi, 2007).

Fatigue cracks are often observed in a rigid panel along the welding junction between the plating and the stiffeners. The ultimate strength behavior of panels depends largely on the types of crack orientations, among other factors. The orientations for such cracks can be classified into three groups, namely vertical, horizontal, and angular cracks, as illustrated in Figure 11 (Paik et al., 2005).

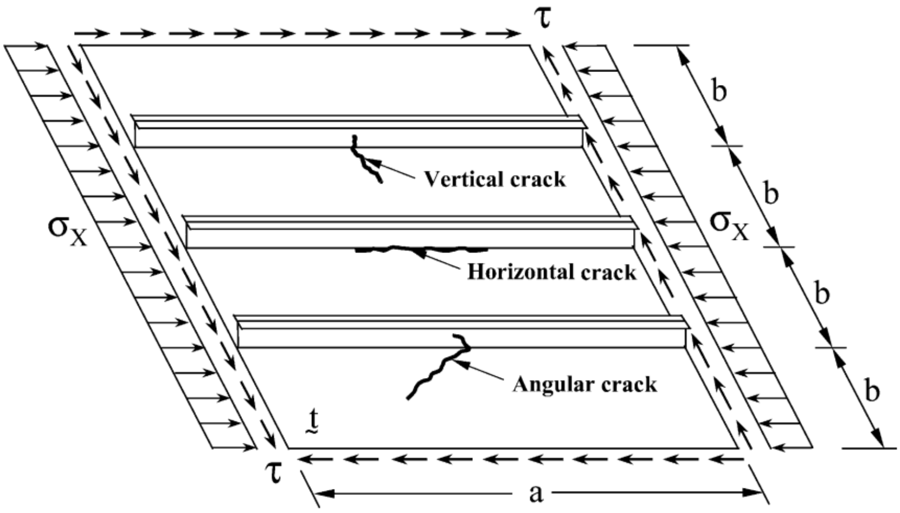


Figure 11: A schematic of a stiffened steel panel with three types of crack orientations and under axial loads or edge shear (Paik et al., 2005).

Figure 12 shows a sample finite-element modeling for a steel plate with edge crack at one side and under axial compressive loads. Based on an experiment and nonlinear finite-element analysis undertaken by (Paik et al., 2005), the ultimate strength of plate cracking can be computed by the use of the strength knock-down factor approach for axial tensile or compressive loading as in Eq. (4.3):

$$R_{xc} = \frac{\sigma_{xu}}{\sigma_{xuo}} = \frac{A_o - A_c}{A_o} \tag{4.3}$$

where R_{xc} = a factor of the ultimate tensile or compressive strength reduction due to cracking damage, σ_{xu} = ultimate axial strength of cracked plating, σ_{xuo} = ultimate axial strength of uncracked plating, A_o = cross-sectional area of uncracked original plating, and A_c = cross-sectional area involved in cracking damage. Further, the ultimate strength of plate cracking can be computed by the use of the strength knock-down factor approach for edge shear as in Eq. (4.4):

$$R_{\tau c} = \frac{\tau_u}{\tau_{uo}} = \frac{A_o - A_c}{A_o} \tag{4.4}$$

where $R_{\tau c}$ = a factor of the ultimate shear strength reduction due to cracking damage, τ_u = ultimate shear strength for a plate with premised cracks, and τ_{uo} = ultimate shear strength of uncracked plating.

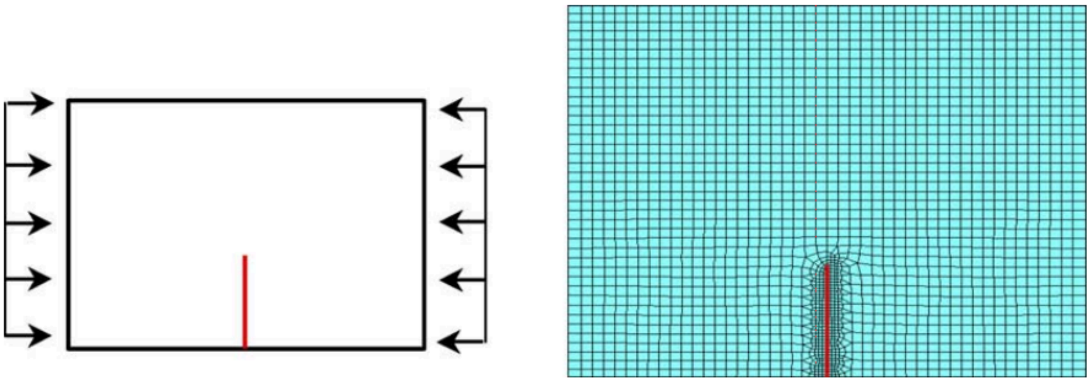


Figure 12: A sample finite-element mesh for a plate with one edge crack and under axial compression (Paik et al., 2005).

4.7.4 Effect of Corrosion Wastage on Plate Ultimate Strength

Corrosion wastage of plate elements can reduce the capacity of ship-shaped offshore installations. Two different types of corrosion damage are normally considered: general corrosion (or uniform) and localized corrosion. General corrosion reduces the plate thickness uniformly, while localized corrosion attacks the plate nonuniformly in selected areas, for example, pitting corrosion in crude oil cargo tanks. The ultimate strength of a steel member with general corrosion can be easily calculated by excluding the loss of plate-thickness due to corrosion. A series of numerical and experimental studies on steel-structures specifies that the plate ultimate strength reduction characteristics resulting from general corrosion develop quite unlike pitting corrosion.

Figure 13 shows four pitting intensity diagrams. To manage the magnitude of breakdown due to corrosion, a parameter defined by degree of pit corrosion intensity (DOP) is typically applied. DOP can be denoted by a volumetric basis as in Eq. (4.5):

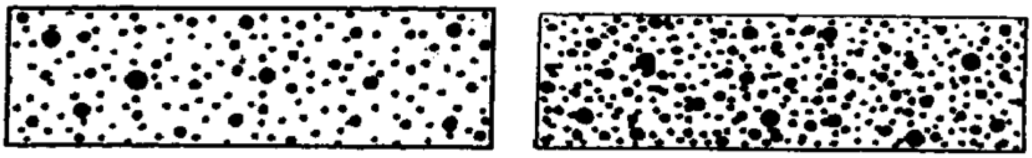
$$DOP = \frac{1}{abt}\sum_{i=1}^{n} V_{pi} \times 100\ (\%) \tag{4.5}$$

where n = number of pits, V_{pi} = volume of the ith pit, a = plate length, b = plate breadth, and t = plate thickness.

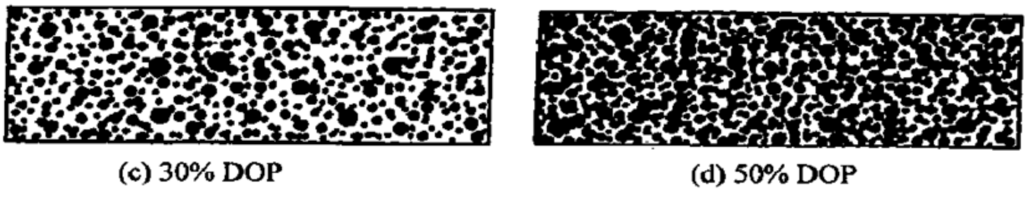
The plate strength can be measured in a more pessimistic way by DOP denoted on a surface area basis as in Eq. (4.6):

$$DOP = \frac{1}{ab}\sum_{i=1}^{n} A_{pi} \times 100\ (\%) \tag{4.6}$$

where A_{pi} = surface area of the ith pit, which is calculated as $A_{pi} = \pi d_{ri}^{2}/4$ with d_{ri} = diameter of the ith pit, for a circular type of corrosion (Paik & Thayamballi, 2007).



(a) 10% DOP (b) 20% DOP



(c) 30% DOP (d) 50% DOP

Figure 13: Pitting Intensity Diagrams (DOP = Degree of Pit Corrosion Intensity as a Ratio of the Pitted Surface Area to the Original Plate Surface Area): (A) 10% DOP; (B) 20% DOP; (C) 30% DOP; (D) 50% DOP.

4.8 Fatigue Analysis and the S-N Approach

4.8.1 Introduction

Offshore structures are exposed to fatigue due to the effects of cyclic loading, especially from wave actions that are increased at welded joints if the geometry introduces significant SCFs. Initiation of fatigue cracks can occur under high cyclic loads acting on welds containing microscopic defects that are inherent due to the welding process. In ageing structures, the likelihood of initiation and propagation of cracks increases as fatigue is a time-dependent process. Therefore, ageing and life extension of structural elements need to be evaluated for the effects of fatigue by applying analytical methods to determine fatigue life predictions as well as an appropriate inspection plan. The stress distribution at a welded joint is illustrated in Figure 14. The nominal stress (S_{nom}) may be defined as the stress in the member without any effect on the geometry of the welded connection and may be used in the nominal stress method for analysis of fatigue. The hot-spot stress (S_{hot}) may be defined as local stress at the hot spot where cracks often will initiate. It includes the stress concentration resulting from the effect of structural geometry on connections and is sometimes referred to as structural stress. By linear extrapolating, the stress at $3/2t$ and $1/2t$ away from the weld toe to the weld toe is found, as shown in Figure 13. This stress is used in the hot-spot stress method for fatigue analysis. The notch stress (S_{notch}) may be defined as the peak stress at the weld toe or notch, including stress concentrations resulting from the influence of structural geometry as well as the presence of the weld. The stress is used in fracture mechanics assessments and the notch stress method of fatigue analysis.

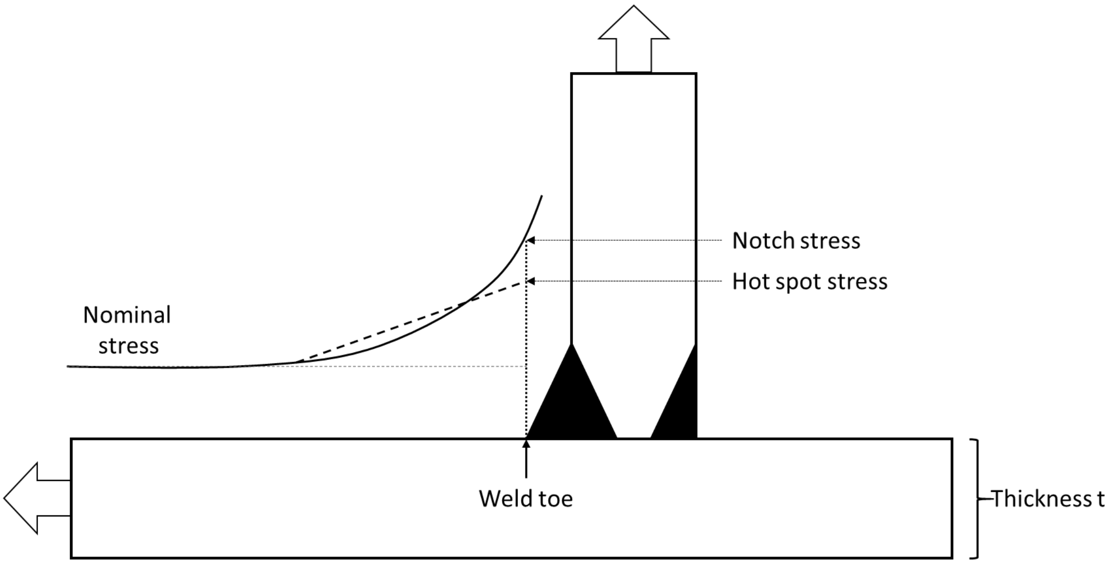
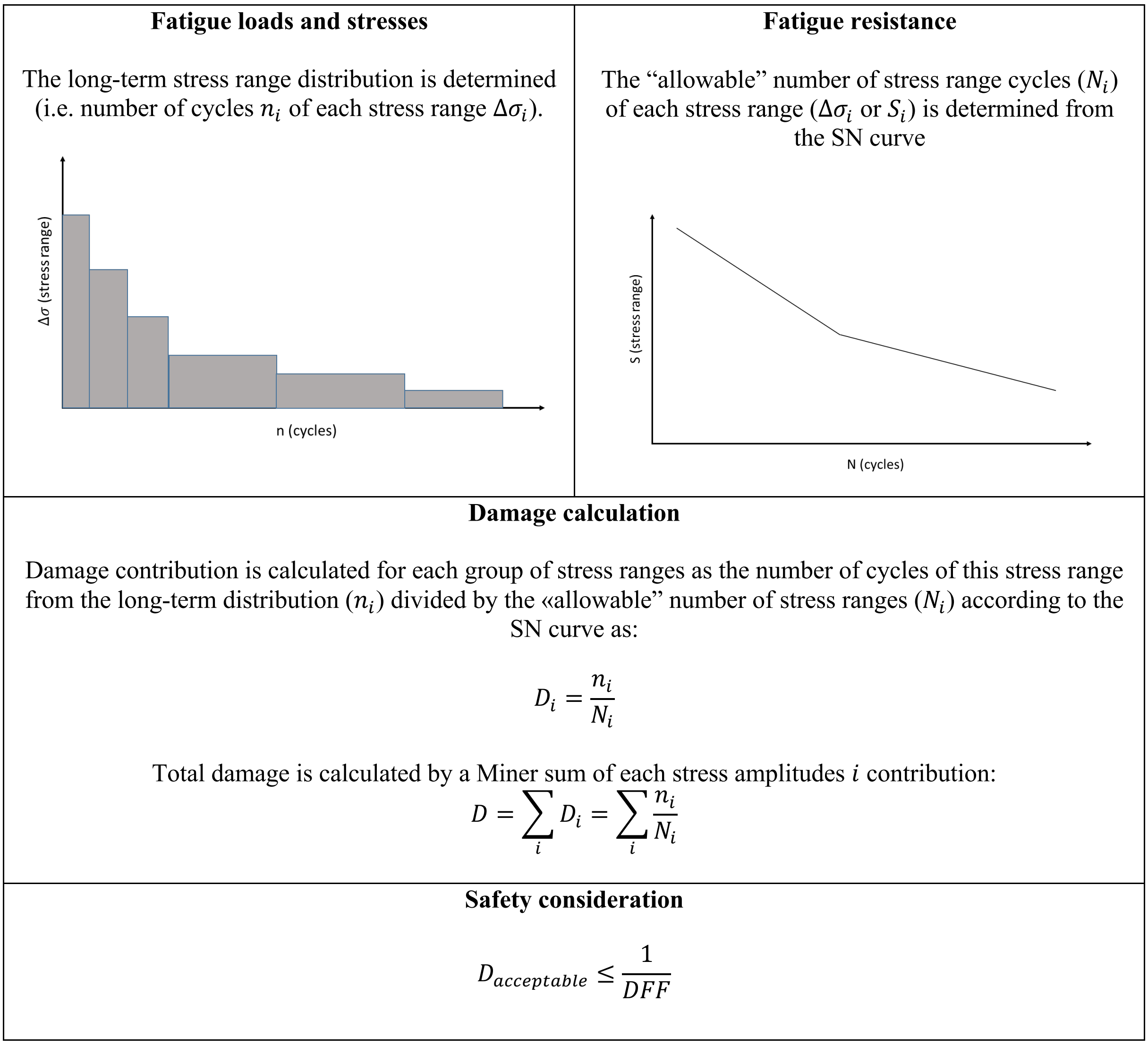


Figure 14: Stresses in a welded connection in a structure (Ersdal et al., 2019).

Methods used for fatigue analysis are based on the assumption that crack will initiate under cyclic loading, where the number of cracks is dependent on the stress applied. The applied stress is sensitive to the microscopic flaw size, which is not found by NDE during fabrication of the structure, emphasizing the importance of weld quality to fatigue life. The crack propagation rate and thus the fatigue life is calculated by the crack size and the cyclic stresses.

4.8.2 $S - N$ Fatigue Analysis

The traditional method of performing fatigue life assessment is the $S - N$ approach, which is based on the use of $S - N$ curves in addition to a long-term fatigue stress range distribution or spectrum, providing the number of fatigue cycles (N) for each stress range (S). A substantial amount of effort has been practiced in recent decades to generate $S - N$ curves in general and specifically for offshore structural components. Figure 15 shows the basic principles of the $S - N$ fatigue approach.



Fatigue loads and stresses

The long-term stress range distribution is determined (i.e. number of cycles n_i of each stress range $\Delta\sigma_i$).

Fatigue resistance

The “allowable” number of stress range cycles (N_i) of each stress range ($\Delta\sigma_i$ or S_i) is determined from the SN curve

Damage calculation

Damage contribution is calculated for each group of stress ranges as the number of cycles of this stress range from the long-term distribution (n_i) divided by the «allowable” number of stress ranges (N_i) according to the SN curve as:

$$D_i = \frac{n_i}{N_i}$$

Total damage is calculated by a Miner sum of each stress amplitudes i contribution:

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_i}$$

Safety consideration

$$D_{acceptable} \leq \frac{1}{DFF}$$

Figure 15: $S - N$ approach calculation flow diagram (Ersdal et al., 2019).

Fatigue loads and stresses

All types of static and fluctuating loads acting on an element and the resulting stresses at potential sites for fatigue, which are calculated by the selected fatigue assessment procedure, need to be considered. The stresses in a structure originate from dead weights, live loads, wind, snow, pressure, waves, dynamic response, accelerations, and transient temperature changes. Insufficient knowledge of fatigue loads and stresses is a primary source of inaccuracy and uncertainty in fatigue life predictions.

The most significant fatigue loading on ship-shaped structures is the global cyclic loading resulting from waves. As an average, every 8-10 seconds, a wave will force a structure through a full cycle of loading in the wave direction and against the wave direction. Waves may also give rise to slamming loads on the structure, which in special cases, the members and plates may vibrate due to this slamming load and may accumulate damage from this loading. The wind is also an essential fluctuating load that may affect cyclic loading on structures above water. The two primary loads from wind contributing to fatigue are fluctuating gust wind and vortex shedding. Fluctuating gust wind is most applicable for dynamic global structures, while vortex shedding is most applicable for dynamic, sensitive single members. Current may also be a source of vortex shedding and hence fatigue in some cases. Also, residual stresses resulting from welding may have a sizeable influence on fatigue life.

Tensile residual stresses decrease the fatigue resistance by raising the mean stress, while compressive stresses improve fatigue resistance with a resulting reduction of the mean stress and hence reducing the tensile stress range. The influence of misalignment (eccentricity) on the secondary bending stress caused by angular or axial misalignment should be considered. Different methodologies for calculating the long-term stress range distribution from global wave loading are described in DNVGL-RP-C210 (DNVGL, 2015).

Fatigue resistance

Three fundamental methodologies are used for evaluation of fatigue stress with particular $S-N$ curves for each method:

- The nominal stress method
- The structural hot-spot stress method
- The notch stress method

These methods are further described in DNVGL-RP-C210 (DNVGL, 2015).

Damage calculation

The $S-N$ curves made for offshore structures are derived from data achieved under variable amplitude loads (which are represented by an effective stress range) to simulate the offshore environment. The most commonly used method to calculate the cumulative damage is the Miner summation. This rule is derived from the assumption that the total damage accumulated is achieved by the linear summation of the damage of each individual stress range, given by Eq. (4.8).:

$$D_t = \sum_i D_i = \sum_i \frac{n_i}{N_i} \tag{4.8}$$

where D_t is the total cumulative damage, n_i is the number of cycles of constant amplitude stress ranges $\Delta\sigma_i$ and N_i is the total number of cycles to failure under constant amplitude stress ranges $\Delta\sigma_i$.

Safety consideration

A safety margin is introduced in the $S-N$ approach through the use of design fatigue factors (DFFs). The value of the DFFs depending on the accessibility and the criticality of the structural component being assessed, and range from 1 to 10 in ISO 19902 (ISO, 2007) and NORSOK N-001(Standard Norge, 2012). The safety factors applicable in NORSOK N-001 (Standard Norge, 2012) are shown in Table 12.

Table 12: NORSOK N-001 Fatigue safety factors (Standard Norge, 2012).

Classification of structural components based on damage consequence	**Not accessible for inspection and repair or in the splash zone**	**Accessible for inspection, maintenance and repair, and where inspections or maintenance are planned**	
		Below the splash zone	**Above the splash zone or internal**
Substantial consequences	10	3	2
Without substantial consequences	3	2	1

4.9 Fracture Mechanics Assessment

4.9.1 Introduction

Fracture mechanics are a complementary approach to the $S - N$ fatigue life of structures and provide a particularly useful role for the evaluation of ageing and life extension of offshore installations.

As opposed to the conventional $S - N$ approach does fracture mechanics enabling assessment of defects found during in-service inspection and fabrication. It enables a more detailed method of assessing the remaining life of a structure than the $S - N$ approach. The life extension phase has a distinct advantage in which it has the flexibility to include the precise geometry and changes in the loading. In addition, it enables both the severity of detected effects and the remaining life to be evaluated. Further, using deterministic and probabilistic approaches provides a means of scheduling the frequency and extent of inspections and determining suitable inspection techniques founded on the acceptable level of risk. However, fracture mechanics analysis is founded on the assumption that a defect is present. The fracture mechanics method also assumes that general linear elastic analysis principles apply beyond the local yielding that occurs in the immediate vicinity of crack or defect. The method does not apply to microscopic defects where non-linear effects dominate the region of the crack, specifically at weld joints with high stress concentrations.

4.9.2 Fatigue Crack Growth Analysis

Fatigue crack growth predictions by the use of fracture mechanics are founded on the use of a fatigue crack growth law. Paris and Erdogan (Paris & Erdogan, 1963) established that the rate of fatigue crack growth was connected to the range of the stress intensity factor, ΔK, as shown in Figure 16. There are three stages of crack growth:

- Stage I: Crack propagation does most likely occur only when the stress intensity factor range exceeds the threshold stress intensity factor range, ΔK_{th}.
- Stage II: At intermediate values of ΔK, there is an approximate linear relationship between the crack growth rate and ΔK on a log-log scale. This is generally characterized by the Paris equation in Eq. (4.9):

  $$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m \tag{4.9}$$

  where C and m are material constants.
- Stage III: This is characterized by accelerated crack growth, which becomes unstable and leads to fracture when the stress intensity factor attains a critical level, K_{cr}.

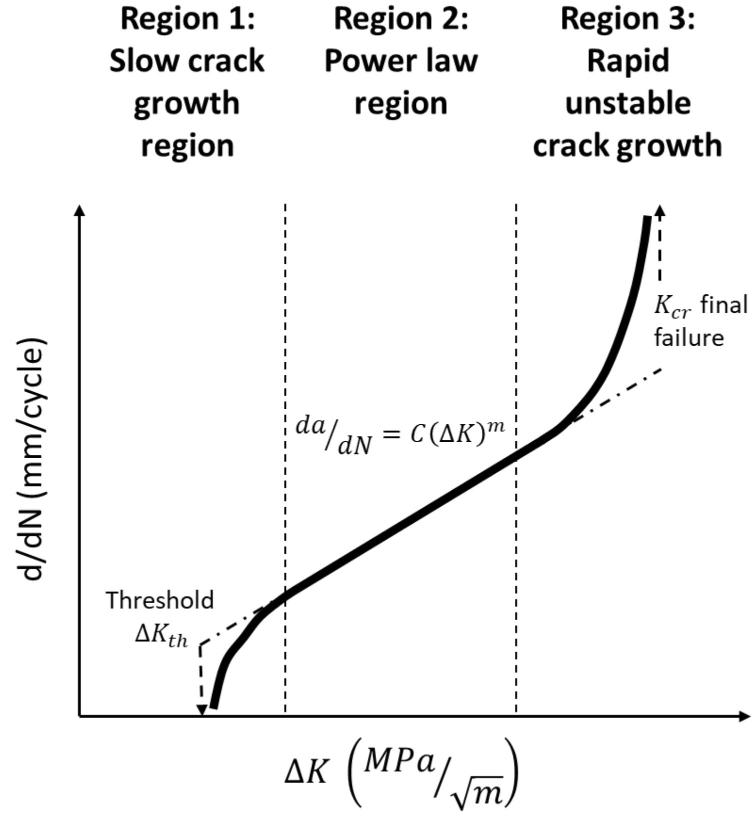


Figure 16: Fatigue crack growth rate curve (Ersdal et al., 2019).

The Paris law is relevant to the Stage II region only. Various other fatigue crack growth laws have proposed to include Stage I crack growth, which may represent a significant proportion of the total fatigue life, and other factors, such as the R-ratio to consider for mean stress effects.

The fatigue life or remaining fatigue life is calculated by the integration of the fatigue crack growth laws. The key inputs to a fatigue crack growth assessment are summarized in Table 13.

The calculation of fatigue life involves integrating the Paris law as in Eq. (4.10):

$$N = \int_{a_i}^{a_f} \frac{\mathrm{d}a}{C \cdot (\Delta K)^m} \qquad (4.10)$$

where a_i is the initial crack size and a_f is the final or critical crack size.

The initiation of the fatigue crack growth law provides a means of relating the number of fatigue cycles, component geometry, defect dimensions, the material properties and the applied loading to enable predictions of remaining fatigue life or critical crack size. Hence, fatigue crack growth is specifically relevant to the assessment of ageing and life extension.

Table 13: Fracture mechanics life assessment (Ersdal et al., 2019).

Loading data	**Material data**
Response analysis	Material parameters
Load-time histories	Environment for selection of crack growth curve
Stress analysis	Crack growth curves
Cycle counting	
Stress spectrum	

4.9.3 Application of Fracture Mechanics in Life Extension

Fracture mechanics analysis is a specifically useful tool for evaluating the integrity of a structure beyond its design life and for evaluating the importance of damage and defects, which are usually associated with ageing and life extension. Fracture mechanics analysis may be applied in the following cases:

- Assessment of the criticality of a defect/the need for repair.
- The prediction of remaining fatigue life.
- Inspection planning and optimization of inspection intervals.
- Assessment of structural modifications or changes in the loading.

An important strength of fracture mechanics is that it relates the relevant parameters such as structural geometry, defect dimensions, loading, failure load, and remaining fatigue life, through the stress intensity factor (K), the fracture toughness and the fatigue crack growth law. Therefore, the method is adequately flexible to allow for variations in the design assumptions and account to be taken of defects to quantify the integrity of ageing structure and the extent of any life extension phase. This differs from the $S - N$ method curves, which, based on the use of the stress cycle spectrum in conjunction with design $S - N$ curves, enables the prediction of the design life and does not account for detected defects.

When evaluation of the remaining life of offshore structures, the assumption that cracks initiate from defects and propagate under environmental fatigue loading is undertaken. The fracture mechanics prediction is sensitive to the input parameters, specifically to the defect dimensions and the applied loading. Therefore, careful consideration of these is required if meaningful results are to be obtained. This involves inspection of the structure using appropriate techniques to set up the relevant defect dimensions.

Additional application of fracture mechanics to ageing and life prediction contains the assessment of structural modifications by modeling the modified structure. Further, reassessment of the remaining life by the use of the updated applied loading, which can be due to structural reanalysis, updated met ocean data, or revised design code criteria. Fracture mechanics analysis is especially applicable to the management of ageing and life extension by inspection. Assessment of defects enables inspection frequencies to be decided from predictions of crack growth, which gives information on the remaining fatigue life (Ersdal et al., 2019).

4.10 Probabilistic Strength, Fatigue and Fracture Mechanics

4.10.1 Introduction

A prediction of fatigue crack growth and strength requires available data that are often subjected to considerable uncertainty. As described in chapter 4.6, this uncertainty is taken into account in design methods by using characteristic values. To ensure that these standardized characteristic values are adequately safe for all possible structures that could be designed according to a standard, design values may be chosen to be on the safe side. For a specific structure, the standardized values may be adequately accurate in life extension.

The fatigue life and strength calculations using standard approaches is subject to uncertainty and statistical variation related to three aspects of the modeling process:

- The marine environment, response, and slowly varying loads.
- The capacity.
- The structure.

Further, uncertainties may also be introduced during the fabrication process (welding defects, misalignments, etc.). For ageing structures, uncertainties will also be influenced by degradation mechanisms and new knowledge (increased knowledge of structural behavior, improved design codes, etc.). An alternative method to the standardized design approach is to apply probabilistic methods, i.e., SRA, and allow for these uncertainties and to determine the probability of limit state failure and crack development. Probabilistic methods may also be applied to plan inspection intervals and to simultaneously update the reliability of the structure after inspection or repair.

For probabilistic procedures to be successful, it requires a high level of experience and expertise, and probabilistic assessment should be undertaken only be appropriate specialists. Further, limit state failure predictions are very sensitive to the input data. Unfortunately, sufficient data may not always be applicable, and extreme care should be exercised before assumptions and approximations are made. The establishment of sufficient probabilistic models for the variables is, in most cases, the key challenge of the reliability analysis (Ersdal et al., 2019).

4.10.2 Structural Reliability Analysis

SRA is applied to analyze limit state failure related probabilities of load-strength systems. The performance of a component is expressed by a limit state function g. The limit state function is involving a set of random variables $\mathbf{X} = (X_1, X_2, \dots, X_n)$ describing the load and capacity of the structural component. Properly described, the event $g(\boldsymbol{X}) \leq 0$ defines the limit state failure of the component. Hence, the limit state of a system may be written as a function of variables $X_1, X_2, \dots, X_n$ such that in Eq. (4.11):

$$g(X_1, X_2, \dots, X_n) = \begin{Bmatrix} > 0\, safe\ state \\ = 0\, limit\ state \\ < 0\, failure\ state \end{Bmatrix} \tag{4.11}$$

where $g(\boldsymbol{X}) = 0$ is known as a limit state surface and each X indicates the basic load or resistance variable.

The limit state functions $g(X_1, X_2, \dots, X_n)$ applied in SRA may be described as shown in

Table **14**.

The probability of this limit state failure of the component is then given by the following expression:

$$P_f = P[g(\mathbf{X} \leq 0)] \qquad (4.12)$$

The reference period corresponding to the determined failure probability is expressed by the reference period for load in the limit state function for structures with a strength that is constant (independent of time) and where the load is taken as the maximum load in a given reference period. This reference period would normally be one year or the design life of the structure, giving an annual failure probability or a life failure probability.

Table 14: Limit state functions used in structural reliability analysis (Ersdal et al., 2019).

Strength analysis	$g = R - S$ where R is a random variable describing the uncertainty in strength of the structure and S is a random variable describing the uncertainty in the loading on the structure
$S - N$ fatigue	$g = \Delta - D$ where Δ is random variable describing the uncertainty with the fatigue accumulation (normally with a mean of 1.0) and D is the accumulated damage calculated by the Miner summation
Fracture mechanics	$g = a_c - \delta a$ where a_c is a random variable describing the uncertainty with the critical crack size and δa is describing the crack growth with time Alternatively, the crack growth can be described by the number of crack cycles as: $g = N_c - N$ where N_c is a random variable describing the critical number of cycles defined by fracture mechanics and N is a random variable describing the number of cycles experienced

In its simplest form, two variables would be applied, representing the strength, X_1, of the component and the load, X_2, on the component. The limit state function would then take the form $g(\mathbf{X}) = X_1 - X_2$. The difference $Y = g(\mathbf{X}) = X_1 - X_2$ is called the safety margin of the component.

If $\mathbf{X}$ is expressed by a joint probability density function f_X, the limit state failure probability of a structural component with respect to a single failure mode can formally be written as in Eq. (4.13):

$$P_f = \int_{g(\mathbf{x})\leq 0} f_X(\mathbf{x}) \cdot \mathrm{d}\mathbf{x} \qquad \text{(Eq. 4.13)}$$

This integral may generally not be solved analytically. Numerical methods, simulation methods such as Monte Carlo simulations or semi-analytical approximate methods, such as FOSM (First Order Second Moment), AFOSM (Advanced First Order Second Moment), FORM (First Order Reliability Method) or SORM (Second Order Reliability Method), may be applied, see the overview of methods in Figure 17.

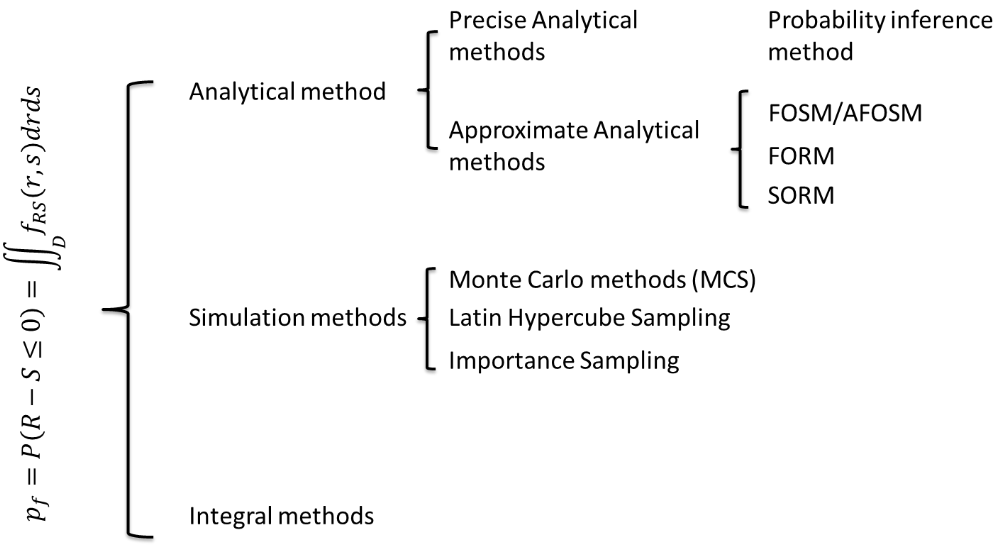


Figure 17: Probability of limit state failure calculation methods (Ersdal et al., 2019).

Different levels of reliability analysis are possible depending on the level of detail applied in uncertainty modeling. The Level I approach is based on one characteristic value for each uncertain parameter and is the basis for the partial factor method discussed in chapter 4.6. The Level II method (FOSM and AFOSM methods) incorporates two values (standard deviation and mean) for each parameter, in addition to including the correlation between parameters. The Level III reliability analysis method (FORM, SORM, and Monte Carlo simulation (MCS) methods) contains a joint probability distribution function for all involved uncertain parameters and is the most frequently applied method at present (Ersdal et al., 2019).

4.10.3 Assessment of Existing Structures by Structural Reliability Analysis

Probabilistic methods are, in many ways, the most applicable method for assessing existing structures for life extension, as they enable direct decision of the safety of the structure including all types of uncertainties, taken into account the changes in uncertainty about the structure as it gets older. However, existing codes and regulations are not adequately developed with respect to making decisions based on a probabilistic approach. The aim of SRA should be to support the decision, not making the decision, as the determined probabilities are an identification of a knowledge-based probability of limit state failure rather than an estimate of a “true” value of the probability of limit state failure. However, the method is very beneficial if applied correctly and when compared with the probability of limit state failure implicit in standards (using the same probabilistic models).

The application of SRA to life extension enables to take into account all uncertain parameters in the fatigue and strength and analysis. Further, the degradation and the uncertainty around future degradation may also be modeled. However, there is a lack of standardized methods to include such information. Probabilistic fatigue analysis of existing structures is discussed to some extent in DNV GL-RP-C210 (DNVGL, 2015).

SRA may provide an alternative assessment method for structures that fail to comply with the partial safety factor methods in standards, which also introduce greater accuracy in the reliability prediction. However, the decision-making has to be performed with care.

Performing an SRA does not have to be a difficult task. As an example, the limit state function for fatigue reliability, i.e. $g = \Delta - D$, in the simplest form of closed form damage calculation is given as follows in Eq. (4.14):

$$g = \Delta - \frac{n}{A} \cdot q^m \cdot \Gamma\left(1 + \frac{m}{h}\right) \tag{4.14}$$

where q and h are the parameters of a Weibull distribution function representing the long-term stress range distribution. A and m are the parameters of the $S - N$ curve. This limit state failure function could also be described using S_{max} (the maximum stress range in the long-term stress range distribution) directly as follows as in Eq. (4.15):

$$g = \Delta - \frac{n}{A} \cdot \frac{{S_{max}}^m}{\ln(n)^{m/h}} \tag{4.15}$$

Such relatively simple limit state problems may be solved by simulation or by the use of simple FORM iteration schemes in spreadsheets or mathematical programs such as MathCad.

SRA is particularly applicable for fracture mechanics analysis in life extension in the following cases:

- Probabilistic inspection planning
- Probabilistic evaluation of crack growth from a known crack, in order to include uncertainties related to the crack size, the loading and the material parameters, etc (Ersdal et al., 2019).

4.11 Regulatory Practice in Norway Regarding Ageing and Life Extension

Petroleum operations in Norway are regulated by the Petroleum Safety Authority Norway (PSA) based on several regulations. These general regulations are the Framework Regulation, which provides general principles. Further, the Management Regulation provides more detailed principles for risk management of petroleum operations. The Facility Regulation sets requirements for the design and layout of primarily new installations. Lastly, the Activity Regulation provides requirements for the operation phase, e.g., including asset ageing management and Structural Integrity Management (SIM).

In Norway, there is a formal regulatory requirement for an operator to get permission from the PSA to continue the petroleum activity beyond the original design life. Further, the application should include an assessment of potential preventive measures as well as:

1. An overview of non-conformities and gaps and how these are handled with regard to risk reduction.
2. A description of the operator's uses of information regarding previous behavior and use of relevant equipment, including experience from similar facilities. This can require cooperation with other operators, shipowners, and classification societies.
3. A description of the period the facility is planned to be used, identification of the factors that will limit the life of the platform, and identification of criteria for safe operation to the extent possible.
4. The operators plan for modifications, replacements, and repairs if required.
5. A description of changes in maintenance philosophy, strategy and program, which will be implemented as a consequence of the expected ageing effects.
6. The period for which consent is applied.

The summary mentioned above should, in accordance with PSA, be prepared in accordance with the Norwegian Oil and Gas Association's Guideline 122 (NOROG, 2017) complete with supplementary standards, and should contain a résumé of analysis carried out according to NORSOK N-006 (Standard Norge, 2015).

4.12 NORSOK N-006 Standard

The NORSOK N-006 standard (Standard Norge, 2015) was developed to cover those aspects that are particularly relevant to the assessment of structures and issues of life extension primarily on the NCS and to be in line with the NORSOK N-series of standards. The basic requirements for structural integrity assessment are given in NORSOK standard N-001 (Standard Norge, 2012). This standard, together with the other NORSOK standards, aims to be an independent document, but it complies with relevant ISO standards where possible. Indifference to the principles for life extension of existing structures given by ISO 19902 (ISO, 2007) the recommendations in the NORSOK standard aim to ensure the same level of safety for personnel required for new installations.

The basic principles adopted for the accidental limit state (ALS) and ultimate limit state (ULS) checks for existing structures are the same as for new structures. Hence, material and load are, therefore, the same as given in the other NORSOK standards. However, since the costs of implementing structural reinforcements or operational limits are large for an existing structure, additional requirements are provided on how to perform advanced non-linear analysis to determine structural strength. When non-linear analysis is applied for calculation of the structural strength, the standard requires that low cyclic fatigue capacity for structures are assumed to be used outside linear elastic behavior.

The different standards, NORSOK N-006, ISO 19902, and API RP 2A, differ from each other in that:

- NORSOK N-006 does not use the term RSR as a result of the non-linear analysis. Instead, it recommends using partial factors also in non-linear analysis. NORSOK N-006 is, as such, a fully partial factor method standard, even when the non-linear analysis is used.
- Since the partial factor method is used in NORSOK N-006 also in non-linear analysis, the standard requires characteristic values of yield stress to be used in these non-linear analyses. In contrast, ISO 19902 and API RP 2A indicate the use of mean values as is traditional in allowable stress design.
- NORSOK N-006 does not allow the use of SRA to document the safety of an existing structure.

Recommendations are also given for fatigue evaluation in NORSOK N-006. If the experienced service life for a structure is longer than the calculated fatigue life, it is indicated that it is possible to safely operate the platform further by using information about the performance and the inspection results. Also, supplementary guidance is given for fatigue analysis, acceptance criteria, and improvement methods that are not given in other standards. Further, special recommendations for details that cannot be inspected are included.

4.13 DNV GL offshore standards and class guidance

According to DNV GL (DNV GL, 2018) ageing units exceeding their initial design life shall be subject to evaluation for special provisions, both with respect to fatigue and coating/corrosion degradation. The special requirements for maintaining the required safety level are related to fatigue and corrosion condition of the hull and supporting structure. Degradation mechanisms due to ageing effects related to other aspects such as marine systems shall also be given due consideration by the owner through maintenance activities, and by surveyors through periodical surveys.

The special provisions with regard to the condition of the protective coating system and minimum measurements are included in the descriptions for the renewal survey as specified in (DNV GL, 2018). The same document also describes thickness measurements and inspection of protective coatings in general. The owner shall document that the corrosion protection of the unit's hull is adequate and in line with conditions assumed in the original design. The corrosion protection system shall be specially surveyed.

When the actual age of the unit exceeds the documented fatigue life, all ship-shaped units shall follow the principles for lifetime extension as given in DNVGL-OS-C102 (DNV GL, 2019), when the unit's design life is exceeded. The owner is responsible for providing the necessary documentation. Associated plans and procedures i.e., condition-based inspection plans applying a risk-based approach, shall be approved by the Society. The scope of the improvement program will depend on the initial assessment and the owner's plans for further use of the unit. Units that have undergone an assessment and improvement program to the Society's satisfaction will be surveyed based on the modified inspection program.

5. Operator experiences on ageing mechanisms

5.1 Introduction

It is desirable to investigate how ageing mechanisms on floating production units are managed during the operational life at the operator companies of these installations. This has been investigated by interviews with two operator companies; Vår Energi and Equinor. Questions about the management of ageing mechanisms were made to compare the answers from the operator companies. The questions asked are as follows:

- How are ageing mechanisms such as cracks, corrosion, deflection, and dents handled at the FPSOs? What assessments are made (related to further inspection/monitoring, whether remaining capacity is acceptable when repairs are needed and choice of repair methods)? When is it considered to perform improvements/repairs about the cracks, i.e., do you have criteria?
- How are the cracks that are found classified, i.e., you have criteria for what is, for example, insignificant, minor, and major cracks?
- What causes the cracks to occur? Is it because of aging or bad weather? Is it because of an increased focus on inspection campaigns as a function of lifetime extension?

These questions are answered in Chapter 5.2 for both operating companies.

Also, actual ageing mechanism data with the emphasis on cracks have been collected for two floating production units (Balder and Jotun A) operated by Vår Energi. The results of the actual ageing mechanism data are illustrated in graphical overviews, together with a discussion of the results found. The cracks are found on the two FPSOs by reviewing reports from the surveillance company CAN and DNV GL. In addition, data is collected from the CODAM database at PSA, where crack history reported through the operational life of the installation is stored.

Inspection findings and incidents in CODAM are to be classified into one of three severity levels; major, minor, or insignificant. The actual ageing mechanism data has been collected and analyzed with respect to:

- The annual number of cracks as a function of severity and time in operation;
- Cracks in terms of structural details;
- Cracks in terms of crack length;
- Distribution of cause of failure.

5.2 Management of ageing mechanisms at the operator companies

5.2.1 Management of ageing mechanisms at Vår Energi

How are ageing mechanisms such as cracks, corrosion, deflection, and dents handled at the FPSOs? What assessments are made (related to further inspection/monitoring, whether remaining capacity is acceptable when repairs are needed and choice of repair methods)? When is it considered to perform improvements/repairs about the cracks, i.e., do you have criteria?

Cracks are constantly monitored and repaired, and criticality is assessed based on the monitoring. Cracks that are unstable and growing are given higher priority for repair than stable cracks. The main goal is to repair all cracks that occur.

For corrosion, a reduction of 10% of the plate thickness is permitted. If any findings exceed this, improvements will be made continuously, and based on severity as well as internal assessment, data will be sent to DNV GL for third-party evaluation.

Any deflections and dents are documented, and based on severity and internal assessment, data is sent to DNV GL for third-party evaluation. Based on DNV GL's evaluation, improvements are made in consultation with Vår Energi.

How are the cracks that are found classified, i.e., you have criteria for what is, for example, insignificant, minor and major cracks?

The cracks are classified according to the PSA's database CODAM structure which is as follows:

Major - The cracks are given the highest priority and are repaired immediately.

Minor - The crack is documented, monitored, and repair is performed continuously.

Insignificant - No immediate remediation is performed, but the cracks are documented and monitored.

What causes the cracks to occur? Is it because of ageing or bad weather? Is it because of an increased focus on inspection campaigns as a function of lifetime extension?

The cracks occur in a combination of weather conditions, loading, and offloading of oil (bending moment and shear forces). For Balder, the cracks are observed to occur where the highest utilization on steel is, combined with a lot of movement (hogging and sagging). Unfavorable detailed design of brackets and longitudinals or stiffeners is also a contributing cause of cracking. It is a major difference between the two FPSOs, Jotun A and Balder, where Jotun A has rounded brackets and does not crack while Balder has brackets that are not rounded. The ageing of steel in areas where there is a lot of movement means that the fatigue has progressed, and it starts to crack. For ULS, the ageing of steel has virtually no significance. It has been found that the cracks on Balder occur mainly around the turret, where there is a lot of movement, as well as in the foreshore where the steel is highly utilized. The design of Balder FPSO is such that the aft end of the structure has lower steel quality than the steel installed around the turret, thus saving money during construction. This area in the transition from high to lower steel quality is also more frequently exposed to cracks.

For Balder, increased focus on inspection campaigns and cracks have resulted in more findings of cracks. It is assumed that several of these cracks have been there for several years but have been stable and therefore not been found in the past. Due to the increased focus, the inspectors have now gained better experience and know what to look for, and hence, they find more cracks.

5.2.2 Management of ageing mechanisms at Equinor

How are ageing mechanisms such as cracks, corrosion, deflection and dents handled at the FPSOs? What assessments are made (related to further inspection/monitoring, whether remaining capacity is acceptable when repairs are needed and choice of repair methods)? When is it considered to perform improvements/repairs about the cracks, i.e., do you have criteria?

Comprehensive inspection programs are established by DNV GL for both the FPSOs Åsgard A and Norne. These inspection programs are based on the rules DNV GL have for their class facilities. In this program, RBI analyzes are included, as well as the crack history for Åsgard A and the crack history from other Equinor installations and for other installations for which DNV GL inspects.

Inspection campaigns are carried out a couple of times a year. For these campaigns, an inspector from Equinor participate in the inspections together with an inspector from DNV GL. Typical of such an inspection is that a discovery is made, one goes through the discovery, and one assesses the cause of the discovery (whether it comes from waves and fatigue, or is it a manufacturing defect, etc.), and evaluates the finding based on severity (major, minor or insignificant). Most crack findings are either insignificant or minor. It has been found one major crack on the tank deck which has a greater damage potential than the other crack findings.

When reporting the crack findings in the CODAM database, the cracks that are generally between ballast tanks and cargo tanks has been classified as minor. Equinor has no specific approach to when improvements of the cracks should be performed or when the cracks should be repaired.

A separate assessment is made (individual assessment for each crack finding that occurs) to decide if improvements and repairs of the cracks that have occurred should be made or not. Equinor has several small cracks in the stern in stairwells that are only followed up by inspection. It has been observed that these cracks have a location that when it starts to crack, the material softens up, and then the crack will stop. Other cracks may have influence of the structural integrity or waterproof integrity. Such cracks will be improved and repaired.

A data program called SAP is used for integrity management. Among other things, this program records crack findings. The inspector, with assistance from colleagues and the academic environment (department centrally) assesses the crack findings. Many of the cracks found on Åsgard A is located in ballast and cargo tanks. Also, in the inner shell between ballast and cargo tanks at knuckle lines several cracks have been found. These cracks will be repaired by welding and detailing (e.g., insert a bracket, or extend a bracket, or alignment of brackets). Detailed analyses are performed of the given geometry. Then, one uses the local FLS model that originally has been used as a basis and incorporates the applied loads from the global model to the local model. The fatigue life of the "as-built" detail is calculated, and improvements are evaluated. Such analysis is performed to find a new life for the crack and compare it with the desired life of the detail. Typically, one can observe that the cracked details have a low lifespan. FLS analysis is not performed on all cracks that occur, but on specifically selected cracks that one considers as critical cracks. Sometimes, such analysis is performed on small equally cracks to ensure that these are in a good condition. The cracks will continue to grow if they remain in the structural detail without any improvements and repairs. Therefore, Equinor has started grinding cracks that forms.

It was a case in the foredeck of the ship at a bulkhead, which was reinforced on the front with a bracket, but which was not reinforced on the rear of the bulkhead. DNV GL performed analysis for detail improvements and it was decided to put on a bracket on the back of the bulkhead. According to stress concentration tables from DNV GL, the stress concentration will be significantly higher at the bulkhead without installing the bracket on the back of the bulkhead. By attaching this bracket, a more favorable stress ratio is provided. The improvement on that structural detail was grounding, welding and an installation of the bracket on the back of the bulkhead to move the hot spot away from the crack area.

Another case is a transverse crack that has been found on the tank deck. The crack arose from a very unfortunate detail, where two brackets had a few cm spacing between them so that all the stress concentration was collected at this point. A coating covered the tank deck, so it was challenging to discover this crack visually. First, corrosion was discovered at that area, then a crack was found under the coating by chopping up the area. This crack was found in the area above one of the cargo tanks. To remedy this crack, double habitat was used to secure a double barrier against hydrocarbons.

Most of the cracks at Åsgard A are first found by visual inspection, then they are confirmed by using NDE methods. At Norne, it is challenging to find cracks by visual inspection due to a thick coating on the deck. The cracks at Norne have appeared at other areas than what is expected from the fatigue analyses which has been made. The fatigue analyses indicate that the hot spot should appear on a different location that the cracks is found. The reason for this may be that when the fatigue analyzes based on the $S - N$ curve is performed; an assumption is made about the choice of the crack curve. Sometimes the fabrication is better than expected, and sometimes it is worse. This will move the hot spot in the analyzes being done.

A screening of the tank deck at Åsgard A has been carried out without any details, and a nominal life for tank deck is determined based on stress distribution given that there is varying plate thickness. Further, different types of details have got a corrected $S - N$ curve using a stress concentration factor, and a new corrected life of various details are found. This has been used to optimize the inspection program. Some details, such as gutter bar knuckle, which have a calculated life of less than one year, are inspected every on every inspection campaign. These details have not shown any kind of crack indication yet, so it may turn out that the fatigue model is not correct.

In general, cracks of a certain size that arise are repaired by welding. The repairs may be complicated, especially cracks that are against the sea in the side shell. At Norne, a particularly suitable habitat has been developed for this purpose. The habitat is placed by means of a magnetic crawler that creeps down along the side of the ship and welding is performed from the inside of the ship to seal it from the outside. Particular welding procedures have been made to this welding operation. Fortunately, there have been no cracks against the sea in the side shell at Åsgard A.

It has been a philosophy in the past at Åsgard A that only the most critical cracks were improved and repaired. Lately, there has been more focus on the economic and time-consuming aspect of such philosophy. Today, cracks found at an early stage will be grinded, and it has been found that a lot of time and money is saved. For example, a crack indication on a bracket of a small dimension can be sanded and softened at the edges. This can be performed as cold work. Hot work, on the other hand, typically a welding repair is often a month of preparation, a month of work and a month of after-work.

The number of cracks per square meter is fairly evenly distributed between the fore ship and the mid-ship on Åsgard A, while there have been found virtually no cracks in the aft ship. Nor are there any cracks between the turret and the fore ship. The number of cracks on Åsgard A until today is accumulated up to approximately 250 cracks, most of which have been repaired along the way. At Norne, there are accumulated up to approximately 200 cracks. This includes cracks found on the hull beam support structure and topside cracks. Cracks in modular structures topside, cracks in pipe supports, as well as cracks in stairwells and door frames, are not included as part of these cracks.

How are the cracks that are found classified, i.e., you have criteria for what is, for example insignificant, minor and major cracks?

Major, minor, insignificant.

What causes the cracks to occur? Is it because of aging, or bad weather? Is it because of an increased focus on inspection campaigns as a function of lifetime extension?

The cracks are most often detected by inspection campaigns. Some of the cracks are due to poor craftsmanship associated with fabrication, while other cracks are fatigue cracks due to wave load over time. There were detected fewer cracks in the beginning of the operational life at Åsgard A than at Norne. The reason for this is due to the lack of local stiffening of plate fields on Norne from the fabrication. No brackets were installed on the cargo tank side at Norne, but this was done at Åsgard A. Further, the cracks found in the mid-ship are often related to the knuckle lines at Åsgard A. Cracks on the tank deck at Åsgard A have been related to unfortunate details on brackets. The brackets have thick flanges, as well as poor craftsmanship of the welds. While at Norne, the cracks found in the mid-ship both are related to both the knuckle lines and a high s/t ratio. The ratio of stiffness to plate thickness at Norne is $s/t = 50$. Experience indicates that a ratio of less than 45, will not give challenges with implementations. But a ratio over 45 gives a fragile construction. Either there is too much distance between the stiffeners, or the thickness of the plate should be greater. To low ratio will result in a high tension of the construction and it will eventually crack. A high number of such cracks have been found on Norne. Such cracks on the ship's side will be continuous in the end. Therefore, these types of cracks have been improved by welding. Some cracks have also been found in the foreship at Norne. In the foredeck, it is more challenging to inspect the cracks due to added thermal insulation on the side shell of the ship.

5.2.3 Results and discussion of ageing mechanisms at the operator companies

The interviews with Vår Energi and Equinor show that neither of the operating companies have a clear approach for improvements and repairs of cracks that are detected. This is usually decided based on the engineer's subjective evaluation of the severity of each crack. The severity levels for classification of cracks have shown to differ between operators and the operator's subjective evaluation. Evaluation criteria, as shown in

Table 15, should be implemented in standards and regulations. This will result in that the classification of cracks at the operator companies is evaluated based on the same criteria, and severity level of the cracks reported in CODAM to the PSA has grounds for being compared.

Further, both the operator companies have a number of small stable cracks at their FPSOs. These small stable cracks should be repaired at an early stage, when the crack start to initiate, by grinding and improvement of the details. By repairing the cracks at an early stage, the cracks will be prevented from growing and will not reach a critical size. Such repairs is possible to perform as cold work, which is a more economical way of treating the cracks and a lot of time is saved.

5.3 Collection of crack data for Balder and Jotun A

5.3.1 Introduction

The purpose of this section is to collect actual ageing mechanism data for the two FPSOs; Balder and Jotun A. This information is of importance to this project to ensure that the engineering methods and analytical procedures used in life extension of ship-shaped floating production units must be consistent to the ageing mechanisms observed. Good communication and shared information from the operator company, Vår Energi, have allowed establishing trends that correlate the FPSOs with actual ageing mechanisms. These trends are based on available information about the cracks, which have been inspection reports from the surveillance company CAN and DNV GL. The inspection reports included the following information about almost every crack, where some information was missing for various of the cracks; photos, crack size, date the crack was found and date the crack was repaired, location of the crack, and NDE method used at the inspection. Design and fabrication details have not been available in this project. This may have been a contributing cause of the crack occurring, or it may have been the triggering cause of the crack occurring.

The impact ageing mechanisms have on the FPSOs depends on several factors, such as the extent, mode of failure, and location of the damage on the FPSO. Small cracks that are isolated, e.g., at the tow of a bracket will hardly affect the overall strength of the structure. In contrast, a crack of significant length on the main deck or the hull can seriously affect the structure's residual strength, which is defined as the strength of the structure after damage. The failure mode also acts upon the remaining residual stiffness of the structure. A structure with brittle failure, like rapid cracking, can hardly possess any reserve strength, and in the worst case, the failure can lead to total collapse of the structure. While a structure with a ductile failure, like deflection and dents, usually possesses post-buckled strength, which allows the structure to continue to carry load after damage. The location of damage on the FPSO also influence the residual strength of the structure. For example, damage at the ends can lead to less loss of residual strength than those in the middle of the hull due to high bending moments in the middle of the hull.

The collected information for Balder and Jotun A is shown in Appendix A. Further, a guidance for classifying the severity of the crack findings have been made. The severity classification is based on the degree of influence of watertight integrity and structural integrity and the structure. A description of each severity classification in addition to examples of typical crack locations for each severity classification is described in

Table **15**.

Table 15: Guidance on severity classification of cracks.

Severity classification	**Description**	**Crack location examples**
Major	Cracks that may threaten the integrity of the main loadbearing structure or the hull girder within 0.4 L amidships or in the moonpool area.	Across the main deck/cargo tank deck Side coaming with crack growth into the deck Stiffeners in the ship's side (horizontal cracks) Girder
Minor	Penetrating cracks in the side shell, bulkheads, tanks or in primary loadbearing structures, or cracks that is not defined as major severity.	Vertical bulkhead Bulkhead stiffener Longitudinal Stiffeners in the ship's side (longitudinal cracks) Stiffeners in ballast/cargo tank with crack growth in deck Major cracks in boiler room Minor cracks in ballast/cargo tanks (in the ship’s side)
Insignificant	Minor cracks in secondary structures, at corners of cut outs, slots and similar details, or cracks that is not defined as minor severity.	Minor cracks in side coaming Stiffeners in ballast/cargo tank Buckling stiffener Minor cracks in boiler room Door frame Minor cracks in ballast/cargo tanks (mid ship)

The evaluation of the reasons for which the cracks have occurred is based on the reasons listed in Table 16.

Table 16: Reasons for which cracks initially occur.

Cracks initiation reasons
Material imperfections
Uneven loading conditions
Fatigue
Corrosion
Unfavorable design of detail
Unfavorable fabrication
Temperature changes (thermal cracking)
Accidents
Unfavorable welded construction
Unfavorable modification/repair of details

5.3.2 Description of Balder FPSO

Balder FPU is a double hull ship-shaped structure. It is located at the Balder Field 190 km west of Stavanger. The water depth is 125m. The hull of the Floating Production Unit Balder is largely conventional with respect to ship structural details. The vessel is permanently moored as weather-vaning by using a semi-active turret mooring and dynamic positioning system (DP system). The general arrangement of Balder is shown in Figure 18. The tank arrangement is shown in Figure 19. A typical web-frame is shown in Figure 20. The hull of Balder FPU was designed without corrosion margin as the usual practice today for FPSOs. This implies that it is essential to maintain the coating to keep it in good condition over the whole service life.

Table **17** summarizes the general particulars of the Balder structure (DNV GL, 2017).

Table 17: Main particulars of Balder FPU (DNV GL, 2017).

Parameter	Value
Length over all:	211.1 m
Length between perpendiculars, LPP:	200.6 m
Beam:	36.0 m
Depth:	20.8 m
Storage Capacity:	380,000 barrels
Topside Weight:	3,700 tons
Turret Diameter:	17.2 m
Maximum no. of risers:	20
Mooring legs:	10

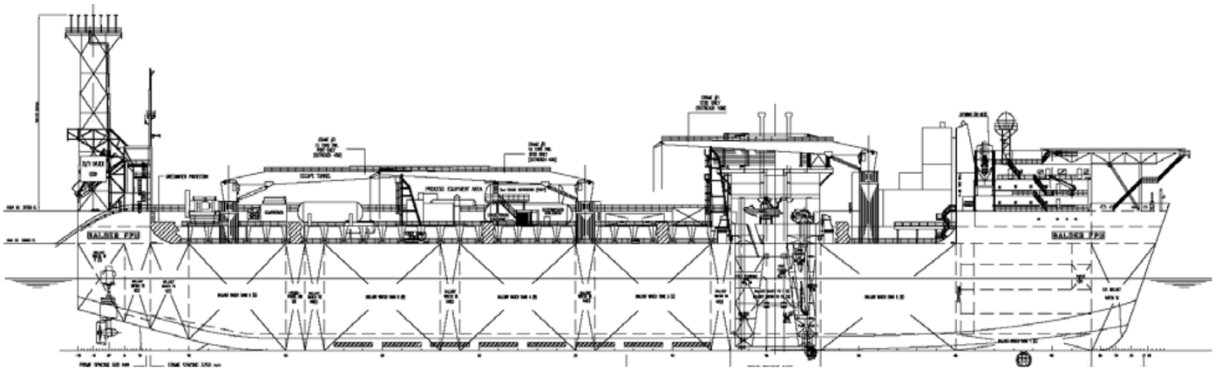


Figure 18: General arrangement of Balder FPU (DNV GL, 2017).

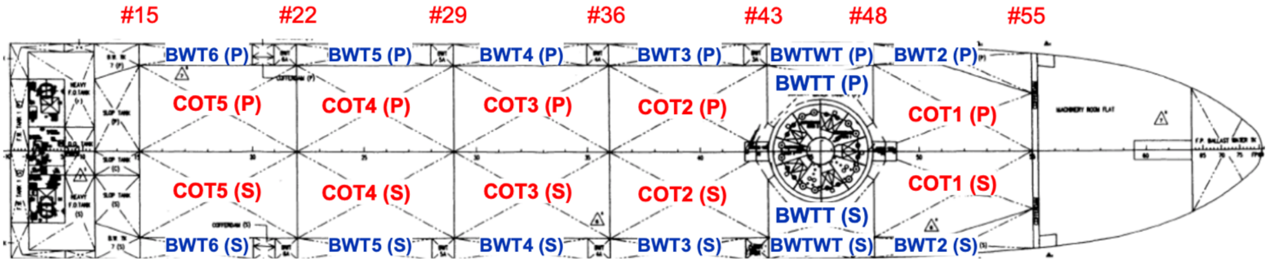


Figure 19: Cargo and Ballast tanks, frame numbers of Balder FPU (DNV GL, 2017).

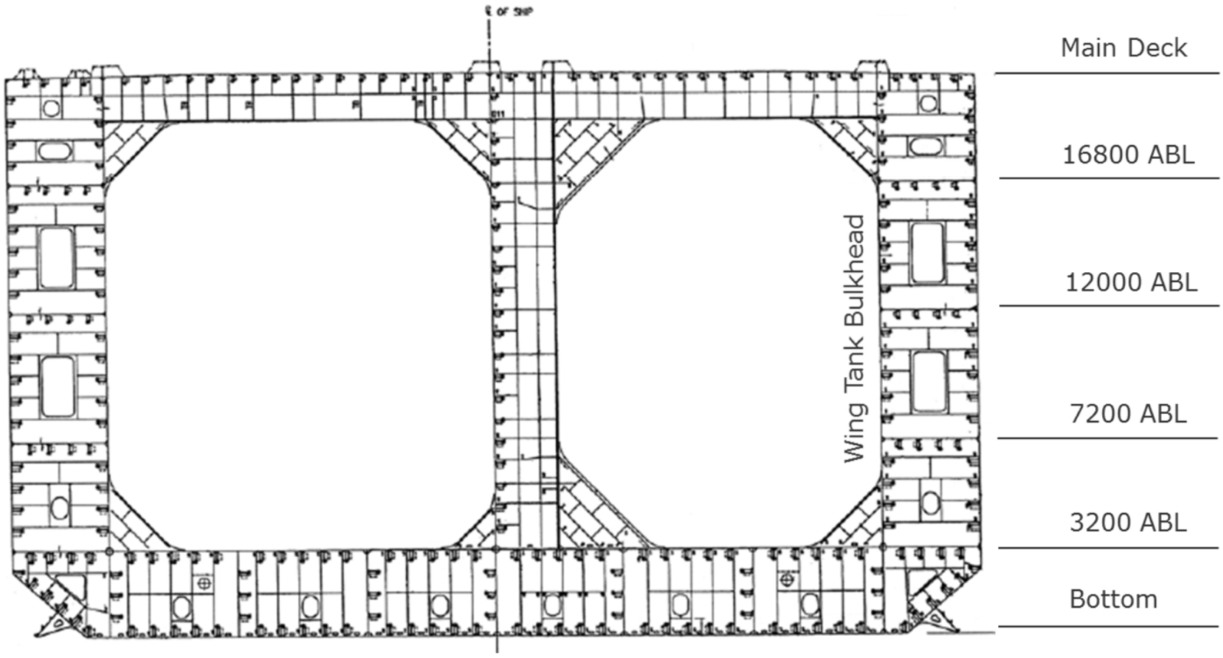


Figure 20: Typical web-frame of Balder FPU (DNV GL, 2017).

5.3.3 Description of Jotun A FPSO

The Jotun A is a double-hulled, ship-shaped vessel with an internal turret that allows the ship to weathervane to reduce the environmental forces. It is permanently moored on location by a 12-chain mooring line spread that is attached to the turret. The hull has been fabricated by usual shipyard methods, using conventional shipbuilding steels, and to the satisfaction of Norwegian regulations, Jotun requirements, and DNV class requirements. Table 18 summarizes the general hull particulars as follows:

Table 18: Main particulars of Jotun A FPU (Vår Energi, 2017).

Parameter	**Value**
Length overall	232.00 m
Length between perpendiculars	216.11 m
Breadth	41.50 m
Depth moulded	23.75 m
Draught, scantling	16.00 m

In addition, the vessel is equipped with a 140-meter long bilge keel starting from approximately 50 meters from the stern.

Design life: The Jotun A is designed for 20 years of continuous infield operation. This special design incorporates such features as:

- Double hull with access to key hull structure for inspection, maintenance, and repair
- Internal retractable thrusters
- Impressed current system instead of non-replaceable anodes
- High fatigue life

Hull overview: Figure 21 shows subsea inspection permit areas and seachest locations on the hull (Vår Energi, 2017).

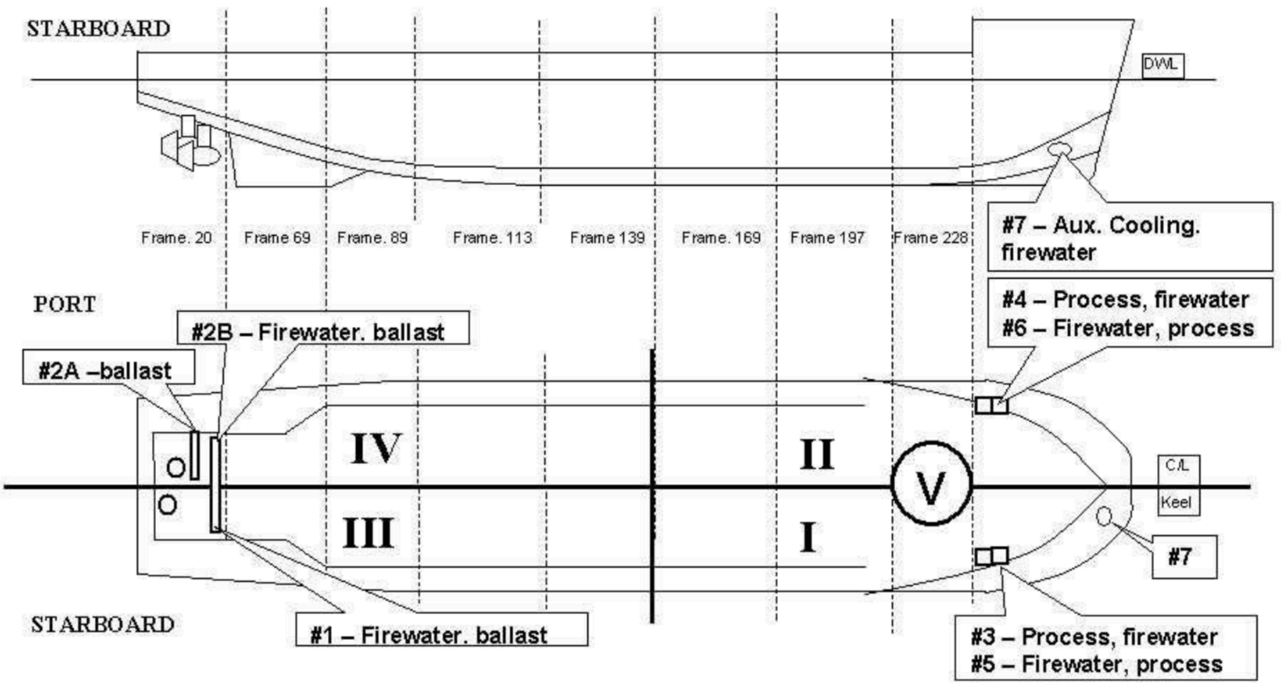


Figure 21: subsea inspection permit areas and seachest locations on the hull (Vår Energi, 2017).

5.4 Results and discussion of crack findings at Balder and Jotun A

5.4.1 Crack findings at Balder FPSO

Figure 22 identifies a general classification of the annual number of cracks in the hull on Balder as a function of the severity of each crack in the period 1999 to 2020. These classifications are based on the author's subjective evaluation and have not been quality assured by the PSA. The total number of cracks found at Balder during this period is 333. The figure indicates that the majority of the cracks have an insignificant severity classification. During this period, the number of insignificant cracks found at Balder is 169, insignificant/minor cracks are 23, minor cracks are 49, major cracks is 23, and unknown cracks is 69.

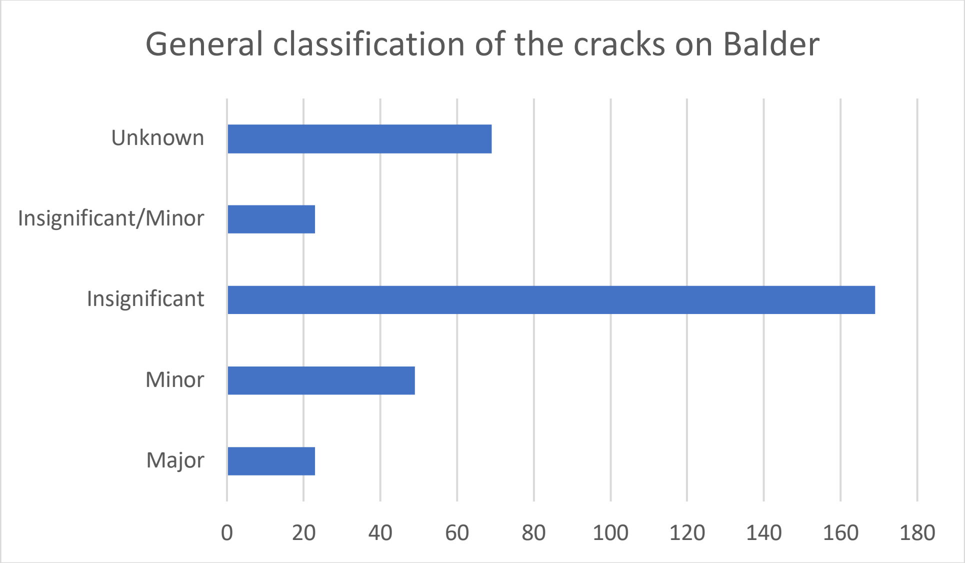


Figure 22: Annual number of cracks on Balder as function of severity of the cracks.

Figure 23 illustrates the cracks in terms of structural details in the hull on Balder. This is based on the author's subjective evaluation of the photos in the inspection reports. Some of the structural details were not possible to evaluate from the photos and have been classified as unknown. Most of the cracks are found in ballast tanks in the way of longitudinal side shell stiffeners connection to transverse frames and bulkheads (bracket toes, lugs, and slots) and in the way of the weld between the side shell and the longitudinals. These cracks are usually caused by fatigue due to reduced effective shear area in the bulkheads of the hull girder. It is found more cracks in the fore ship than the mid-ship and aft of the ship. Further, many cracks are reported in the void spaces such as cable transit frames, and door frames. These types of cracks are typically caused by unfavorable design of details with a small radius in the corners of the cut-outs. Few cracks are reported on the deck plate, in the cargo area, and the bulkheads between cargo and ballast tanks. Further, a low number of cracks are found in the girder, wind wall, and side coaming.

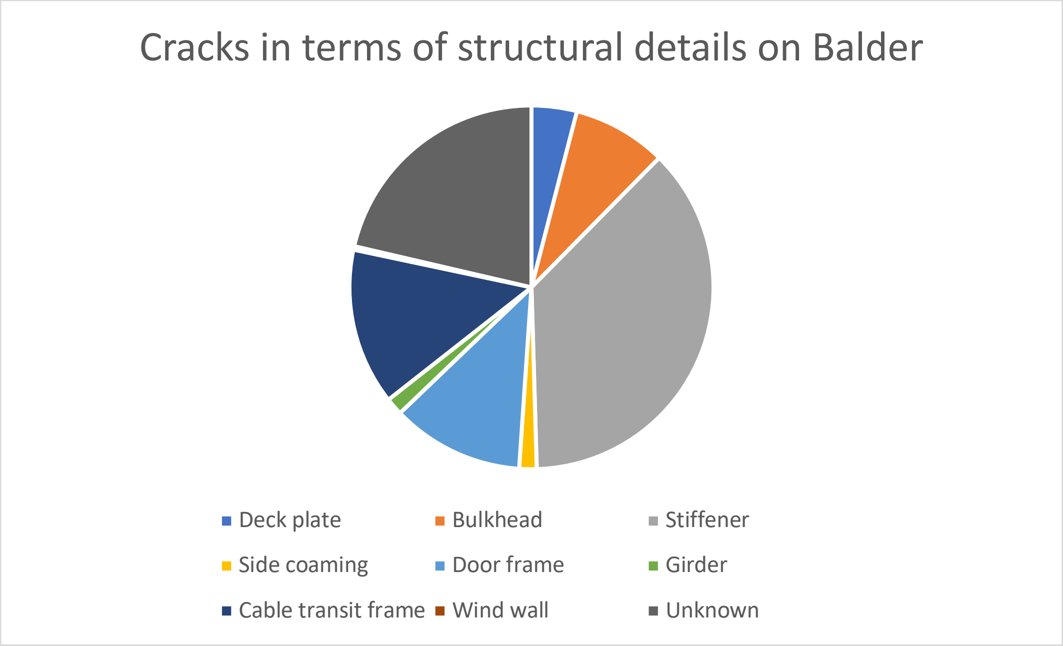


Figure 23: Cracks in terms of structural details on Balder.

A closer study has also been performed on the crack lengths and the causes of failure of the cracks. Figure 24 shows a distribution of measured crack length on Balder. This is based on the reported length of the cracks in the inspection reports. Most of the cracks found at Balder has a length between 25-500 mm. The total number of cracks in between 0-25 mm is 85, 25-500 mm is 235, 500 mm, and above is 2, and the number of unknown reported cracks is 11. The two cracks which are reported to be above 500 mm in length have been found in the main deck out to ship side, and one of which is unknown.

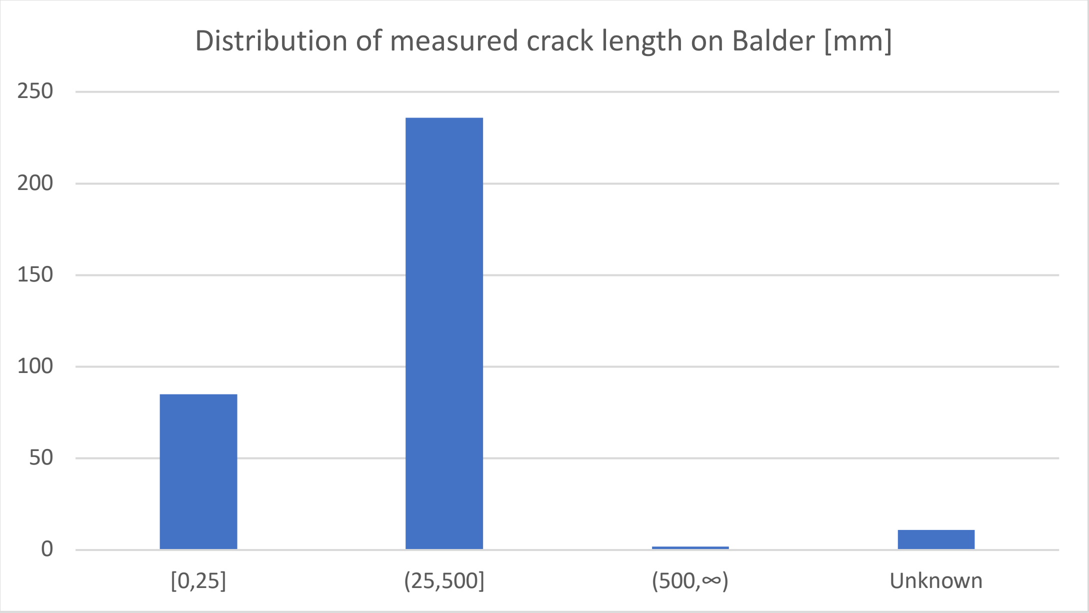


Figure 24: Distribution of measured crack length on Balder.

Figure 25 shows the distribution of cause of failure on Balder. This distribution is based on the author’s subjective evaluation and has not been quality assured by the PSA. Most of the cracks seem to be caused by unfavorable design of details and fatigue failure. However, some of the cracks are also caused by unfavorable welded constructions and unknown reasons. A small portion of the cracks is also caused by corrosion and unfavorable modification/repair of details.

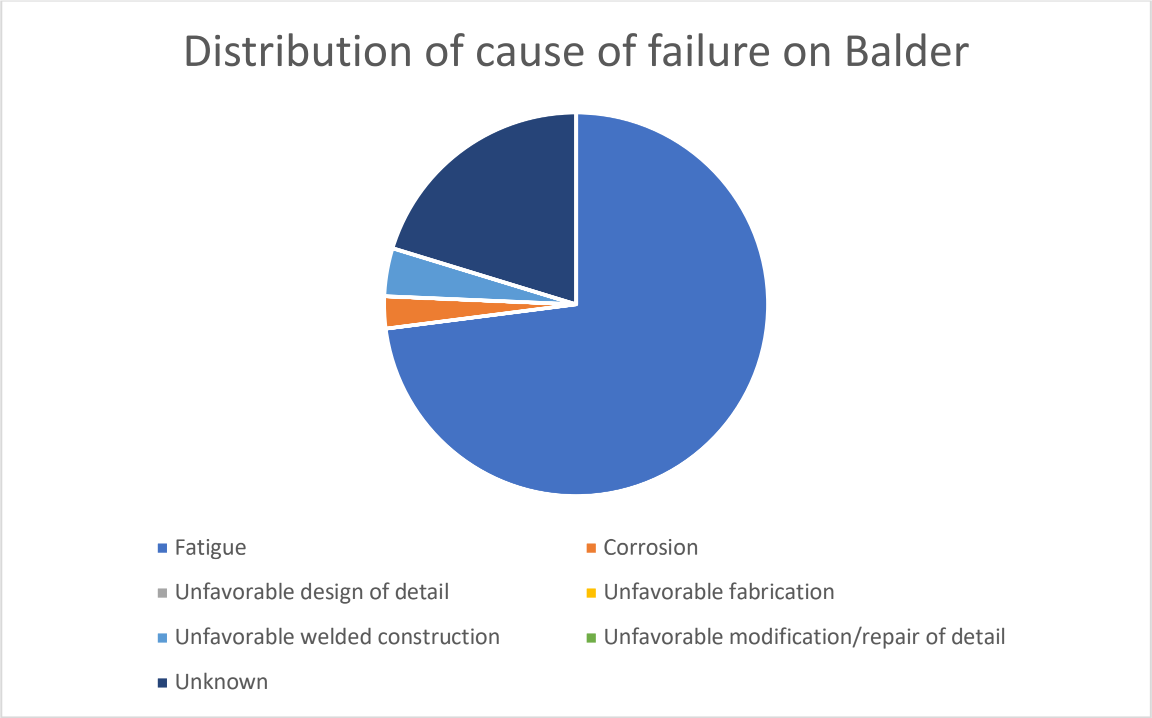


Figure 25: Distribution of cause of failure on Balder.

5.4.2 Crack findings at Jotun A FPSO

Figure 26 identifies the annual number of cracks in the hull on Jotun A as a function of yearly reported cracks and the severity of each crack in the period 1999 to 2020. These classifications are based on the author's subjective evaluation and have not been quality assured by the PSA. The total number of cracks found at Jotun A during this period is 12. Figure 26 indicates that the majority of the cracks have an insignificant severity classification. During this period, the number of insignificant cracks found at Jotun A is 8, and the number of minor cracks is 4.

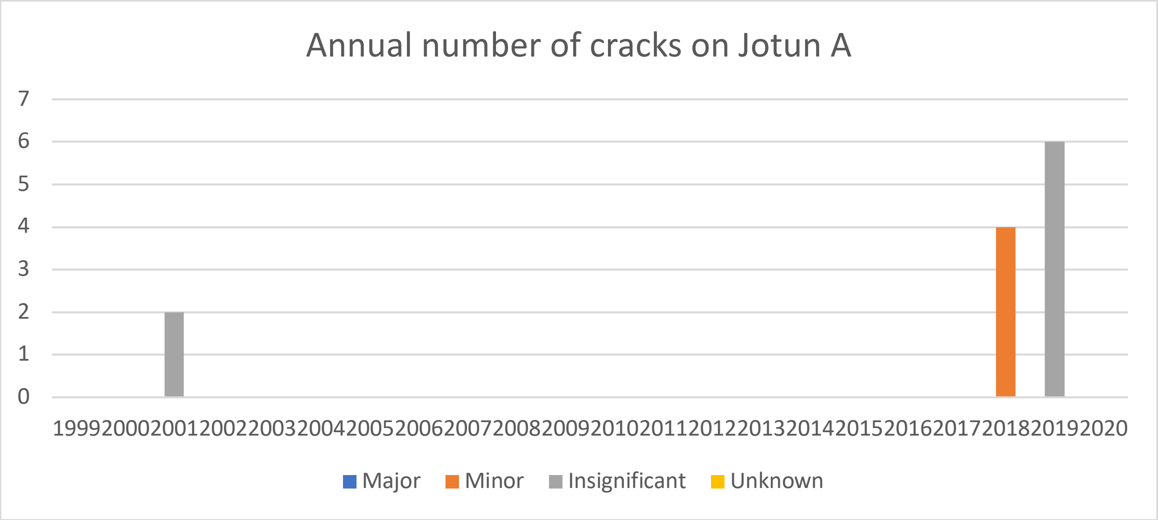


Figure 26: Annual number of cracks on Jotun A.

Figure 27 illustrates the cracks in terms of structural details in the hull on Jotun A. This is based on the author's subjective evaluation of the photos in the inspection reports. Some of the structural details were not possible to evaluate from the photos and have been classified as unknown. Most of the cracks were found in void spaces at door frames. These types of cracks are typically caused unfavorable design of details with a small radius in the corners of the cut-outs. Further, cracks are also found ballast tanks in longitudinal bulkheads and hopper knuckles. These cracks are usually caused by reduced effective shear area in the bulkheads of the hull girder in combination with unfavorable welded constructions.

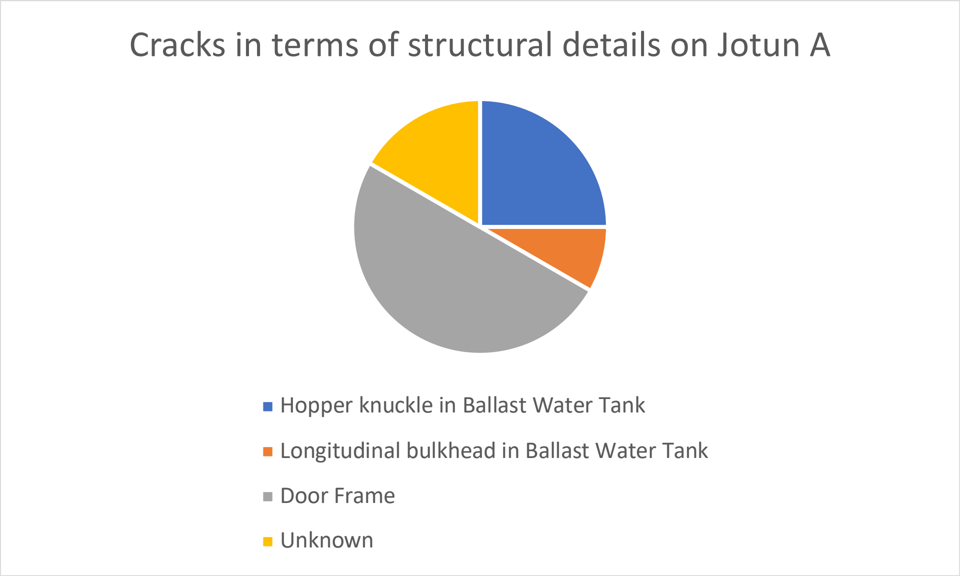


Figure 27: Cracks in terms of structural details on Jotun A.

A closer study has also been performed on the crack lengths and the causes of failure of the cracks. Figure 28 is illustrated in shows a distribution of measured crack length on Jotun A. This is based on the reported length of the cracks in the inspection reports. Most of the cracks found at Jotun A has a length between 25-500 mm. The total number of cracks in between 0-25 mm is 2, 25-500 mm is 8, and 2 cracks are reported as unknown.

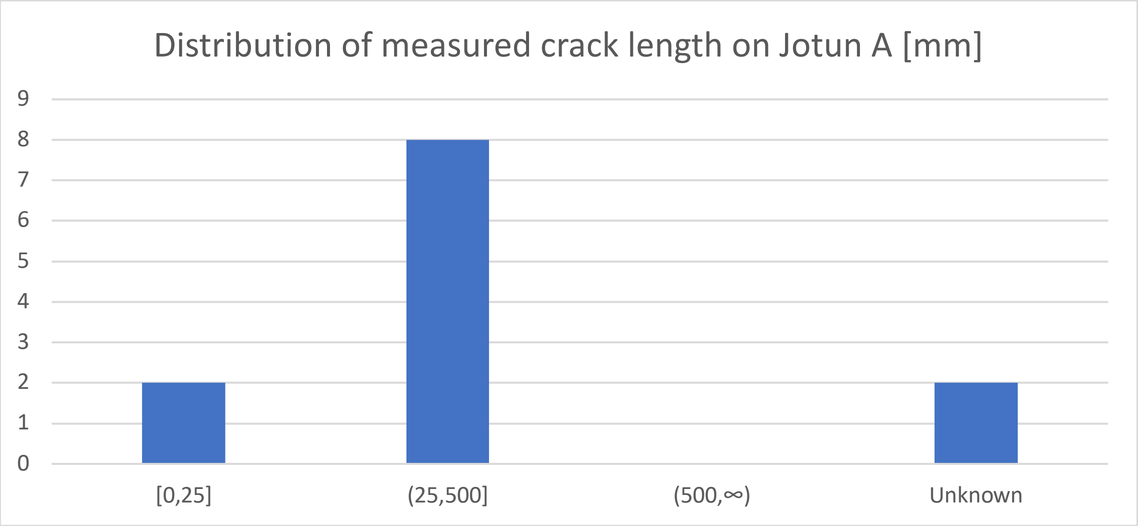


Figure 28: Distribution of measured crack length on Jotun A.

Figure 29 shows the distribution of cause of failure on Jotun A. This distribution is based on the author's subjective evaluation and has not been quality assured by the PSA. Most of the cracks seem to be caused by unfavorable design of details. However, some of the cracks are also caused by unfavorable welded constructions and unknown reasons.

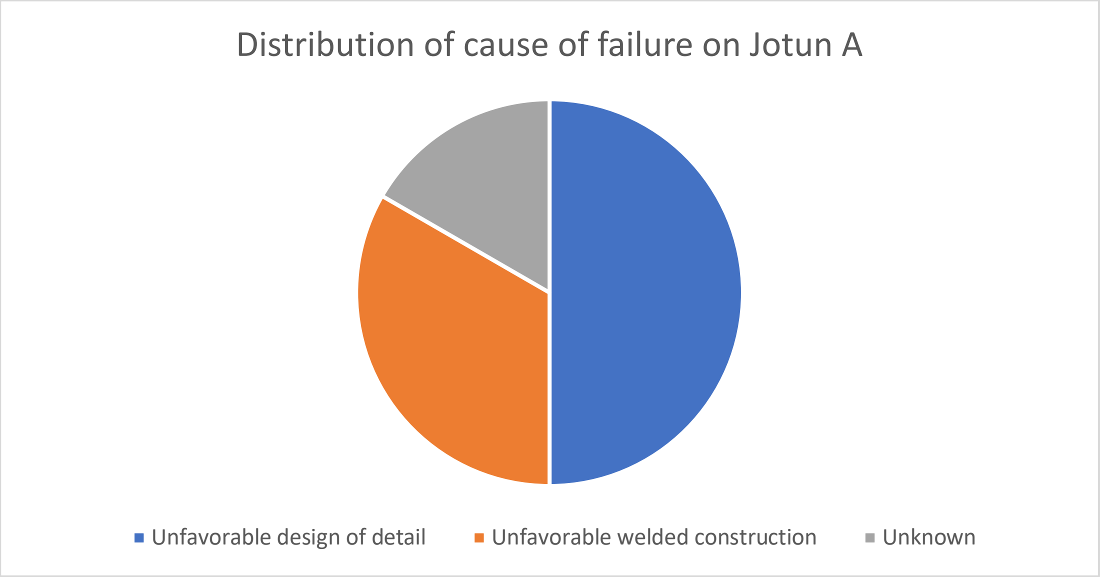


Figure 29: Distribution of cause of failure on Jotun A.

6. Life Extension Practices at the operator companies

6.1 Introduction

Life extension practices of ship-shaped units have been investigated to identify improvements and possibly standardization for future projects. Investigations of the life extension process for FPSOs have been performed by interviews with the operator companies, Vår Energi and Equinor. A question about the life extension process were made to compare the answers from the operator companies. The question asked for is as follows:

- How is the life extension process performed?

The life extension assessment practices for FPSOs are described in Chapter 4. This chapter will further investigate the life extension practices at the operator companies, Vår Energi, and Equinor. Also, this chapter will investigate in which degree the operator companies have performed life extension assessment of these FPSOs in accordance with Norwegian regulation and the standard NORSOK N-006. Lastly, a discussion of suggestions for improvements to the NORSOK N-006 standard for assessments of FPSOs.

6.2 Life extension practices at Vår Energi

The lifetime extension processes of marine structures are at the operator company Vår Energi, prepared in cooperation with DNV GL. A new inspection framework program is created which specifies the performance of annual inspections. RBI analyses are performed in advance of the inspection program and specify areas of which the likelihood is greatest for damage and degradation, and hence, require more frequent inspection. The inspection program is prepared based on FLS analysis for the entire ship. Evaluations and analyzes are performed for all equipment on the ship to ensure that the equipment is in accordance with the latest updated requirements of the PSA. Updated analyzes is also prepared for the hull and anchor lines. The inspection program aims to identify cracks, corrosion, deflections, and dents that should be repaired.

The reports developed by the operator in cooperation with DNV GL as the basis for the life extension decision on Balder FPU is as follows:

- Assessment of fatigue cracks in the hull
- Life extension evaluation
- Hull Structural Design Brief
- Longitudinal strength analysis (ULS)
- Global Fatigue and RBI analyses of Balder FPU
- Balder FPU, Deck, Hull, and Mooring System Structural Inspection Framework Programme 1999-2030.
- Summary report

The reports conclude that Balder life extension project is possible to document life extension of Balder FPU until 2030. The conclusion is based on performed analyses and fatigue testing of the mooring chain.

6.3 Life extension practices at Equinor

The life extension process at the operator company Equinor is performed in cooperation with DNV GL. The NORSOK N-006 standard was used when DNV GL made its lifetime extension assessments of Åsgard A FPSO. As an example, calculations of the hull, mooring lines, and marine systems was performed by DNV GL as a part of the life extension process of Åsgard A FPSO.

Analyzes of the stresses of the area around the turret and the hull beam with regard to ballasting were updated. Further, a gap analysis was performed of the hull beam to identify changes in relevant regulations and guidelines compared to when Åsgard A was designed. A qualitative assessment, an engineering judgment, was performed on whether this would influence Åsgard A. The gap analysis provided insight into regulatory changes that have been introduced. The analysis indicated that that the influence on the hull beam on Åsgard A was insignificant. Further, the global model was updated and checked against new regulations.

With regard to cracks in the hull, two different analyses have been performed in the life extension process of Åsgard A. First, FLS analysis was performed to determine fatigue life predictions as well as an appropriate inspection plan. These analyzes are determined of the detail both "as-built", without the accumulated damage, and for which it is planned to be after the repair. An FLS analysis of Åsgard A has also been determined in which there has been a hypothetical condition where one has extensive corrosion. This is a condition that is not present, but purely hypothetical if the maintenance was excluded and the painting had been performed. Such fatigue analysis is performed to screen the impact this situation will have on the ship.

An assessment of existing cracks and how long it will take before they reach the exponential growth phase of the fatigue crack growth curve. As an example, a crack in a cargo tank had reached a considerable size. Although it was desirable to postpone the repair of the crack due to another important project. Fracture assessments were performed by DNV GL to calculate the growth rate of the crack and find the time when the crack reached an exponential phase. The estimated time to reach the exponential phase for that specifically crack was 4-5 years. Then the repair of the crack was desired to postpone based on these analyzes, and a temporary repair of the crack was performed by sealing. The crack was followed up through the inspection program twice a year during this period. Fortunately, there was little change in the crack size of this specific crack during this period.

Further, an evaluation was made of the condition of Åsgard A with regard to corrosion. DNV GL performed a visual inspection at Åsgard A of the ballast tank with the worst condition. The ballast tank had a lot of local corrosion, but no corrosion which led to limited strength and capacity. DNV GL found that the corrosion did not influence the structural integrity of the installation. Also, DNV GL performed a parameter study and calculated the life of some typical details on the structure with respect to corrosion. It was determined how many details of which would have a life span shorter than the target if the condition was as freshly painted. The result was that around a hundred details would have a shorter life than the target. These details were not critical, and they were easy to inspect. Further, it was desired to repair the cracks which appear in another condition that had changed the $S-N$ curve due to corrosion. The result was that a thousand of details had too low fatigue life. In this situation, one had suffered a loss of thickness on the details. The loss of material thickness that DNV GL determined was the largest allowable loss of thickness, where one still met the ULS requirement. This is a good argument that it is essential to maintain the paint program. If one does not maintain the paint program, one will get an extreme amount, several thousand, of cracks that must be performed over the next few years.

6.4 Results and discussion of life extension practices at the operator companies

By comparing to the literature study in Chapter 4 about life extension assessment practices for FPSOs, the condition of the structure as it is at the current state has to be assessed, including deterioration mechanisms such as corrosion, cracks, and dents. Then, based on this assessment, existing computer models and drawings have to be updated to perform the necessary analysis. This is done at both the operator companies in cooperation with DNV GL. To ensure reliable results of the analysis, the load description has to be updated based on the changes in loads or load specifications. Such updates in the loading computer are performed at both the operator companies. Degradation history data of the structures, such as the number of cracks and extent of the corrosion, is essential information when performing a life extension of a structure. This information is followed by using the inspection framework program made at both companies.

Further, the assessment should also cover risk analysis, including future operations, which is updated with relevant incident and accident history data of the structure. By reviewing the reports from Vår Energi, they have one report regarding global fatigue and RBI analyses of Balder FPU. Equinor has also performed such analysis.

Lastly, all planned modifications and changes to the structure during the life extension period have to be covered in the assessment. This part is indicated in the reports for the life extension of Balder FPU. This part is not included in this project for Equinor due to missing information.

6.5 Suggestion for improvements in the NORSOK N-006 standard for assessment of FPSOs

Interviews with the operator companies Vår Energi and Equinor shows that the NORSOK N-006 standard is used as a basis for the life extension assessment process. Still, the standard is more or less followed unconsciously. Both operator companies convey that the needs are met for the life extension of FPSOs.

A discussion arose as to whether the standard should be specifically detailed with carefully listed all the work activities needed to be performed to conduct a life extension process, or if the standard should describe the process in more general terms. The positives of having a specific standard are that the activities listed in the standard will be performed, and it is clear which activities should be performed. On the other hand, the consequences are that activities which are not specifically indicated in the standard will not be performed. In other words, it is two methods of writing a standard. Either the standard is describing which activities needed to be completed, or the standard describes in addition, in detail, the process of which methodology should be used to perform the analysis. The operator companies conclude that it is essential to require expertise, rather than that the standards are specifically detailed. The NORSOK N-006 standard does not include competence requirements. However, other NORSOK N-series standards include competence where the competence of the surveillance companies while the competence of engineers is vague. This may be implemented in the NORSOK N-006 standard in the future.

The expectation from the authorities at a general level for a life extension process of an FPSO is that the documentation is indicating that the installation is sufficiently safe during the extension period. Unfortunately, often there may be insufficient documentation on various installations for life extension. The interviews indicated a difference between the opinion of the operator companies and the PSA’s expectations regarding the content in the documentation for life extension. The applications from the operating companies are often unclear and vague. Nevertheless, it is usually apparent when the PSA requests more thorough documentation that sufficient assessments have been made. It turns out that the applications are often written unclear and vague with the intention that the operating companies are trying not to commit to too many activities in the applications.

On the other hand, PSA wants sufficient documentation to ensure that the installations have the safety required at all times. Both the operating company and the PSA agree that it is essential that safety is maintained. Therefore, updated standards would be favorably describing the expectations of documentation required for a life extension so that what is required in the standards is sufficient for the PSA and, at the same time, documentation that the operating companies wish to include in the life extension application of their installations. It will be difficult for the PSA to confirm to the authorities that the operating companies have a good plan for lifetime consultation if this is not clearly stated in the lifetime extension applications. It is essential that the NORSOK N-006 standard is as sufficient as possible so that what is expected of the PSA and what the industry thinks is sufficient is described in the NORSOK N-006 standard. That would be the ideal situation because then the operating companies could say that they have done all the assessments as described in N-006 and felt confident that this ensures the safety required. If the NORSOK N-006 standard is at such a level for all types of facilities, then both the operating companies and the PSA could be assured that if this standard is followed, then the requirements are set to ensure safety. In such a situation, what would be expected of the PSA would be no doubt, and there would also be no doubt as to what is required of documentation from the operating companies in a lifetime extension application.

Both the operating companies Equinor and Vår Energi has stated that the standard NORSOK N-006 seems to be based on common sense. Much of what is being done at the operating companies today is made unconscious in accordance with this standard (without being aware that this is being followed).

It was pointed out that NORSOK N-006 did not give very detailed guidance for the assessment of ship-shaped structures, including guidance in unfavorable structural details typically found in FPSOs or how to check capacity is damaged and deteriorated stiffened plates, However, in most cases, damage and deterioration such as cracks were repaired and an assessment was less needed.

7. Concluding remarks

7.1 Summary and conclusions

In this project, life extension of ship-shaped floating production units has been investigated. This includes an assessment of relevant ageing mechanisms for FPSOs, such as cracks, corrosion, load changes, deflection, and dents in the hull girder. In addition, two literature studies have been performed, one on hull structural integrity management and one on life extension practices for FPSOs. Furthermore, investigations of operator experiences on managing actual ageing mechanisms on their FPSOs. Ageing mechanism data with the emphasis on cracks is collected and analyzed for two FPSOs at one operator company. The project also investigates the life extension process for ship-shaped units. This investigation addresses the extent to which the operating companies have performed the life extension assessment of their FPSOs in accordance with Norwegian regulation and the standard NORSOK N-006. Results show that the companies are following this regulation and standard. The project closes with a discussion regarding suggestions for improvements in the standard NORSOK N-006 for assessments of FPSOs.

Studies on crack data of two floating production units of the same age, Balder and Jotun A, shows that the annual number of cracks partitioned on the two units is very uneven, which one of the FPSOs have 333 cracks and the other one only 12 cracks. Investigations have shown that the majority of the cracks have an insignificant severity classification on both FPSOs. For Balder, most of the cracks are found in ballast tanks in the way of longitudinal side shell stiffeners connection to transverse frames and bulkheads and in the way of the weld between the side shell and the longitudinals. These types of cracks are typically caused by fatigue due to reduced effective shear area in the bulkheads of the hull girder given to low thickness of the flange of the longitudinals. For Jotun A, most of the cracks were found in void spaces at door frames. These types of cracks are typically caused unfavorable design of details with a small radius in the corners of the cut-outs. A closer study has also been performed on the crack lengths and the causes of failure of the cracks. It is shown that most of the cracks found at both FPSOs have a length between 25-500 mm. For Balder, most of the cracks seem to be caused by unfavorable design of details and fatigue failure. For Jotun, A most of the cracks seem to be caused by unfavorable design of details.

When comparing the life extension practices for FPSOs at the operator companies with the Norwegian regulation and standard NORSOK N-006, it is found that the companies are following this regulation and standard. Further, it would be a favorable situation to continuously improve the NORSOK N-006 standard with updated expectations of documentation. Then, requirements in the standards would be sufficient for the PSA and documentation that the operating companies wish to include in the life extension application of their installations.

7.2 Recommendations for future work

In further work regarding life extension of ship-shaped floating production units, the following should be included:

- Crack investigations of multiple FPSOs should be performed to improve the basis of comparison of the FPSOs for future standards and regulations.
- Other ageing mechanisms from which is described in Chapter 2 should be included in the investigations of FPSOs for life extension.
- Compare the crack lengths of the cracks found at inspections with the determined fatigue life of these cracks “as-built” for the specific details on the FPSOs.
- NORSOK N-006 should be further evaluated with respect to:
  - Overview of typical unfavorable details resulting in cracking and low fatigue life.
  - Reference to acceptable methods for calculating the strength of damaged and deteriorated stiffened plates.

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Appendix A

This appendix includes crack diagrams with the collected data for Balder and Jotun A.

Color and symbol codes:
🟦 Same crack number but different cracks
🟧 Same crack with two different NDT methods
🟩 Repaired cracks
🟥 Crack growth
☆ Unknown

CRAKS ON BALDER FPSO

					Location of crack								
Crack no	**Date found**	**NDE method**	**Material**	**Causes**	**Structural detail**	**Longitudinal**	**Transverse**	**Vertical**	**Failure Type**	**Length of crack [mm]**	**Comments**	**Categorization**	**Date repaired**
Cracks Aft of Frame 55													
1	☆	MPI	CS	Fatigue	Main deck outside ballast tank no.3	Frame 38	Stb. side	☆	Crack	160	670 mm from side shell	Major	☆
2	☆	MPI	CS	Fatigue and unfavorable repair of detail	Main deck outside ballast tank no.3	Frame 38	Stb. side	☆	Crack	880	210 mm down on side shell and 670 mm on main deck	Major	☆
3	28.09.2017	EC	CS	Fatigue	Wall (bulkhead) inside ballast tank no. 3	Frame 41	Stb. side	El 16800	Crack	50	Can cause contamination of oil in ballast tank. May be considered as a minor crack.	Insignificant	☆
4	☆	MPI	CS	Corrosion in combination with fatigue	Stiffened plate and deck plate	Frame 41	Port side	Main deck	Crack	225	200 mm on the stiffener plate and 25 mm on deck plate out too ship side	Major	☆
5	☆	CVI	CS	Unfavorable design of detail	Bulkhead stiffener, Ballast Water Tank 3	Frame 39	Stb. side	☆	Crack	70	Hard to find the crack on photo.	Minor	☆
6	☆	MPI	CS	Fatigue	Stiffened plate on main deck	Frame 34	Stb. side	☆	Crack	65		Minor	☆
7	☆	CVI	CS	Corrosion	Deck plate, Ballast tank no. 4A	Frame 35/36	Stb. side	Main deck	Crack	230	120 mm from outside of gutter barge and 110mm on inside of gutter barge	Major	☆
8	☆	CVI	CS	Corrosion	Buckling stiffener, Ballast Water Tank 3	Frame 38	Port side	☆	Crack	18	Weld between deck and hull.	Insignificant	☆
9	☆	CVI	CS	Corrosion	Deck plate, Ballast Water Tank 3	Frame 37	Port side	☆	Crack	25		Major	☆
10	☆	CVI	CS	Corrosion	Deck plate, Ballast Water Tank 3	Frame 37	Port side	☆	Crack	20		Major	☆
11	☆	MPI	CS	Unfavorable design of detail	Stiffened plate outside ballast tank no. 3	Frame 39	Stb. side	Main deck	Crack	200		Minor	☆
12	☆	CVI	CS	Fatigue	Cargo Tank 3 Stb deck plate.	Frame 35	Stb. side	☆	Crack	☆		Major	☆
13	☆	CVI LP	CS	Fatigue	WBT 4S, vertical bulkhead	Frame 33	☆	El 16800	Crack	95		Minor	☆
14	☆	CVI LP	CS	Fatigue	WBT 4S, vertical bulkhead	Frame 34	☆	El 16800	Crack	55		Minor	☆
14b		MPI	CS	Fatigue	Bulkhead stiffener, Ballast tank 4	Frame 34	Stb. side	☆	Crack	55	Between COT3 og BWT4	Minor	☆
15	26.02.2018	CVI	CS	Fatigue	Stiffener, WBT 4A	Frame 35	☆	☆	Crack	63		Insignificant	☆
15d	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT 4A	☆	Port side	☆	Crack	5		Insignificant	☆
15e	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT 4A	☆	Port side	☆	Crack	25		Insignificant	☆
15f	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT 4A	☆	Port side	☆	Crack	8		Insignificant	☆
15g	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT 4A	☆	Port side	☆	Crack	5		Insignificant	☆
15h	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT 4A	☆	Port side	☆	Crack	4		Insignificant	☆
P41101	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41102	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	40		Insignificant	☆
P41103	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41104	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41201	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	50		Insignificant	☆
P41202	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	45		Insignificant	☆
P41203	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41204	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	10		Insignificant	☆
P41205	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41206	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41207	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41301	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	10		Insignificant	☆
P41302	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	15		Insignificant	☆
P41303	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	10		Insignificant	☆
P41304	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	10		Insignificant	☆
P41305	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	10		Insignificant	☆
P41306	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	20		Insignificant	☆
P41307	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41308	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	60		Insignificant	☆
P41401	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	40		Insignificant	☆
P41402	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	20		Insignificant	☆
P41403	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41404	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41405	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	50		Insignificant	☆
P41501	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41502	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	40		Insignificant	☆
P41503	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	50		Insignificant	☆
P41504	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41505	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	20		Insignificant	☆
P41601	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	4		Insignificant	☆
P41602	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	5		Insignificant	☆
P41603	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	15		Insignificant	☆
P41604	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41605	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	30		Insignificant	☆
P41606	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	35		Insignificant	☆
P41607	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	4		Insignificant	☆
P41608	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	2		Insignificant	☆
P41609	04.11.2018	MPI	CS	Fatigue	Stiffener, BWT 4	☆	Port side	☆	Crack	50		Insignificant	☆
	☆	EC								190	In addition, a 30 mm long crack was found i the deck plate on the inside of the side coaming, and a 30 mm long crack in the deck plate on the outside of the side		

16	☆	MPI	CS	Fatigue	Side Coaming	Frame 38.5	Port side	Tank deck	Crack	210	coaming. Total length of the crack in the deck plate was measured to 60 mm.	Major	☆
17	22.04.2018	EC	CS	Fatigue en combination with corrosion	Side Coaming	Frame 30	The center	Tank deck	Crack	70		Insignificant	☆
18	☆ ☆	EC MPI	CS	Fatigue	Side Coaming	Frame 24.5	Stb. side	Tank deck	Crack	100 76		Insignificant	☆
19	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	5	BWT4AP	Insignificant	☆
20	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	5	BWT4AP	Insignificant	☆
21	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	3	BWT4AP	Insignificant	☆
22	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	25	BWT4AP	Insignificant	☆
23	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	8	BWT4AP	Insignificant	☆
24	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	30	BWT4P	Insignificant	☆
25	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	25	BWT4P	Insignificant	☆
26	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	30	BWT4P	Insignificant	☆
27	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	45	BWT4P	Insignificant	☆
28	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	30	BWT4P	Insignificant	☆
29	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	45	BWT4P	Insignificant	☆
30	04.11.2018	MPI	CS	Fatigue	Stiffeners in BWT		Port side		Crack	50	BWT4P	Insignificant	☆
31	28.07.2019	MPI	CS	Fatigue	Deck plate	Frame 38.5	Port side	Tank deck	Crack	62	The crack is contiguous with crack no. 16 in the side coaming.	Major	☆
32	25.07.2019	MPI	CS	Corrosion in combination with unfavorable design of detail	Wind wall	Frame 39	Stb. side	Main deck	Crack	110	Stable crack	Insignificant	☆
33	28.07.2019	MPI	CS	Fatigue	Deck plate	Frame 38	Stb. side	Tank deck	Crack	75		Major	☆
34	25.07.2019	MPI	CS	Fatigue	Deck plate	Frame 38	Stb. side	Tank deck	Crack	15		Major	☆
35	25.07.2019	MPI	CS	Unfavorable design of detail	Side Coaming	Frame 36	Stb. side	Tank deck	Crack	135		Major	☆
☆	08.10.2019	MPI	CS	Fatigue	Stiffener in BWT 3	Frame 40/41	Stb. side	El 16800	Crack	13		Insignificant	☆
☆	08.10.2019	MPI	CS	Fatigue	Stiffener in BWT 3	Frame 37/38	Stb. side	El 16800	Crack	15		Insignificant	☆
					Location of crack								
Crack no	**Date found**	**NDE method**	**Material**	**Causes**	**Structural component**	**Longitudinal**	**Transverse**	**Vertical**	**Failure Type**	**Extent of damage**	**Comments**	**Categorization**	**Date repaired**
Cracks forward of Frame 55													
1	☆	EC	CS	Fatigue	Bulkhead stifferner	☆	Stb. side	El 3200	Crack	88	Over junction box 792 EJ312. Stable crack	Minor	18.01.2019
2	28.03.2017	MPI	CS	Fatigue	Side Coaming	☆	Port side	El 3200	Crack	90	Stable crack	Insignificant	☆
3	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 3200	Crack	90	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
4	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 3200	Crack	15	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
5	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 7200	Crack	130	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
6	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 7200	Crack	30	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
7	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 7200	Crack	90	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
8	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Stb. side	El 7200	Crack	30	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
9	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 12000	Crack	140	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
10	24.06.2017	MPI	CS	Unfavorable design of detail	Door frame	☆	Port side	El 12000	Crack	45	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
11	28.03.2017	MPI	CS	Fatigue	Door frame	☆	Port side	El 12000	Crack	120	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
12	28.03.2017	MPI	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 12000	Crack	60	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
13	28.03.2017	MPI	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 12000	Crack	100	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
14	01.01.2018	MPI	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 3200	Crack	25	This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
15	☆		CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	4		☆	☆
16	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
17	☆	☆	CS	Unfavorable welded construction	Buckling stiffener	☆	☆	☆	Crack	60		Insignificant	☆
18	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
19	☆	☆	CS	Unfavorable modification/repair of detail	Bulkhead stiffener	☆	Stb. side		Crack	70		Minor	29.10.2014
20	☆	EC	CS	Fatigue	Bulkhead stifferner	☆	Stb. side	El 3200	Crack	120	Over junction box 792 -EJ- 655. Stable crack	Minor	23.01.2019
21	☆	☆	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	☆	Crack	15		Insignificant	☆
22	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	0		☆	09.01.2016
23	☆	☆	CS	Fatigue	Buckling stiffener	☆	Stb. side	☆	Crack	70		Insignificant	☆
24	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	0		☆	09.01.2016
25	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	0		☆	09.01.2016
26	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	76		☆	28.04.2015
27	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	530		☆	29.04.2015
28	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	76		☆	29.04.2015
29	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	70		☆	29.04.2015
30	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	60		☆	29.04.2015
31	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
32	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
33	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
34	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
35	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
36	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	150		☆	29.04.2015
37	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	60		☆	28.04.2015

38	☆	☆	CS	Unfavorable welded construction	Buckling stiffener	☆	Stb. side	☆	Crack	190		Insignificant	☆
39	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	140		☆	28.04.2015
40	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	87		☆	28.04.2015
41	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	30		☆	28.04.2015
42	Same crack as crack 33												
43	Same crack as crack 13												
44	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	75		☆	28.04.2015
45	☆	EC	CS	Fatigue	Top of main vertical beam support		Port side		Crack	90	Crack growth: 10 mm	Minor	08.02.2019
46	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	152		☆	☆
47	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	60		☆	☆
48	☆	☆	CS	Fatigue	☆	☆	Port side	☆	Crack	20		☆	☆
49	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	70		☆	☆
50	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	300		☆	☆
51	Same crack as crack 10												
52	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	30		☆	29.04.2015
53	Same crack as crack 28												
54	Same crack as crack 9												
55	Same crack as crack 38												
56	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	140		☆	29.04.2015
57	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	210		☆	29.04.2015
58	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	50		☆	☆
59	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	40		☆	28.04.2015
60	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	40		☆	28.04.2015
61	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	50		☆	☆
62	☆	☆	CS	☆	☆	☆	Stb. side	☆	Crack	20		☆	28.04.2015
63	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	75		☆	28.04.2015
64	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	8		☆	28.04.2015
65	Same crack as crack 50												
66	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	10		☆	☆
67	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	55		☆	29.04.2015
68	☆	☆	CS	☆	☆	☆	Port side	☆	Crack	28		☆	29.04.2015
69	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	200		☆	☆
70	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	200		☆	☆
71	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	25		☆	☆
72	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	22		☆	29.04.2015
73	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	8		☆	29.04.2015
74	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	17		☆	29.04.2015
75	☆	☆	CS	Unfavorable design of detail	☆	☆	Stb. side	☆	Crack	17		☆	29.04.2015
76	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	30		☆	29.04.2015
77	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	70		☆	☆
78	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	55		☆	☆
79	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	130		☆	☆
80	☆	EC	CS	Fatigue	Buckling stiffener	Frame 60	Stb. side	El 3200	Crack	110	Crack growth: 18 mm	Insignificant	14.01.2019
81	☆	☆	CS	☆	☆	☆	☆	☆	Crack	☆		☆	☆
82	☆	EC	CS	Fatigue	Bulkhead stiffener		Stb. side	El 3200	Crack	15	Over junction box 792 - EJ312. Stable crack.	Minor	20.01.2019
83	☆	EC	CS	Fatigue	Bulkhead stiffener		Stb. side	El 3200	Crack	55	Over sign for air pump valve. Fwd of blue tank. . Stable crack	Minor	11.07.2019
84	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	80		☆	☆
85	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	75		☆	☆
86	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	18		☆	☆
87	☆	☆	CS	Unfavorable design of detail	☆	☆	Port side	☆	Crack	55		☆	☆
88	☆	EC	CS	Fatigue	Top of main vertical beam support		Port side	El 3200	Crack	10	Stable crack	Minor	08.02.2019
89	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	25		☆	☆
90	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	0		☆	☆
91	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	0		☆	☆
92	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	60		☆	☆
93	☆	☆	CS	Unfavorable design of detail	☆	☆	Stb. side	☆	Crack	160		☆	☆
94	☆	☆	CS	Unfavorable design of detail	☆	☆	Stb. side	☆	Crack	60		☆	☆
95	☆	☆	CS	Unfavorable design of detail	☆	☆	Stb. side	☆	Crack	80		☆	☆
96	☆	☆	CS	Unfavorable welded construction	☆	☆	Stb. side	☆	Crack	70		☆	☆
97	☆	EC	CS	Unfavorable design of detail	Buckling stiffener	Frame 60	Stb. side	El 3200	Crack	159	Stable crack	Insignificant	13.01.2019
98	☆	EC	CS	Unfavorable welded construction	Buckling stiffener	Frame 60	Port side	El 3200	Crack	105	Crack growth: 35 mm	Insignificant	28.02.2019
99	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	60		☆	☆
100	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	30		☆	☆
101	☆	☆	CS	Fatigue	☆	☆	Port side	☆	Crack	32		☆	☆
102	☆	☆	CS	Unfavorable welded construction	☆	☆	Port side	☆	Crack	50		☆	☆
103	28.04.2018	EC	CS	Unfavorable design of detail	Inner door frame to main switchboard, 871-EM-01A.	☆	Port side	El 16800	Crack	45	Stable crack	Insignificant	18.12.2019
104	28.04.2018	EC	CS	Unfavorable design of detail	Door frame to transformer room	☆	Port side	El 16800	Crack	38	Stable crack	Insignificant	13.03.2020
105	28.04.2018	EC	CS	Unfavorable design of detail	Door frame to main switchboard, 871-EM- 01B	☆	Port side	El 16800	Crack	10	Stable crack	Insignificant	
106A	28.04.2018	EC	CS	Unfavorable design of detail	Aft door frame to switchboard room.	☆	Port side	El 16800	Crack	115	Stable crack	Insignificant	12.10.2019
106B	28.04.2018	EC	CS	Unfavorable design of detail	Aft door frame to switchboard room	☆	Port side	El 16800	Crack	100	Crack growth: 60 mm	Insignificant	12.10.2019
107	28.04.2018	EC	CS	Unfavorable design of detail	Aft door frame to switchboard room	☆	Port side	El 16800	Crack	15	Stable crack	Insignificant	12.10.2019
108	28.04.2018	EC	CS	Fatigue	Door frame to electrical office	☆	Port side	El 16800	Crack	69	Stable crack	Insignificant	24.03.2020
109	28.04.2018	EC	CS	Unfavorable design of detail	Fwd door frame to switchboard room	☆	Port side	El 16800	Crack	59	Stable crack	Insignificant	24.03.2020
110	28.04.2018	EC	CS	Unfavorable design of detail	Fwd door frame to switchboard room	☆	Stb. side	El 16800	Crack	64	Stable crack	Insignificant	12.03.2020
111A	28.04.2018	EC	CS	Unfavorable design of detail	Door frame to transformer cooling fan room	☆	Stb. side	El 16800	Crack	42	Stable crack	Insignificant	15.03.2020
111B	28.04.2018	EC	CS	Unfavorable design of detail	Door frame to transformer cooling fan room	☆	Stb. side	El 16800	Crack	5	Stable crack	Insignificant	15.03.2020

112	30.04.2018	EC	CS	Unfavorable design of detail	Door frame in boiler room	☆	Port side	El 12000	Crack	281	Stable crack	Insignificant	02.01.2019
113	30.04.2018	EC	CS	Fatigue	Door frame in boiler room	☆	Port side	El 12000	Crack	103	Stable crack	Major	07.01.2019
114	30.04.2018	EC	CS	Unfavorable design of detail	Bulkhead, boiler room	☆	Port side	El 12000	Crack	43	Stable crack	Insignificant	08.01.2019
115A	30.04.2018	EC	CS	Fatigue	Bulkhead, boiler room	☆	Port side	El 12000	Crack	93	Stable crack	Minor	08.01.2019
115B	30.04.2018	EC	CS	Fatigue	Bulkhead, boiler room	☆	Port side	El 12000	Crack	18	Stable crack	Minor	08.01.2019
116	30.04.2018	EC	CS	Unfavorable welded construction	Bulkhead, boiler room	☆	Port side	El 12000	Crack	50	Stable crack	Insignificant	02.01.2019
117	30.04.2018	EC	CS	Fatigue	Deck plate	☆	Port side	El 12000	Crack	260	Crack growth: 19 mm	Major	31.05.2019
118		EC	CS	Unfavorable welded construction	Door frame	☆	Stb. side	El 12000	Crack	70	Crack growth: 10 mm. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	16.04.2019
119	30.04.2018	EC	CS	Unfavorable design of detail	Deck plate	☆	Port side	El 12000	Crack	176	Stable crack	Major	08.03.2019
120	30.04.2018	EC	CS	Unfavorable design of detail	Bulkhead, watertight door	☆	Stb. side	El 12000	Crack	75	Crack growth: 12 mm. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	17.04.2019
121	30.04.2018	EC	CS	Unfavorable welded construction	Bulkhead, watertight door	☆	Stb. side	El 12000	Crack	64	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	17.04.2019
122		EC	CS	Unfavorable design of detail	Bulkhead, boiler room	☆	Stb. side	El 7200	Crack	26	Stable crack	Insignificant	16.11.2019
123	24.04.2018	EC	CS	Unfavorable design of detail	Deck plate	☆	Stb. side	El 12000	Crack	180	Stable crack	Major	17.03.2019
124	30.04.2018	EC	CS	Unfavorable design of detail	Door frame, boiler room	☆	Stb. side	El 12000	Crack	97	Stable crack	Insignificant	30.12.2018
125	30.04.2018	EC	CS	Unfavorable design of detail	Deck plate, boiler room	☆	Stb. side	El 12000	Crack	165	Crack growth: 28 mm	Major	30.12.2018
126	30.04.2018	EC	CS	Unfavorable welded construction	Door frame, boiler room	☆	Stb. side	El 7200	Crack	62	Stable crack	Insignificant	15.10.2019
127	30.04.2018	EC	CS	Unfavorable design of detail	Door frame, boiler room	☆	Stb. side	El 7200	Crack	53	Stable crack	Insignificant	16.10.2019
127A	01.05.2018	EC	CS	Fatigue	Vertical bulkhead, boiler room	☆	Port side	El 7200	Crack	330	Stable crack	Minor	08.10.2019
127B	01.05.2018	EC	CS	Fatigue	Vertical bulkhead, boiler room	☆	Port side	El 7200	Crack	114	Stable crack	Minor	08.10.2019
127C	01.05.2018	EC	CS	Fatigue	Vertical bulkhead, boiler room	☆	Port side	El 7200	Crack	113	Stable crack	Minor	08.10.2019
128	01.05.2018	EC	CS	Unfavorable welded construction	Girder	Frame 60	Stb. side	El 3200	Crack	160	Crack growth: 7 mm	Major	27.01.2019
129	01.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	Frame 60	Stb. side	El 3200	Crack	142	Stable crack	Minor	27.01.2019
130A	01.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	Frame 60	Stb. side	El 3200	Crack	58	Crack growth: 12 mm	Minor	27.01.2019
130B	01.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	Frame 60	Stb. side	El 3200	Crack	190	Crack growth: 158 mm	Minor	27.01.2019
131	01.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Stb. side	El 3200	Crack	58	Crack growth: 4 mm	Minor	17.07.2019
132	01.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Port side	El 3200	Crack	42	Stable crack	Minor	14.07.2019
133	03.05.2018	EC	CS	Corrosion in combination with unfavorable welded construction	Buckling stiffener	☆	Port side		Crack	16		Insignificant	13.07.2019
134	02.05.2018	EC	CS	Unfavorable design of detail	Bulkhead stiffener	☆	Stb. side	El 12000	Crack	233	Stable crack	Minor	21.04.2019
135	02.05.2018	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 7200	Crack	28	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	04.07.2019
136	02.05.2018	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 7200	Crack	18	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	04.07.2019
137	02.05.2018	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 7200	Crack	25	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	04.07.2019
138	02.05.2018	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 7200	Crack	28	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	04.07.2019
139	02.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Stb. side	El 7200	Crack	105	Stable crack	Minor	20.03.2019
140A	03.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Port side	El 3200	Crack	34	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Minor	22.07.2019
140B	03.05.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Port side	El 3200	Crack	35	Stable crack. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Minor	22.07.2019
141	03.05.2018	EC	CS	Unfavorable design of detail	Buckling stiffener	Frame 60	Port side	El 3200	Crack	105	Stable crack	Insignificant	27.02.2019
142	03.05.2018	EC	CS	Unfavorable design of detail	Buckling stiffener	Frame 61	Port side	El 3200	Crack	80	Crack growth: 25 mm	Insignificant	21.02.2019
143	03.05.2018	EC	CS	Unfavorable design of detail	Buckling stiffener	Frame 62	Port side	El 3200	Crack	130	Crack growth: 46 mm	Insignificant	21.02.2019
144	03.05.2018	EC	CS	Unfavorable design of detail	Buckling stiffener	Frame 63	Port side	El 3200	Crack	54	Stable crack	Insignificant	21.02.2019
145	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 3200	Crack	32	Crack growth: 23 mm. This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	02.09.2019
146	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 3200	Crack	80	Crack growth: 12 mm	Minor	02.09.2019
147A	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	52	Stable crack	Minor	24.09.2019
147B	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	34	Stable crack	Minor	24.09.2019
148	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	38	Crack growth: 20 mm	Minor	24.09.2019
149A	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	28	Stable crack	Minor	24.09.2019
149B	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	14	Stable crack	Minor	24.09.2019
150	03.05.2018	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	25	Stable crack	Minor	24.09.2019
151	03.05.2018	EC	CS	Fatigue	Vertical bulkhead	☆	Port side	El 7200	Crack	55	Crack growth: 2 mm	Minor	02.10.2019
152	01.10.2018	EC	CS	Unfavorable design of detail	Bulkhead stiffener	☆	Stb. side	El 3200	Crack	30		Minor	11.07.2019
153	01.10.2018	EC	CS	Fatigue	Door frame	☆	Stb. side	El 12000	Crack	10	Boiler room	Insignificant	30.12.2018
154	01.10.2018	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 16800	Crack	30	This is basically an insignificant crack, but in regards to watertight integrity it can be	Insignificant	☆
155	01.10.2018	EC	CS	Fatigue	Door to local control room	☆	Stb. side	El 16800	Crack	30		Insignificant	☆
156	01.10.2018	EC	CS	Fatigue	Bulkhead stiffener	☆	Stb. side	El 7200	Crack	60		Minor	17.03.2019
157	01.10.2018	EC	CS	Unfavorable welded construction	Vertical bulkhead	☆	Stb. side	El 7200	Crack	25		Minor	03.04.2019
158	01.10.2018	EC	CS	Unfavorable welded construction	Vertical bulkhead	☆	Stb. side	El 7200	Crack	100		Minor	04.04.2019
159	01.10.2018	EC	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 7200	Crack	85		Insignificant	22.10.2019
160	01.10.2018	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Stb. side	El 7200	Crack	135		Minor	19.11.2019
161	01.10.2018	EC	CS	Fatigue	Door to switchboard	☆	Port side	El 16800	Crack	70		Insignificant	12.04.2020
162	13.03.2019	EC	CS	Fatigue	Vertical bulkhead	☆	☆	El 3200	Crack	120		Minor	05.07.2019
163	13.03.2019	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	☆	El 7200	Crack	55		Minor	07.07.2019
164	13.03.2019	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	☆	El 7200	Crack	55		Minor	07.07.2019
165	25.03.2019	EC	CS	Fatigue	Girder	☆	Stb. side	El 12000	Crack	90		Major	31.03.2019
166	25.03.2019	EC	CS	Fatigue	Girder	☆	Stb. side	El 12000	Crack	90		Major	31.03.2019
167	25.03.2019	EC	CS	Fatigue	Girder	☆	Stb. side	El 12000	Crack	90		Major	31.03.2019

168	01.04.2019	EC	CS	Fatigue	Girder	☆	Stb. side	El 12001	Crack	30		Major	05.04.2019
169	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆		☆	☆
170	15.06.2019	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Stb. side	El 3200	Crack	30		Minor	23.06.2019
171	24.07.2019	EC	CS	Unfavorable design of detail	Buckling stiffener	Frame 61	Stb. side	El 3200	Crack	28		Insignificant	27.09.2019
172	10.10.2019	EC	CS	Unfavorable welded construction	Bulkhead stiffener	☆	Port side	El 7200	Crack	80		Major	12.10.2019
173	10.10.2019	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Port side	El 7200	Crack	60		Minor	12.10.2019
174	18.11.2019	EC	CS	Unfavorable design of detail	Vertical bulkhead	☆	Stb. side	El 7200	Crack	80		Minor	☆
175	18.11.2019	EC	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 16800	Crack	40		Insignificant	13.03.2020
176	18.11.2019	EC	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 16800	Crack	80	This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
177	18.11.2019	EC	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 16800	Crack	50	This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
178	18.11.2019	EC	CS	Unfavorable design of detail	Door frame	☆	Stb. side	El 16800	Crack	125	This is basically an insignificant crack, but in regards to watertight integrity it can be classified as a minor crack.	Insignificant/Minor	☆
179	18.11.2019	EC	CS	Unfavorable welded construction	Cable transit frame	☆	Stb. side	El 16800	Crack	50		Insignificant	☆
180	18.11.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 16800	Crack	120		Insignificant	☆
181	18.11.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 16800	Crack	120		Insignificant	☆
182	18.11.2019	EC	CS	Unfavorable design of detail	Door frame	☆	Port side	El 16800	Crack	35		Insignificant	24.03.2020
183	15.11.2019	EC	CS	Fatigue	Buckling stiffener	☆	Port side	El 3200	Crack	☆		Insignificant	22.11.2019
184	03.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	42		Insignificant	☆
185	04.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	35		Insignificant	☆
186	04.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	30		Insignificant	☆
187	04.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	34		Insignificant	☆
188	04.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	87		Insignificant	☆
189	04.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	62		Insignificant	☆
190	05.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	22		Insignificant	☆
191	05.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	62		Insignificant	☆
192	05.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	27		Insignificant	☆
193	05.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 12000	Crack	39		Insignificant	☆
194	05.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 16800	Crack	72		Insignificant	☆
195	19.02.2020	EC	CS	Bad welded construction	Buckling stiffener	☆	Port side	El 7200	Crack	115		Insignificant	☆
195	20.03.2020	EC	CS	Unfavorable design of detail	Doorframe to electrical office	☆	Port side	El 16800	Crack	90		Insignificant	22.03.2020
196	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Port side	El 3200	Crack	24		Insignificant	☆
196	19.03.2020	EC	CS	Unfavorable design of detail	Doorframe to electrical office	☆	Port side	El 16800	Crack	15		Insignificant	22.03.2020
197	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	27		Insignificant	☆
197	23.03.2020	EC	CS	Unfavorable design of detail	Doorframe to electrical office	☆	Port side	El 16800	Crack	70		Insignificant	24.03.2020
198	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	22		Insignificant	☆
198	23.03.2020	EC	CS	Bad welded construction	Doorframe to electrical office	☆	Port side	El 16800	Crack	50		Insignificant	24.03.2020
199	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	47		Insignificant	☆
199	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	22		Insignificant	☆
200	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	15		Insignificant	☆
200	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	32		Insignificant	☆
201	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	60		Insignificant	☆
201	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	12		Insignificant	☆
202	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	12		Insignificant	☆
202	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	12		Insignificant	☆
203	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	22		Insignificant	☆
203	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	22		Insignificant	☆
204	20.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	82		Insignificant	☆
204	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	27		Insignificant	☆
205	20.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	82		Insignificant	☆
205	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	17		Insignificant	☆
206	05.12.2019	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	27		Insignificant	☆
206	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	12		Insignificant	☆
207	20.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	64		Insignificant	☆
207	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	57		Insignificant	☆
208	20.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	79		Insignificant	☆
208	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	27		Insignificant	☆
209	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	182		Insignificant	☆
210	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	32		Insignificant	☆
211	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	32		Insignificant	☆
212	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	32		Insignificant	☆
213	09.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	32		Insignificant	☆
214	21.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	64		Insignificant	☆
215	21.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	79		Insignificant	☆
216	21.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	27		Insignificant	☆
217	21.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	82		Insignificant	☆
218	21.02.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Port side	El 12000	Crack	82		Insignificant	☆
219	19.02.2020	EC	CS	Bad welded construction	Buckling stiffener	☆	Stb. side	El 3200	Crack	47		Insignificant	☆
220	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	15		Insignificant	☆
221	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	61		Insignificant	☆
222	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	25		Insignificant	☆
223	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	20		Insignificant	☆
224	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	27		Insignificant	☆
225	19.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 3200	Crack	22		Insignificant	☆
226	11.04.2020	EC	CS	Bad welded construction	Side coaming	☆	Stb. side	El 7200	Crack	72		Insignificant	☆
227	11.04.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. side	El 7200	Crack	13		Insignificant	☆
228	11.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 7200	Crack	23		Insignificant	☆

229	11.04.2020	EC	CS	Unfavorable design of detail	Cable transit frame	☆	Stb. side	El 7200	Crack	18		Insignificant	☆
230	11.04.2020	EC	CS	Bad welded construction	Bulkhead stiffener	☆	Stb. side	El 7200	Crack	61		Minor	☆
231	11.04.2020	EC	CS	Bad welded construction	Bulkhead stiffener	☆	Port side	El 7200	Crack	53		Minor	☆
232	11.04.2020	EC	CS	Unfavorable design of detail	Bulkhead stiffener	☆	Port side	El 3200	Crack	32		Minor	☆
233	18.02.2020	EC	CS	Unfavorable design of detail	Buckling stiffener	☆	Stb. Side	El 3200	Crack	24		Insignificant	☆
234	05.04.2020	EC	CS	Unfavorable design of detail	Stiffener, Electrical stock	☆	Stb. Side	El 20800	Crack	33		Insignificant	☆
235	18.02.2020	EC	CS	Unfavorable welded construction	Stiffener, Lifting equipment stock	☆	Port side	El 20800	Crack	180		Insignificant	☆
					Location of crack								
Crack no	**Date found**	**NDE method**	**Material**	**Causes**	**Structural component**	**Longitudinal**	**Transverse**	**Vertical**	**Failure Type**	**Extent of damage [mm]**	**Comments**	**Categorization**	**Date repaired**
Historic cracks													
Cracks from DNV GL report													
☆	2004	☆	CS	Fatigue in combination with unfavorable welded construction	Cracks in plating connecting bollard and gutter	Frame 38	☆	Main deck	Crack	☆	The cracks were at the weld between the gutter and the connecting bracket towards the main deck.	☆	☆
☆	2007	☆	CS	Unfavorable welded construction	Connection between a radial stiffener and a circumferential stiffener	Frame 47/48	☆	Main deck underside	Crack	☆		☆	☆
☆	2008	☆	CS	☆	Crack in bracket toes of Drag Chain Tower.	Frame 43	Port side	El 13600	Crack	70	Two small indications	☆	☆
☆	2008	☆	CS	☆	Crack in bracket toes of Drag Chain Tower.	Frame 44	Port side	El 11200	Crack	90	One indication	☆	☆
☆	2009	☆	CS	☆	Ullage hatch – crack in weld.	Frame 37/38	☆	☆	Crack	☆	Five cracks were detected in an ullage hatch	☆	☆
☆	2010	☆	CS	☆	Watertight doors – cracks in corners.	☆	☆	☆	Crack	☆	Soft brackets were installed.	☆	☆
☆	2012	☆	CS	☆	Possible crack in the Main Deck above cargo tank 2S, just forward of Crane Pedestal 2 at an instrument support connection to deck	Frame 36/37	☆	☆	Crack	☆		☆	☆
☆	2012-2013	☆	CS	Fatigue	About 100 cracks in beams in the Machinery room	☆	Port/Stb. Side	El 3200/7200	Crack	☆		☆	☆
☆	2017	☆	CS	Fatigue in combination with unfavorable welded construction	Crack in stiffening plate at main deck	Frame 35	☆	☆	Crack	65	The crack is in a connection between a coaming plate and the column for the green water wall.	☆	☆
☆	2017	☆	CS	Fatigue	Crack in Main Deck and Ship Side	Frame 38	☆	☆	Crack	1050	Two cracks located close to each other were found in Frame #38 at starboard side. 160 mm and 890 mm	☆	☆
☆	2017	☆	CS	Fatigue	Crack in coaming plate	Frame 41	☆	☆	Crack	230	200 mm in coaming plate and 30 mm in deck plate	☆	☆
☆	2017	☆	CS	☆	Crack in Wing Tank Bulkhead	Frame 41	Stb. Side	El 16800	Crack	☆		☆	☆
Cracks from CODAM													
☆	2005	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 1	Minor	☆
☆	2008	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 1	☆	☆
☆	2009	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 1	☆	☆
☆	2010	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 5	☆	☆
☆	2012	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 3	☆	☆
☆	2013	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 3	2 cracks is classified as minor, and 1 crack is not classified	☆
☆	2016	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 2	☆	☆
☆	2017	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 38	32 cracks is classifed as minor, and 6 cracks is not classified	☆
☆	2018	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 84	Minor	☆
☆	2019	☆	CS	☆	☆	☆	☆	☆	Crack	☆	Number of cracks found: 10	Minor	☆

Color and symbol codes: 🟨 Same crack with two different NDT methods
☆ Unknown

CRACKS ON JOTUN A FPSO

Crack no	Date found	NDE method	Material	Causes	Location of crack				Failure Type	Length of crack	Comments	Categorization	Date repaired
					Structural detail	Longitudinal	Transverse	Vertical					
1	04.11.2018 05.11.2018	EC MPI	CS	Unfavorable welded construction	Hopper knuckle in Ballast Water Tank	Frame 197	Stb. Side	☆	Crack	110 mm	Intermittent toe crack, 110mm up from deck	Minor	☆
2	04.11.2018 05.11.2018	EC MPI	CS	Unfavorable welded construction	Hopper knuckle in Ballast Water Tank	Frame 197	Stb. Side	☆	Crack	30 mm	Toe crack, 295mm up from deck	Minor	☆
3	09.11.2018 10.11.2018	EC MPI	CS	Unfavorable welded construction	Longitudinal bulkhead in Ballast Water Tank	Frame 154	☆	☆	Crack	25 mm	Toe crack	Minor	☆
4	09.11.2018 10.11.2018	EC MPI	CS	Unfavorable welded construction	Hopper knuckle in Ballast Water Tank	Frame 154	Aft Side	☆	Crack	15 mm	HAZ crack. 325mm up from the tank top and 25mm left from the weld.	Minor	☆
5	15.08.2019	CVI	CS	Unfavorable design of detail	Door frame	☆	☆	☆	Crack	100 mm	Top left corner of the door/structure on the UPS-room (HC10A21C)	Insignificant	☆
6	15.08.2019	CVI	CS	Unfavorable design of detail	Door frame	☆	☆	☆	Crack	55 mm	The middle of the door on the left corner on the UPS-room (HC10A21C)	Insignificant	☆
7	15.08.2019	CVI	CS	Unfavorable design of detail	Door frame	☆	☆	☆	Crack	80 mm	Top right corner of the door/structure on the UPS-room (HC10A21C)	Insignificant	☆
8	15.08.2019	CVI	CS	Unfavorable design of detail	Door frame	☆	☆	☆	Crack	55 mm	The middle of the door on the UPS-room (HC10A21C)	Insignificant	☆
9	15.08.2019	CVI	CS	Unfavorable design of detail	Door frame	☆	☆	☆	Crack	75 mm	Inside the Hydraulic unit-room (HC10A14A), top right corner of the door/structure	Insignificant	☆
10	15.08.2019	CVI	CS	Unfavorable design of detail	Door frame	☆	☆	☆	Crack	70 mm	Top left corner of the door/structure. (from the other side of the door, Hydraulic unit room)	Insignificant	☆
Cracks from CODAM													
☆	2001	☆	☆	☆	☆	☆	☆	☆	☆	☆	Number of cracks found: 2	Insignificant	☆
☆	2019	☆	☆	☆	☆	☆	☆	☆	☆	☆	Number of cracks found: 9	Minor	☆