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COMMITTEE V.7

STRUCTURAL LONGEVITY

COMMITTEE MANDATE

Concern for the structural longevity of ship, offshore and other marine structures. This shall include diagnosis and prognosis of structural health, prevention of structural failures such as corrosion and fatigue, and structural rehabilitation. The focus shall be on methodologies translating monitoring data into operational and life-cycle management advice. The research and development in passive, latent and active systems including their sensors and actuators shall be addressed.

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KEYWORDS

Ship structures, fatigue, service life, corrosion, structural health monitoring, digital twin, structural longevity, structural inspection, structural repair, structural maintenance, structural damage detection, fatigue life, crack detection, structural life-cycle assessment, structural life-cycle management, structural sensing, acoustic emission

CONTENTS

1. INTRODUCTION

1.1 Background & Mandate

The structural longevity of ships, offshore, and other marine platform structures is a function of design, operation, and life-cycle management. Each of these aspects together determines the ability of a structure to endure safely and effectively without risk of significant failures, significant need for repair, or early retirement. This committee was formed to explore these aspects and encompasses technical domains across the ISSC technical community. Care was taken in the development of this report to investigate recent research and practice that determine, evaluate, and affect longevity of ship and offshore structures in accordance with the mandate, beyond that contained in the ISSC 2015 report of this committee (Hess et al, 2015).

Concern for structural longevity requires assessment of the technology reviewed by all of the committees of ISSC 2018 from loading to design to fabrication, but with an emphasis on maintenance of the structure to ensure a successful life. The design process requires development of conservative estimates of loading (including environmental and seaway), fabrication methods and tolerances, material performance, operation, and maintenance (e.g. inspection, monitoring, corrosion-prevention). Assumptions are made during design regarding construction methods, loading, environment, design criteria, material performance, operation, maintenance, and service life. However, if any design assumption proves incorrect then this could result in a risk and cost to the owner and operator.

The mandate of this committee overlaps that of committees IV.2, Design Methods, which calls for "integration [of design] with production, maintenance and repair" and V.2, Experimental Methods, which calls for "…advances in…in-service monitoring and their role in the design, construction, inspection and maintenance of ship and offshore structures". Efforts have been made to avoid repetition of overlapping material in the reports of the three committees.

1.2 Structural Longevity Considerations

The heart of current practice for assessment of the structural condition of a ship or offshore structure is the periodic survey where the condition of the structure is compared to the standards of a classification society or other standards. The ideal of structural management for longevity is that assessment be carried forward to a prediction of future deterioration over the planned lifetime, that appropriate maintenance activities be performed, and that a monitoring and inspection plan be developed and instituted to ensure that the goals for continued operation are met. In forecasting future conditions of the structure, assumptions of operational effects are made. These, in general, are not as conservative as the assumptions made in design, where the worst operational conditions are assumed. For a structural longevity assessment, an estimate of future operating conditions is made. If possible, the loading history from hull monitoring and operational records is used to make that forecast. With a structural health monitoring system, the actual operational conditions are used to regularly update that forecast and modify it on the basis of detected changes in the integrity of the structure. The actual condition, use, and performance of the platform structure changes over time. This requires updated maintenance requirements for scheduling and budgeting, decisions on limiting or expanding the operational use, and predicting remaining useful service life.

Life-cycle management can evoke risk-based inspection, which rather than using a preset timetable for inspection and structural assessment, establishes inspection intervals on the basis of the probability of deterioration or fatigue fracture and the consequences of such failures. Structural health monitoring is an important part of that process, providing updates based on actual operation and indications of changes in the structure.

Establishment of a digital twin of the structure is a new concept that exploits the capability for structural computations and management of data. A mathematical model of the structure is constructed through finite element modeling, and that model is constantly updated as information from condition assessments, structural hull monitoring, and other sources such as modification and repairs to the structure is received. This digital twin can then be used for "what-if" studies of different scenarios of operation, inspection, maintenance, and repair for management of the structure over its lifetime.

There are great challenges in ensuring today's complex ships, offshore, and other marine structures have an affordable and adequate service life, which, ideally, should not be limited by structural considerations such as deterioration from corrosion, fatigue cracking or structural overload (buckling, collapse, or fracture). Developing technology for diagnosis and prognosis of structural health enhances prediction and planning of future structural maintenance costs. Classification societies are providing guidance and additional class notation for the installation of onboard structural monitoring systems, and research continues into means of translating the data collected from those systems into operational advice and life-cycle management. Making new designs more resilient by going beyond the safety-based requirements specified by the cognizant authority such as a classification society involves a greater initial cost, which can be justified by incorporating life-cycle maintenance considerations into the initial design cycle. Allowance for condition-based maintenance strategies might be made in the design process to reduce conservatism in design assumptions and support a more sophisticated and economical life-cycle management scheme.

1.3 Report Content

Chapter 2 describes the need to assess the structural lifetime of ships/vessels and offshore structures and the subsequent management for structural longevity. It also provides an overview of how structural longevity is handled using existing rule-sets and processes that result from governing requirements such as Class rules and the International Maritime Organization (IMO).

Chapter 3 focuses on inspection and structural hull and health monitoring technologies including relative costs and effectiveness, data acquisition systems, existing guidelines/rules. This chapter builds upon the reports of ISSC 2003 V.3, Inspection and Monitoring, and ISSC 2015 V.7, Structural Longevity.

Chapter 4 describes offshore structure specific aspects of longevity, including secondary load-carrying structure (risers, conductors, etc.), lifetime extension, and decommissioning.

Chapter 5 describes ship structure specific aspects of longevity, including failure modes of ship structure, lifetime extension, and conversion. Methods for ensuring safe operation are discussed, including monitoring, inspection, maintenance and repairs as well as assessment of damage. Examples on a naval ship, tanker, and inland vessel are provided.

2. LIFE-CYCLE ASSESSMENT & MANAGEMENT FOR STRUCTURAL LONGEVITY

2.1 Introduction

This chapter will provide an overview of how structural longevity for ship and offshore structures is handled using existing rule-sets and processes that result from governing requirements such as Class rules. Additionally, this chapter reflects upon advances in analytical methods that can be directed for structural assessment and current practice across other industry sectors concerned with maintaining and extending the life of high value, safety critical assets.

Following the definition in ISSC 2015, life-cycle assessment is defined as that which monitors structural health and extrapolates, or predicts, the expected structural life of the asset allowing informed but complex decisions by the owner/operator on the asset's future, including the facility for life extension (Hess et al., 2015). As such the "cycle" is defined from the point that assessment of the structure in the as-built/as-fabricated condition is made to the final end of life, including where the asset has been life extended. During this time, information on the asset's condition is utilized for life assessment.

2.2 *Life-cycle Assessment & Integrity Management*

Whether a ship or offshore structure, an asset's current structural condition is determined by periodic survey whereby all the present characteristics of the structure are described in detail, recording all service history including routes and loading conditions, damage incurred, subsequent repairs, refitting, and any modifications from the original as-built condition. To complete a picture of structural health, a comprehensive thickness measurement of all the structural components should be carried out. This information is recorded in a database which can be continuously updated and integrated with subsequent surveys and made available to the technical office in charge of evaluating the residual structural capacity of the asset.

An increasingly common practice to facilitate the residual capacity is to have a mathematical model, a "digital twin", of the asset as-built and by this approach it is possible to continually update it and get a "real-time" life prediction. These digital twins will become increasingly powerful as inverse finite element methods (iFEM) develop. Classification societies are encouraging the installation of structural hull monitoring systems which produce a large volume of live on-board strain data. This spatially discrete data can be input to FE models which then infers the asset's global shape. From the strain-displacement relationship, the full field strains are produced which, with the material properties of the structure, allow the full field stresses to be calculated that would elicit these strains (Kefal and Oterkus, 2016).

Preliminary hull girder and local strength assessment are carried out on the basis of the as-built scantlings and compared with respect to the Rules currently enforced for new builds. A detailed fatigue analysis of structural details is carried out by calculating the fatigue damage originated by the fluctuating stresses induced in the critical areas as identified in the initial analyses by the hull girder and local wave loads, combined with the ballast and full load cargo conditions. The fatigue life of the detail, in years, is calculated from the fatigue damage index. In the case where there is little data on the actual sea loads an asset experiences, this information must be supplemented by design code information or modelling, using seakeeping models and spectral fatigue analysis. Bayesian updating could be used to combine any initially assumed wave-load information with actual observed data (see, for example, Zhu & Frangopol, 2013).

Classification, certification, and verification ensure compliance of an asset's structural and equipment safety with internationally recognized industrial standards (for example, API or ISO) and IMO codes and regulations. The process of classification, certification, and verification covers all stages of design, construction, installation, operation, life extension and decommissioning and is undertaken by the classification societies.

2.2.1 *Classification Societies*

Most classification societies have guidelines for evaluating the structural condition of assets of different typologies. The aim of these guides is to provide criteria to carry out an objective condition assessment in order to assign a rating based on the condition of an asset, independently of its classification. The asset's condition assessment is based on the evaluation of (hull) structures, coating rating, machinery, and most importantly outfit components.

At the end of the evaluation procedure a rating is assigned to the ship. This rating consists typically of four levels:

1. Very good: Items examined and measured, found to have deficiencies of a superficial nature not requiring correction or repairs and/or found to have thicknesses significantly above class limits.
2. Good: Items examined and measured, found to have deficiencies of a minor nature not requiring correction or repairs and/or found to have thicknesses significantly above class limits.
3. Satisfactory: Items examined and measured either found to have deficiencies which do not require immediate corrective actions, or found to have thicknesses which, although generally above class renewal levels, have areas of substantial corrosion.
4. Poor: Items examined and measured either found to have deficiencies which may affect the ship's potential to remain in class, or found in some areas to have thicknesses that are at or below the class renewal levels.

Each classification society has their own procedures and a few examples are given here. A number of classification societies, including the US' American Bureau of Shipping (ABS), the Italian classification society, RINA S.p.A, France's Bureau Veritas (BV) and UK's Lloyds Register (LR) have what they term a condition assessment program or procedure (CAP) (e.g. RINA S.p.A, 2008; BV, 2015). Initially, the asset's operational records are examined and any information from, say, ultrasonic thickness measurements, are included in preliminary analyses. These include a re-assessment of the asset using its as-built scantlings measured against the latest rules and, generally, a fatigue assessment of identified critical areas. These analyses would provide an inspection protocol for the CAP survey, allowing close visual inspection of critical "hot spot" locations.

ABS rules have 3 groups to which they apply fatigue assessment: ships (ABS, 2017a), ship-shaped (e.g. FPSO) (ABS, 2017b–d) and non-ship-shaped offshore structures (e.g. Mobile Offshore Units, MOU) (ABS, 2017e). In any of the cases, the simplified treatment of the structures with 2-D analyses or 3-D FEA can be advanced to include a spectral-based fatigue assessment (ABS, 2017f; ABS, 2014a&b) where the loads are obtained through seakeeping analysis and a full asset FEA model deployed. For the offshore units (ship or non-ship-shaped), the analyses incorporate Environmental Severity Factors, previous damage and the consideration of the loading/unloading profile, which is significantly different from the loading profiles for more conventional ships. The significant outfitting and equipment mounted on the hull topsides and the interaction of this with the hull is evaluated using the Offshore rules. Offshore non-ship-like assets are treated under MOU rules. If a more advanced rating is required, then spectral based fatigue methods are deployed.

DNV GL determine the remaining strength of an aged ship using their Hull Life Cycle Programme (HLP) (DNV GL, 2017a). This captures the current condition of the ship for 3D FEA, including detailed thickness measurements, from which residual life is calculated (Wilken et al., 2013; DNV GL, 2015). As thicknesses change, the FEA analysis updates to re-evaluate remaining life constrained by an acceptable level of steel diminution through corrosion (DNV GL, 2016a). DNV GL provides a class notation, HMON (DNV GL, 2017a), to recognize assets incorporating live hull monitoring and stress warning alarms to inform immediate action and future maintenance and repair strategies.

2.2.2 *Offshore platform - API and ISO Rules*

An effective survey of rules development on this subject has been outlined in Copello et al. (2015). During the early 1990's the American Petroleum Institute (API) developed a new section (Section 17—Assessment of Existing Platforms), to provide guidance for evaluating the fitness-for-purpose of old existing fixed offshore platforms.

Further updating to that guidance was provided by API in the mid 2000's by either revision of that Section 17 (by issue of a "supplement" to API RP 2A in October 2005) or development of a new recommended practice (RP), initially called RP 2SIM, as described in API (2005), which covers the management of existing platforms.

In the mid-1990's the International Standard Organization (ISO) developed the 19900 suite of guidelines to address design requirements and assessment of all types of offshore structures, including fixed steel structures (ISO, 1995). The rules were subsequently updated in 2007, becoming ISO 19902 (ISO, 2007).

According to both mentioned API and ISO rules, the actual structural performance is revised by introducing the present conditions of the structure, which means a reassessment process carried out by a procedure which can be summarized in five main steps:

1. *Data gathering*: before starting the reassessment process, a complete set of information about the platform is collected, including original design data, date and site of installation, construction and fabrication data, and platform history. This last one series of data consists of environmental loading history, changes in topside layout and weight, accidental events and relative damages, survey and maintenance records, repairs etc.
2. *Current platform survey*: to complete the previous data collection, the present condition of the platform is described with specific field inspections and on-site measurements, relative to the above water (deck, layout of wells, conductors) and underwater structures (jacket pipes members and nodal joints, anodes, marine growth measurements).
3. *Updating of the platform model*: by the gathered information the structural scheme and the FE model is updated for subsequent verifications.
4. *Review of the loads*: the new design loads, (relative to those used at the construction age) are defined according to updated design codes and rules. The data upon which predictions of environmental extremes were made at the design stage might no longer be appropriate for the reassessment.
5. *Strength assessment of the existing platform structure*: the structural updated model of the platform is verified with respect to both operational and extreme storm loading conditions, as normally done in the design of the new platform, by checking that prescribed limit state verification for the structural components are compliant. Present fatigue and corrosion conditions of each component are analyzed and verified according to the original design safety margin. According to the philosophy suggested by Copello et al. (2015) and ISO (2007), in the verification procedure it is permissible to have limited individual component failures provided that the remaining parts of the structure have sufficient reserve strength to redistribute the loads.

According to the described methodology, the existing structure can be considered adequate when, introducing the specific site conditions and given operational requirements (such as the desired life extension) the risk of structural failure leading to unacceptable consequences is adequately low. Thus, the required safety target can be related to the actual system capacity of the platform, measured by the residual strength reserve of the whole jacket evaluated by a push-over analysis, and then introduced in a reliability assessment system capable of determining the actual residual life of the structure and maximum return period of the extreme environmental loading that the platform is still capable of withstanding.

2.3 Lifetime Extension

The design life of any marine asset depends on the load type and return periods of the highest considered load. In the case of ships and offshore platforms this period is typically in the range of 20 – 25 years. On the other hand, due to changes in worldwide economic conditions, in particular the current low price of oil, it is more cost effective for operators to continue exploiting assets beyond their 20–25-year designed life instead of investing in a new asset. Experience shows that for many assets at the end of this period, they appear to have the structural capacity to continue their operative life. The challenge then is to quantify and qualify the true residual capability of the asset: to continue to safely use ships and offshore platforms that have reached the end of their designed lifetime and have an extended use approved by statutory authorities.

The lifetime extension of the asset should be undertaken on the basis of the present design load rules. By verifying the model with the current design loads as imposed by the most recent Rules, it is possible to assign a theoretical remaining lifetime. This is crucial as with the case most clearly seen with offshore assets, API RP2A has evolved to consider a 25-year return period as insufficient and in fact the asset should be designed now for 100-year return period. This, Potty and Mohd Akram (2009) write, increases the loading on offshore assets from 2–4 times the recommendations from early editions of the same guidance. Aeran et al. (2017) propose a new framework for the life-cycle assessment of structural integrity for offshore jacket platforms, specifically with the view to life extension. Guidance for operation of assets beyond their original design requirements can be found in e.g. NORSOK N-006, “Assessment of Structural Integrity for Existing Offshore Load-Bearing Structures (NORSOK, 2015).” Further, in the ISO community, a new guideline on structural integrity management is under preparation.

2.4 Challenges and Opportunities

Recently Ibrahim (2015a–d; 2016a–b) undertook an extensive six-part review of the current state-of-the-art in ship and offshore structural life assessment based on over 1,800 references: “Overview of Structural Life Assessment and Reliability Parts I–VI.” Ibrahim (2016b) concluded that despite the volume of research invested in structural life assessment and structural health monitoring, in nearly all instances these two areas had not been integrated. Current approaches for mapping motions and loads into stress responses can be advanced (using for example coupled fluid structure interaction hydroelasticity) to include the research advances in the areas of fracture mechanics and probabilistic design, providing an integrated solution for ship and offshore structure design. In particular, there is a need to develop probability and reliability methods for extreme values where Monte Carlo simulations combined with the path integral approach benefit computational speed with accuracy (see for example, Kougioumtzoglou & Spanos, 2013).

Similarly, Caines et al. (2013) in looking at the treatment of corrosion under insulation noted that while risk-based inspection (RBI) is well documented and becoming standard practice in industry, the methods are based on simplified probability and consequence modelling. More long-term testing of materials and laboratory standards as well as better probability models are required if RBI is going to be accurate. New inspection techniques to determine corrosion rates from on-line monitoring need to be developed.

Shafiee and Animah (2017) conducted an extensive review of the literature published between 1986 and 2015 on the mechanisms of life extension of assets across a wide range of sectors. The breadth of this review is captured in their figure reproduced in Figure 1.

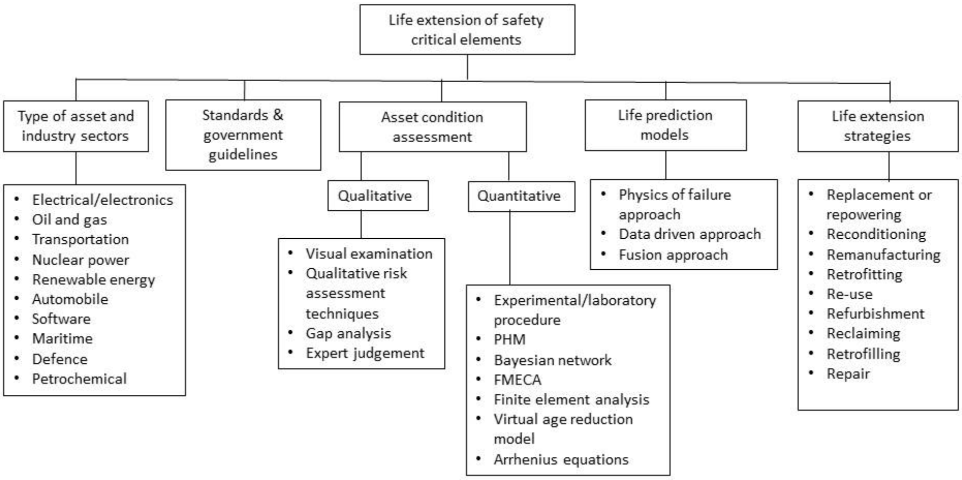


Figure 1. A framework to classify the literature on life extension of safety critical assets (Shafiee & Animah, 2017).

While their review concentrated on life extension, the decision supporting framework by necessity incorporates condition assessment strategies and life prediction models for life-cycle structural assessment. They identified that while there was a sizeable amount of research on life extension of safety critical assets there were many unresolved issues for future study, namely:

1. A lack of integration of life extension considerations within the more studied areas of design, installation, operation and maintenance; this could be used to improve life-cycle decision making. Furthermore, life-cycle management should include the combination of techno-economic and social effects on decision making.
2. A need to better understand alternative strategies to prolong and manage structural health in “reconditioning,” “remanufacturing,” and “use-up.”
3. Much research has focused on the development of condition assessment tools. However, there is a need to understand their limitations, the constraints under which they should be deployed, and how these tools change their effectiveness for different applications.
4. Accurate lifetime prediction models capable of determining residual life are still lacking.
5. Despite life extension being deemed as economically attractive, little research has focused on how a life-extended asset’s maintenance strategy may change.
6. Asset obsolescence management is a challenge. As the asset is operated beyond the end of its life, integrating state of the art control and automation systems to support safe operation may not be achievable or economically viable.
7. Quality of data supporting life-cycle assessment and management must be improved by the investment in platforms, policies, and procedures to store and manage the data acquired during the asset’s life-cycle.
8. Little attention has been paid to the study of human and organizational challenges such as an ageing workforce and loss of expertise and the retention of historical information and knowledge about an asset’s past. In preserving such knowledge there is a primary question as to how to “capture tacit knowledge and transfer it to successors” (IAEA, 2006).

9. As already available in the electrical/electronic, offshore oil and gas, and nuclear power industries, more case studies and analysis of best practice on successful life-cycle and life extensions examples should be centered on offshore renewables and shipping.

Shafiee and Animah's conclusions are echoed by Aeran et al. (2017), who add that where issues related to technological, knowledge-base and operational ageing are concerned, the incorporation of these elements in decision-making is most important for future research.

Ibrahim (2015a-d, 2016a-b) identified key areas for future research in life-cycle assessment and management for ship and offshore structures in each of his six studies.

- Given the importance of initial flaws or cracks, fatigue life assessment should be based upon fracture or crack propagation approaches.
- Designers and builders should revise rules for tankers based on climate changes and extreme weather conditions.
- IACS characteristic wave bending moment should be revised (following Bitner-Gregersen et al., 2011).
- Pierson-Moskowitz spectrum should be revised to accommodate extreme weather conditions.
- Consider corrosion and hydrogen embrittlement in life assessment of ocean structures.
- The dynamic progressive failure of marine structures under extreme loads (slamming, sloshing, grounding, collisions, etc.) needs more attention to account for the random response and nonlinear processes.
- Extend the quasi-static analyses to impact analyses.
- Application of structural reliability methods to consider the extreme tail events with the additional influence of corrosion, hydrogen embrittlement, joints and welds.
- Phenomenological models of preload fasteners and joints should be integrated with the probabilistic description of failure.
- For composites, delamination under impact should be included in reliability analyses.
- Conduct sinusoidal and random excitation tests to monitor and measure the evolution of structural joint's dynamic characteristics under preload.
- Continue development of methods for analysis of multiaxial fatigue on ship structural details as the current tools are insufficiently validated or developed: what is the fatigue response of complex welded details under loading conditions with variable time-dependent principal stress?

Despite these major reviewers' comments on the sparsity of publicly accessible integrated research into fatigue life assessment and lifecycle management, a joint industry project (VALID) between the U.S. Coast Guard and MARIN provides an example of such a holistic treatment whereby the state of the art practice in fatigue assessment and implications on vessel lifetime management has been tested against reality (Stambaugh et al., 2014). This case study showed the importance of capturing and quantifying the operating wave environment. It was recommended that future fatigue damage modelling should include impact loading and whipping responses; that FEA analyses could be used to monitor fatigue damage accumulation in key areas for operator benefit and route planning (e.g. Frangopol & Decò, 2015); and that small investments in fatigue life predictions lead to large improvements in reducing total operating costs and greater returns on investment when spectral fatigue analysis is included early in the design stage. Additionally, Soliman et al. (2016) suggested a probabilistic approach for integrating inspection, maintenance, and repair actions for a fatiguing ship's side shell detail, optimizing the action against minimal life cycle cost and maximizing service life. They showed how sensitive optimal decisions were on accurate costs for structural failure and cost and time for inspection techniques.

2.5 Conclusions

Since ISSC 2015, there has been increasing research on the incorporation of structural life-cycle assessment practice for ship and offshore structures and a transfer of knowledge across industry sectors. Much of this is driven by the advantages in capital expenses and operating expenses, advances in sensing technology and condition monitoring practices, better material knowledge and construction practices and increasingly attractive life extension opportunities for ageing assets.

Class societies and standards are evolving and starting to embrace technological advancements that can better capture operational profiles, structural response and statistical methods for material- through to asset's structural-life prediction.

Two major reviews have identified current limitations, challenges and opportunities in issues related to life-cycle assessment of an asset's structure, but it is clear that the need for an integrated approach of measuring, modelling, monitoring, analyzing, and forecasting is recognized as being critical for short term actions, long term strategic decision making, and reduced operational costs and that this approach should be incorporated as early as possible in future designs.

Comparing the ship and the offshore communities, it seems that life cycle management and the ability to predict the remaining life of a structure is more matured in the offshore industry which now uses some of the latest methods for model updating including cloud computing on a commercial level.

3. INSPECTION AND MONITORING

3.1 Introduction

This chapter builds upon the ISSC 2003 V.3 "Inspection and Monitoring" (Bruce et al., 2003) and the ISSC 2015 V.7 (Hess et al., 2015) reports and describes current practices and trends in structural inspection and monitoring techniques to optimize maintenance, repair, and operation (MRO) practices.

From the perspective of classification, legal requirements and proper asset integrity management, structural inspections are a necessity to safeguard structural longevity. A leading paradigm is that inspections should be carried out as a result of the intersection between the economic principle of reasonableness and the fact that unnecessary, disruptive and costly inspection and maintenance could result in unintended and expensive downtime, subsequent damage, and inherent risks.

3.2 Inspection

At this moment, (empirical) inspection practices are deployed as the key instrument to identify and mitigate system anomalies and unanticipated defects. In general, the outcome of periodical and event-driven asset inspections provide input for repairs and the future determination of the components' (compiled) probability of failure. Subsequently, the latter can be combined with the consequences of failure to provide a risk profile and future inspection scheme to prevent incidents, maintain a specific safety level, and to enhance design and operational practices (such as future inspections) through feedback. Although this structured method is a step forward from overall inspection with some specific focus on hot-spots, inherently, it is still a reactive measure.

The advances in sensing and monitoring technologies and inspection methodologies (e.g. risk-based inspection) are now being combined in state-of-the-art methodologies, such as advisory hull monitoring systems (AHMS). The expectation is that this will trigger a paradigm-shift into a more holistic and pro-active system approach. This is nicely captured in the model of drivers for predictive maintenance by Adams (2007). Figure 2 shows these perceived benefits of structural health monitoring (SHM) as a methodology for pro-actively managing the structural and functional integrity during the useful life of physical assets. These benefits consist of:

1. Reduction of initial risk after fabrication;
2. Optimization of the system performance;
3. Extend asset life;
4. Reduce the logistics burden without introducing risk;
5. Manage risk as wear accumulates;
6. Impact design to reduce risk and conservatism;
7. More ambitious design.

In addition, the highly stochastic nature of the aging process has provided a multitude of models and inherent uncertainties, which emphasize a probabilistic foundation. Despite considerable developments in both structural reliability theory and computational methods, the probabilistic approach has gained little ground on the deterministic practices (Van den Berg et al., 2014). The lack of acceptance of probabilistic methods for the assessment of aging may be assigned to the complexity and computational effort concerned with the approach, and the long absence of research into practical applications.

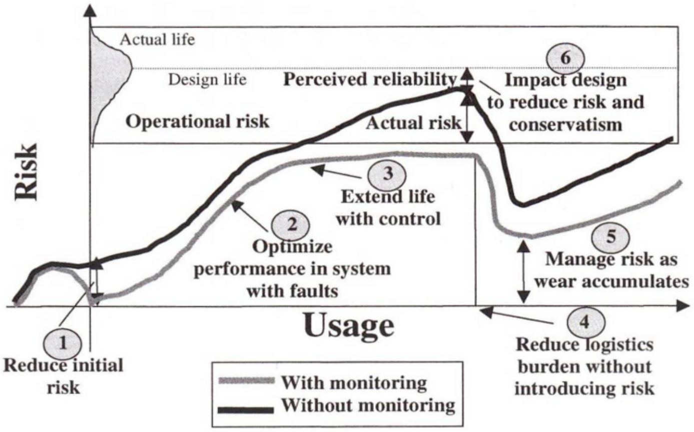


Figure 2. Potential Impact of Structural Health Monitoring (Adams, 2007).

Consequently, most operators of ship and offshore structures base decisions regarding Inspection, Repair, and Maintenance (IMR) efforts primarily on empirical procedures (ergo: inspection). Hence, structural inspection practices are deployed as the key instrument to assess the actual asset integrity by identification and mitigation of system anomalies and unanticipated defects to ensure structural longevity and an adequate level of safety to comply with statuary rules and company policy. The general perspective of inspections is still (and logically) based on empirical findings. Current practices therefore consist of the a-priori determination of technical and organizational measures to ensure future economic system effectiveness and safety. Measure optimization is generally done by posteriori analysis on correlation and causality of usage, external influences, and costs to improve the knowledge of physical system degradation, predict the future behavior, and further refine the measures accordingly.

However, by integrating this understanding of degradation propagation with the classification of the inherent risks of this process and the consequences of failure and the addition of (hot-spot) monitoring, a far more specific inspection plan can be made as an alternative for prescriptive practices - which could be unsuitable for a specific asset design and/or operational context (over- or under stringent). In essence, this is the foundation upon which practices such as risk-based inspection (RBI) are based (Tammer and Kaminski, 2013).

It is clear that the application of such (integrated) methodologies asks for sound inspection and monitoring techniques and proper data acquisition, transfer, processing, and management, which are outlined in the following paragraphs.

The offshore industry has been aware of the importance of Inspection, Maintenance and Repair (IMR) to the long-term structural integrity management (SIM) of marine and offshore structures. The aim of an inspection is to detect defects and their sizing. In structural integrity assessment such as engineering critical assessment (ECA), the results are generally evaluated in terms of acceptable assessment criteria (BS 7910, 2013). However, inspections on offshore structures are costly, and can be hazardous and often difficult because of the access limitations. In order to obtain optimized inspection schemes, risk and reliability techniques, generally referred to as risk-based inspection (RBI) schemes, have been used. Among a variety of RBI strategies available, quantitative approaches are preferred in engineering practice for the rationality in direct assessment of the probability and consequences of failure. A state-of-the-art example is the inspection planning approach for fatigue cracks which couples fracture mechanics with Bayesian updating (Chen et al., 2011). The detected crack size is also an important input parameter in this RBI approach.

For the capability of accurately identifying damage and irregularities in materials, non-destructive testing (NDT) has been introduced into a wide range of industries for structure inspection and health monitoring. There are many NDT techniques, each with their specific capabilities and limitations. The particular choice of a NDT technique is application specific, dependent not only on the structure and material of the component to be examined, but also on the nature of the defects (crack, corrosion, erosion, etc.). The studies initiated by the offshore industry and academia to apply and improve NDT techniques for various ships and offshore structures are fruitful. Ibrahim (2015) made a review on the NDT technologies of marine composite structures. Raišutis et al. (2016) performed a comprehensive overview of NDT for defects in wind turbine blades. Constantinis et al. (2016) proposed a new approach for underwater hull inspection of floating offshore assets. Feng et al. (2016) reviewed NDT techniques applied to in-line inspection for defects in pipeline girth welding.

NDT techniques for general applications include visual inspection, magnetic testing (MT), liquid (or dye) penetrant inspection, radiography (X-rays or gamma-rays), ultrasonic testing (UT), eddy current (EC), acoustic emission (AE), thermography and so on. Among those NDT techniques, time of flight diffraction (TOFD), alternating current potential drop (ACPD), and alternating current field measurement (ACFM) are often used for assessing fatigue and weld defects. Magnetic flux leakage (MFL) is a magnetic method for detecting corrosion, and pitting in metallic structures, most commonly pipelines and storage tanks. Some methods are only able to measure the length of a defect, while others also have the capability to measure the height of a defect. The methods also vary in their capacity to characterize a defect, i.e. to determine if a defect is voluminous, planar, sharp etc. Different physical principals cause differences in performance on which the methods depend and in conditions of application. To inspect a structure fully, the use of more than one method is often required. For example, the UT helps in the detection of internal defects while the EC examination is more appropriately applied in the detection of surface breaking defects. However, information from different NDT systems can be conflicted, incomplete, or vague. The concept of data fusion can be used to combine information from multiple NDT techniques and help in decision making to reduce human errors associated with interpretation.

NDT rules and guidelines can be found in the NDT yearbook by British Institute of Non-Destructive Testing (BINDT, 2017), NDT handbook by the American Society for NDT (ASNDT, 2012), and ASM Handbook by American Society for Metals (ASM, 1989). ABS also published guidelines for NDT Inspection of Hull Welds (ABS, 2014c) in which radiographic, ultrasonic, liquid penetrant, magnetic particle, ACFM, as well as eddy current NDT techniques are included. The American Petroleum Institute (API) published a Recommended Practice RP 580 (API, 2009) for risk-based inspection of pressure containment systems, pipelines, storage tanks, and other process equipment. NDT is also mentioned in BS 7910 (2013) and API 579 (2016) for engineering critical assessments (ECA).

The outcome of NDT-inspections and the quality of the information gained is limited by the Probability of Detection (PoD) and Probability of Sizing (PoS), which are highly influenced by these constraints:

1. The deployed methodology and technology. References that denote specific PoD/PoS-curves for different inspection methods and -scenarios are quite limited;
2. Inspector competency. Often the framework for both competency/qualification and execution is limited.
3. If qualified, intrinsic human limitations in observation and interpretation (still) play a significant role;
4. Circumstances during inspection execution, such as non-ideal conditions due to limited visibility, weather etc.
5. The inspectability of details due to accessibility limitations.

Stringent codes and the deployment of complementary techniques are used to limit the first constraint. More focused (such as RBI) and automated inspection and monitoring techniques are gaining more and more interest to rule out constraints 2 to 5.

3.3 Monitoring techniques

While inspection supplies discrete measurement at points in time, the monitoring system gives actual time histories of measurands in terms of conditions on structures, equipment/machinery, cargo, ballast, metocean, and so on. Maritime and offshore industries are developing a strong interest in on-board and real-time monitoring systems in line with a noticeably growing trend in the Internet of Things (IoT), Big Data, machine learning, SHM, and digital twin. The monitoring system is supposed to provide essential or useful information for optimizing Maintenance, Repair, and Operation (MRO).

Also, the latent need to integrate (or enhance) the functionality of inspection techniques with condition monitoring activities and pro-active management strategies (e.g. RBI) was emphasized upon in the conclusion of the ISSC Fatigue and Fracture Committee III.2 (Horn et al, 2009).

"*The re-assessment of fatigue loading is important and fatigue hotspots need to be re-evaluated, in order to ensure a safe operation. The (class) societies today are working in order to peruse guidelines and recommendations, however there are still several uncertain questions that have to be fulfilled, like to judge if an old unit has operated within the design conditions specified. The fast development of monitoring technology opens new possibilities for continuous recording and new platforms today can be monitored in order to ensure that the unit operates within design conditions specified. However, monitoring of platforms will* *create tremendous information and one main challenge would be how to analyze the data and draw meaningful conclusions.*" Section 0 will focus on the data paradigm.

The ISSC 2015 V.7 report recommended that SHM systems need to be expanded to address real structures. The strong trend toward using monitoring data in various aspects is a driving force to apply the monitoring system to operating ships and structures. Promising examples are found in:

- The Monitas (Monitoring Advisory System) Joint Industry Project, which has concluded and delivered an automated measurement system and data analysis procedure to monitor the fatigue lifetime consumption of FPSO hulls. The background of the Monitas system is described by Kaminski (2007) and the Monitas methodology and -application are discussed in more detail by Aalberts et al. (2010), L'Hostis et al. (2013), and Van der Meulen and Hageman (2013).
- The CrackGuard Joint Industry Project hinges on the principle of Quantitative Non-Destructive Evaluation (QNDE) for automated in-service inspection and monitoring. Current practices after anomaly detection consist of ultrasonic testing, magnetic and/or radiographic testing and sometimes strain monitoring on critical locations. The CrackGuard project goal consists of precompetitive research and the development of an affordable system for (wireless) monitoring of detected fatigue cracks (Van der Horst et al, 2014).
- The Japanese Joint Industry Project, i-Shipping, supported by Japanese government between 2016 and 2020, is aiming to apply the digital twin concept for estimating vessel performance in actual service condition (Yonezawa et al., 2017). In this project, SHM for container ships, in which data obtained from hull and metocean monitoring are shared, is addressed to enable safer maneuvering with consideration for hull strength and rational design.
- VALID I and II Joint Industry Projects led by MARIN have employed structural hull and metocean monitoring to determine fatigue life predictions on a range of U.S. Coast Guard ships and vessels, to inform remaining service life estimates and maintenance needs (Stambaugh et al., 2014 and Drummen et al., 2017). The project includes hull structure monitoring on two U.S. Coast Guard cutters, one of which has been instrumented for strains and ship motions as part of an ongoing hull structure monitoring effort of long-term monitoring to support life-cycle decisions and improve supporting technologies. Other aspects of the project include development of the technology of the ship as a wave buoy to measure the actual sea states encountered, better understanding of fatigue, and structural reliability assessment.

With the development of state-of-the-art technologies in terms of the monitoring system, the classification societies' standards and guidelines on conventional hull monitoring system have been formatted well for ship structures. On the other hand, SHM systems for offshore structures are currently being more and more mature. These are described in the following subsections.

3.4 Hull monitoring systems

Hull monitoring systems are intended to close the gap between design and operation, i.e. in design the vessel is designed to withstand still water loads and wave loads, while in operation the hull monitoring system should work as a dynamic loading computer and verify the static loading computer on board when installed. The hull monitoring system can include sensors for several purposes, e.g., global structural response of the hull, local structural response of the hull, motions and accelerations, pressures, sloshing and slamming, ice response monitoring, environmental monitoring, comfort and vibration.

The measured signals are typically split into given time intervals for data processing and the results from the data processing for each time interval are stored. The filters are initiated at the start-up of the hull monitoring system, and are continuously active as long as the system is running during normal operation. The following statistical parameters may be calculated for each of the selected response parameters: maximum value, minimum value, mean value, standard deviation, skewness, kurtosis, mean zero crossing period (or mean crossing up count), maximum peak to peak values, and number of observations used to calculate statistical parameters.

The hull girder stress monitor may warn a vessel's operating personnel that the hull girder stresses, resulting from still water loads and wave loads, are approaching a level at which corrective action is advisable. To reduce the risk of local bow damage due to slamming, the whipping response from the global strain sensors may be considered and an alert would be provided to the operators if the levels exceed some predetermined damage threshold value. The accumulated fatigue damage may be estimated based on the stress response histogram, a relevant stress concentration factor (K factor) and the S-N curve. Miner's cumulative damage techniques, in conjunction with rain-flow counting, are typically used for fatigue life estimation. Alarm settings refer to warning values for global strain sensors, motions (roll and pitch), and accelerometers.

The results from the calculations for each time interval may be arranged in such way that a sequence of the latest data from each individual sensor can be displayed as a trend. The sequence should at least include data from the last few hours for displacement ships and 30 minutes for high-speed light craft. One approach is to use a four-hour data sequence from each individual sensor to form the basis for a forecast trend prediction of the expected response from each individual sensor for at least the half or the next hour. When the signal from an individual sensor exceeds a certain fraction of a specified threshold value (e.g., 80%) for that sensor, the expected time to reach the threshold value can be predicted based on trend analyses. If a critical limit level will be expected to be reached, then changes to the vessel's operation may be advisable. This decision process may be enhanced through the use of an artificial intelligence algorithm or an expert system.

The specific requirements for a hull monitoring system by different classification societies are listed in Table 1 (ABS, 2015; ABS, 2011; BV, 2017; CCS, 2015; DNVGL, 2017a; KR, 2017; LR, 2012; NK, 2017).

The use of structural hull/health monitoring (SHM) systems is thereby becoming a key discipline for re-assessing of offshore structures due to the fact that SHM systems have the potential for extensive increase in the lifetime of ageing platforms, reduction of maintenance costs, and at the same time reducing uncertainties and increase of safety. While used rather interchangeably, "Hull" monitoring involves acquiring data about the hull through sensors while "Health" monitoring includes the use of the collected data to determine meaning and thus insight into the "health" of the structure. For the purposes of this report, SHM will denote "Structural Health Monitoring" according to the preceding definition.

Today, the SHM systems range from "simple" updates of FE models based on measurements to advanced models, which incorporate the newest analysis methods of today including non-linear system identification, expansion processes, probabilistic FEM updating, wave load calibration, quantification of uncertainties (Bias and CoV), and re-assessment analysis with input to Risk- and reliability Based Inspection planning (RBI). The more advanced components of the SHM systems combine the latest developments from a number of other related disciplines such as from Electrical Systems, Control Systems, Machine Learning, Data mining, etc. An overview of some of the features forming part of the current state of SHM systems (marked by heavy dashed lines in the lower right quadrant) and future/less matured features is given in Figure 3.

Table 1. Requirements for hull monitoring system by classification societies.

Year	ABS 2015	ABS(ice) 2011	BV 2017	CCS 2015	DNVGL 2017	KR 2017	LR 2012	NK 2017
Notation	HM1 (motion) HM2 (stress) HM3 (Voy. Data)	ILM	MON-HULL	HMS	HMON	HMS	SEA(HSS) SEA(ICE)	HMS
Strain Range Acc range	x x	x x	±2000μ ±2G	x ±2G	±2000μ ±2G	x ±1G	x ±2G	x ±2G
Angle range	x	x	x	-90º~+90º(roll) -45º~+45º(pitch) -180º~+180º(yaw)	-90º~+90º(roll) -45º~+45º(pitch) -180º~+180º(yaw)	x	-30º~+30º(roll) -10º~+10º(pitch)	
Frequency Range (Strain/Acc)	0-5Hz/0-5Hz	0-150Hz	0-1Hz/ 0.2Hz-1Hz	0.01-3Hz(motion) 5-100Hz(slamming) 30-1200Hz(sloshing)	0.01-5Hz(motion) 5-100Hz(slamming) 30-1000Hz(sloshing)	0-5Hz/ 0-5Hz	0-5Hz/ 0-5Hz	0-5Hz/ 0.5HZ (fw.0~100Hz)
Sampling Rate	3 times the maximum F.R.	More than 150Hz	20 times the low-pass filtering freq.	20Hz(motion) 500Hz(slamming) 3000Hz(sloshing)	20Hz(motion) 300Hz(slamming) 2000Hz(sloshing)	3 times max F.R.	4 times max F.R.	x
Accuracy St./Acc/ang. Setting/ Calibration	5μ/±0.01G in a known LC/ annually	1μ/x in a known LC/annually	20μ/x in a known LC/-	x/0.01G/0.5º in a known LC/-	5μ/±0.01G/0.5º in a known LC/annually	20μ/1% in a known LC/annually	5μ/0.02G in a known LC/annually	10μ/0.01G in a known LC/-
UPS	4h	30 min	30 min	10 min	10 min	10min	x	x
VDR	IMO Res.A.861(20)	x	IEC61162	IEC61162	IMO Res.A.861(20) IEC61162	x	IEC61162	x

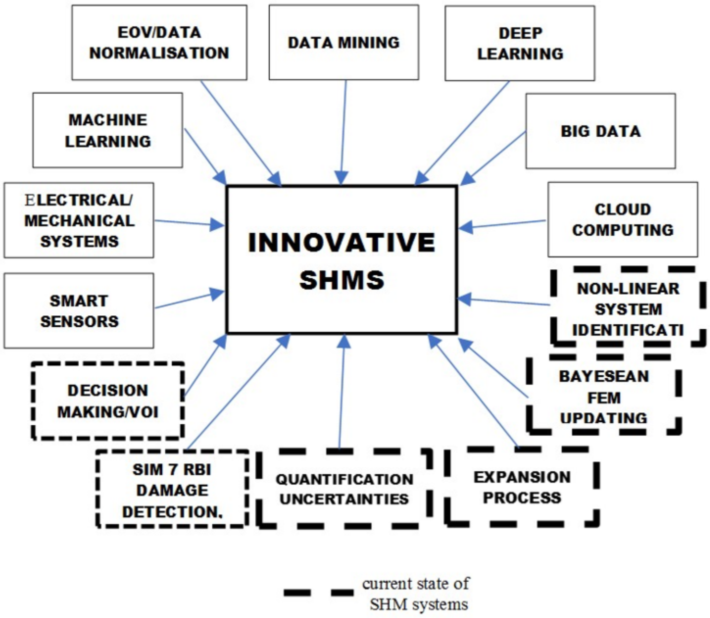


Figure 3. Innovative SHM systems reproduced from overview by Tygesen et al. (2016).

One issue with field measurements is that they normally generate large amounts of data that have to be processed. However, the analysis of huge data sets from the SHM systems can now be accomplished using the latest development within Big Data processing by cloud computing solutions, i.e. now available computational power enables extracting of information from measured data, which was not possible just a few years ago.

When designing SHM systems, one has to distinguish between platforms which are "born" with measuring devices installed and platforms where measuring devices are post-installed. This section presents some examples of how field and laboratory measurement can feed into the SHM system models of today allowing for increased accuracy in areas such as fatigue life estimations. The focus is on systems, which are based on post installed devices allowing for evaluation of existing platforms including their possible lifetime extension.

The accumulated fatigue damage is known to be one of the main factors, which dominates the "structural health" of a ship or offshore platform exposed to significant wave loading. Hence, when trying to extend the life of an existing platform beyond the design fatigue life, an accurate determination of the accumulated fatigue life is of major importance.

One of the simpler and oftentimes efficient methods of increasing the predicted fatigue life of a structure, is to reduce some of the conservatisms inherited in the existing fatigue analyses. Rosen et al. (2016) used data from accelerometers mounted on the topsides of a wellhead platform and a mono-tower platform. The two platforms were positioned at 100 m and 52 m of water depth, respectively. Based on measured data covering years for both platforms, the natural period and damping of the platforms were determined. Relative to the 2% structural damping prescribed by the code (API), significant increases of damping could be justified by the measurements and predicted fatigue lives could be increased correspondingly.

When determining the fatigue lives using standard "code-based assessments" there will often be significant conservatisms on the action side. A direct measuring of the actual loading is usually not feasible due to sensor/data limitations. To overcome that problem, Perišić and Tygesen (2014) presented an evaluation of two methods for load calibration based on a limited number of measurements of dynamic responses, i.e. modal expansion or Kalman filter-based methods. Both methods were found to provide relatively accurate estimations of loading allowing for wave load calibration using the single measuring points positioned on the topsides. The advantages and disadvantages of the load estimation methods are summarized in Table 2. Further, it is noted that the use of calibrated loading reduces the uncertainty in the load modelling significantly, which is a significant input to the RBI models.

Table 2. Pros and cons using Kalman filter or Modal expansion methods, Perišić and Tygesen (2014).

Property	**Kalman filter-based method**	**Modal expansion method**
Computational complexity	Low	High
Stochastic model	Yes	No
Number of estimations	Operational	All
Operational in real time	Yes	Near-real time
Structural model complexity	Low	High

Skafte et al. (2017) have worked on a more direct methodology for full field strain estimations using a limited number of vibration sensors. These sensors can be post installed on existing platforms above water minimizing the cost for field measurements. The main idea is that the measured response of an offshore structure exposed to wave loading can be split into two parts using complementary filters, i.e. a low frequency response imposed by quasi-static action from the waves and a high frequency response given by the modal properties of the structure. The low frequency part of the signal is decomposed and expanded using Ritz-vectors that represent the displacement of the structure imposed by wave loading while the high frequency part of the signal is decomposed using experimentally obtained mode shapes and expanded using the analytical mode shapes. The expanded signals from the two frequency domains are added together to the full strain history. Skafte et al. (2017) performed physical tests on a 1:50 scale version of a typical tripod jacket platform. The test model was equipped with 12 accelerometers which were positioned on the topsides and top of the center column (i.e. above water). The analytical Ritz vectors were determined by adding a static load to an FE model of the test setup. The theoretical/experimental work shows promising results regarding estimation of the strain history in the full structure using a limited number of measuring points. However, for full scale structures, the wave force will be acting at frequencies lower than 0.05 Hz requiring that the accelerometers have a very good signal-to-noise ratio in the frequency region. One way to overcome this issue can be to combine accelerometers with GPS sensors as these often are superior to accelerometers in the very low frequency region.

An overview of the current state-of-the-art for predictive modelling using machine learning for maintenance is given in Tygesen et al. (2018). The focus of the paper is the creation of a validated model of the jacket structure, including an estimate of the wave loading, updated with information from the measured sea state. Measurements from a jacket installed in the North Sea is used for validation and good agreement is found. One of the main experiences gained from working with SHM is that the uncertainties in the prediction models are reduced. Any reduction in uncertainties results in cost reductions for maintenance.

3.5 Data acquisitions, transfer, processing, and management

Diagnosis of structural integrity is implemented based on NDT inspection and/or structural hull monitoring. Future behavior of damage/degradation and the remaining useful life of an in-service system are predicted based on the diagnosis result and prognostics methods. Inspection and sensor data also facilitate the prognostics which use data-driven and physics-based approaches. Data-driven approaches use information from previously collected data (training data) to identify the characteristics of the currently measured damage state and to predict the future trend. The data-driven approaches are divided into two categories: (1) artificial intelligence approaches that include neural network and fuzzy logic and (2) statistical approaches that include gamma process, the hidden Markov model, and a regression-based model. Physics-based approaches assume that a physical model describing the behavior of damage is available and can be combined with measured data to identify model parameters and predict the future behavior. Model parameter identification is performed with an estimation algorithm, such as the Kalman filter and Bayesian method (An et al., 2013).

The capabilities of inspection tools collecting precise defect data and sensing devices monitoring actual conditions are vital to diagnosis/prognosis. The higher the data precision is, the narrower the safety redundancy, meaning a lower cost for structural construction and maintenance. Accuracy and reliability are two essential aspects of inspection and monitoring data.

Accuracy in inspection is established by determining if all the defects above a certain size are detected and reported, as well as the precision of the detected defect size measurement of depth and length. Thus, the PoD and PoS are required. The reported dimensions of a defect may be increased by sizing errors. Risk is related to both the consequences and probability of failure. The required inspection reliability and the rigor with which it is determined should be agreed between the interested parties and documented: see ASME Boiler and Pressure Vessel Code, Section V (ASME, 2010) and ENIQ Report NR 31 (European Commission, 2007). Provisions for NDT detection precision are given, for example, in DNV-OS-C101 (DNV, 2012), NASA-STD-5009 (NASA, 2008), ECSS-E-ST-32-01C (ECSS, 2009), and ASME Boiler and Pressure Vessel Code, Section XI, Mandatory Appendix VIII (ASME, 2010). Precision of NDT inspection can usually be improved if complementary techniques or repeated inspections are conducted.

Installation, calibration, and the usage environment of sensors should be carefully taken into account, since accuracy in monitoring with the sensors is influenced by them. The installation and calibration procedures of sensors in a hull monitoring system can be submitted to a certification society for approval. For fiber-optic sensors that have been commonly used in a hull monitoring system, standards or reports are helpful to understand their capabilities or limitations (e.g., IEC 61757-1-1, 2016 and SAE AIR 6258, 2015). Sensor faults substantially affect sensor data and compromise the reliability and accuracy of SHM. The integrity of the sensor data needs to be preserved to enhance the reliability and accuracy of SHM system outputs as well as the robustness of algorithms implemented for SHM (Smarsly et al., 2016).

Represented by IoT technologies such as cloud computing, big data analytics, wireless intelligence and robotics, the current trend of automation and data exchange (called “industry 4.0”) has brought great changes to traditional NDT inspection. The inspection tool can be made “smarter” invoking state-of-the-art machine leaning techniques based on big data acquired, or more specifically by re-designing the software to incorporate efficient machine-learning algorithms. For example, it is very practical to train and test magnetic flux leakage (MFL) tools to accurately interpret a feature (such as its dimensions: length, width, and depth) indicated by reflected signals, using a known collection of measured defects. Extensive testing/learning can be performed before the MFL tool undertakes an inspection task. Knowing the actual dimensions of a feature makes it relatively easy to make simple correlations of signals to actual anomalies found in the material. When signals in an actual inspection have similar characteristics to the signals found during testing it is logical to assume that the features would be similar. Specific algorithms should be devised for calculating the dimensions of a defect feature. A carefully designed artificial intelligence network then selects defect candidates and reduces the number of indications to be manually checked. The display of the data, using at-times proprietary software, will allow the analyst to quickly access the relevant portions of the data and enter conclusions. With the anomaly reported in a simplified fashion as a cubic feature of estimated length, width and depth, the effective area of metal loss can be calculated easily (Rao and Jayakumar, 2012).

Recent advances in NDT inspection also include signal digitizing and image processing techniques, and model-based optimization. There is a trend of combining multiple tasks and NDT techniques (Karuppasamy et al., 2016). For example, the pig for in-line inspection of subsea pipelines (Figure 4) uses array sensors, image fusion, inversion approaches, and model-based investigations to significantly enhance the application of the NDT techniques for material evaluation. Miniaturization of sensors, wireless sensor networks, and multi-sensor fusion techniques extracting different data from different regions by different sensors are expected to further enhance the capability of the tool. In order to optimize the capability of corrosion inspection and wall thickness measurement, the compound NDT techniques such as MFL and UT, each enhancing and extending the capability of detection and sizing of the tool, have led to increased values regarding the PoD and confidence levels for sizing and feature identification.

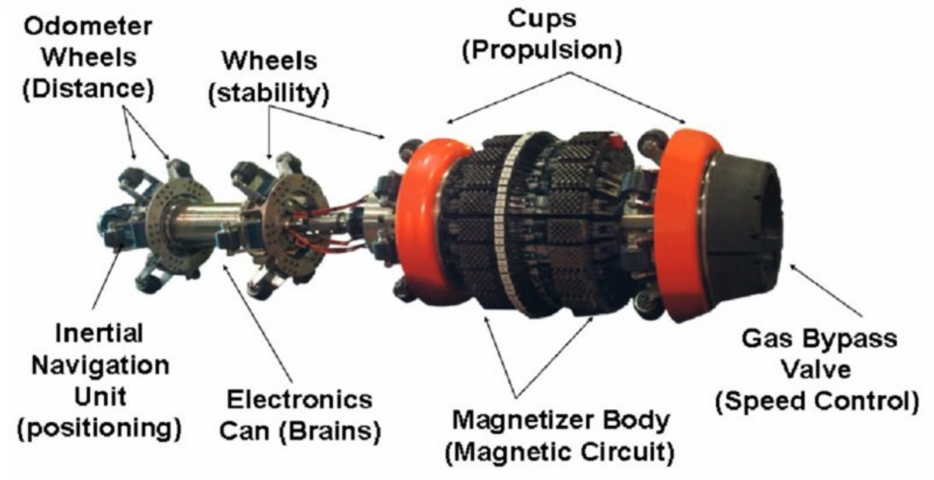


Figure 4. Pig used for in-line inspection for pipelines (Orabi, 2016).

The field feedback can contribute to the new NDT system's maturity as well. Since it is impossible to replicate all the defects that exist in all cases in the field in the shop, good communication between the inspection operators and the R&D staff as to what was reported and what was visually observed in the field is even helpful to the new inspection system's redevelopment. As electronics and software become more and more powerful, one trend we may expect is a new generation of "smart robotic" NDT inspection system (Figure 5) which will offer automated efficient inspection with optimized tool performance and precise defect identification (Shukla and Karki, 2016).

Ships and offshore plants are increasingly using systems that rely on digitization, integration, and automation, which requires paying more attention to data management and cyber risk management on board as well as on shore. Two international standards for collecting shipboard data are under development. One is ISO/DIS 19847 (ISO, 2017a) whose scope is to specify requirements for a shipboard data server that is used to collect data from other onboard equipment or systems and further share the collected data in a safe and efficient manner. Another is ISO/DIS 19848 (ISO, 2017b) which is intended for implementers of software used for capture and processing of sensor data from the structure of the ship and onboard machinery and equipment. IMO has developed guidelines that provide high-level recommendations on maritime cyber risk management to safeguard shipping from current and emerging cyber threats and vulnerabilities (IMO, 2017). A joint industry project is offering guidelines

(Fitzsimons, 2018) (AWI, 2018)

Figure 5. Robotic ultrasonic inspection systems

on cyber security onboard ships which are aligned with the IMO guidelines and provide practical recommendations on maritime cyber risk management (BIMCO et al., 2017).

In addition, services on data transfer and data platform are being enhanced to handle large amounts of data from inspection and monitoring. Inmarsat is operating the Fleet Xpress which offers high-speed broadband maritime satellite communication. Some certification societies and maritime companies are providing data platform services, such as Veracity (DNV GL), ShipDC (Class NK), and kognify (Kongsberg).

3.6 Conclusions

Inspection and the monitoring systems are still based on empirical findings and conventional schemes (i.e., HMS), respectively. However, the fusion between multiple inspection data or between inspection and monitoring data helps in mitigation of the limitation, such as low PoD, uncertainty, difficult accessibility, and human error, with each inspection/monitoring technique. IoT technologies and digital twin concepts promote data-driven and physics-based approaches in RBI and the diagnosis/prognosis of structural integrity. Furthermore, maritime and offshore industries are developing an interest in automated inspection and measurement techniques that can not only rule out the existing constraints, but also realize labor-saving or unmanned operations. Standards, guidelines, or services on data acquisition/transfer/platform/security have been recently developed for such a highly digitized system.

One of the main experiences gained from working with SHM is that the uncertainties in the prediction models are reduced. Any reduction in uncertainties results in cost reductions for maintenance.

3.7 Recommendations

- Automated inspection and measurement techniques should be developed to mitigate the existing constraints.
- The applicability of data-driven and physics-based approaches with inspection and measurement data should be investigated and compared in both laboratory and full-field testing to enhance the implementation of the RBI, SHM, or digital twin.
- Efforts to improve the accuracy and reliability of existing inspection and monitoring techniques should be continued, since these are essential for the subsequent processes.
- Reference should be made to standards and guidelines and then feedback provided to the governing bodies to support the safety and reliability activities in the industries.

4. OFFSHORE STRUCTURAL LONGEVITY METHODS AND EXAMPLES

4.1 Introduction

In this chapter, a critical review of the literature has been conducted in relation to application of the principles discussed in Chapters 2 and 3 to offshore structures. This chapter deals with bottom-fixed as well as compliant and floating offshore structures. This implies that structures such as Tension-Leg Platforms (TLPs), Spar buoys, and semi-submersibles are also addressed. As compared to ships, offshore structures are generally more difficult both to inspect and to repair. While ships regularly visit harbor areas with the possibility of dry-docking, offshore structures are typically located in areas far from shore and are only occasionally taken away from their sites.

In the following, the main focus is on steel structures while concrete structures are only briefly addressed.

4.2 Prediction of Longevity

Prediction of longevity and integrity assessments of critical structures and marine systems normally require numerical analyses which simulate the effect of actions on structures and marine systems. In order to cover all hazard scenarios (storm, fatigue, impact, etc.), a comprehensive set of analyses may be required for each structural and marine system.

These analyses must be updated if their assessment premises are significantly altered by surveillance findings. The following basic Key Performance Indicators (KPIs) are therefore typically appropriate for the integrity assessment analyses, NORSOK N-005 (2016): existence of analysis models covering all relevant action scenarios, status of anomalies which have been registered and status of as-is assurance analyses.

A concept which is becoming more and more widespread in connection with asset integrity management (ISO, 2014a and ISO, 2014b) in relation to ships and offshore structures is the so-called “digital twin.” The term “device shadow” is also used for the concept of a digital twin. This concept refers to computerized companions of physical assets that can be used for various purposes. Digital twins use data from sensors installed on physical objects to represent their near real-time status, their working condition, and/or their position.

One example of digital twins can be the use of 3-D modeling to create a digital companion for the physical object. It can be used to view the status of the actual physical object, which provides a way to project physical objects into the digital world. As an example, when sensors collect data from a connected device, the sensor data can be used to update a “digital twin” copy of the device's state in real time. The digital twin is meant to be an up-to-date and accurate copy of the physical object's properties and states, including shape, position, gesture, status, and motion.

In another context, a digital twin can be also used for monitoring, diagnostics, and prognostics. In this field, sensory data is sufficient for building digital twins. These models help to improve the outcome of prognostics by using and archiving historical information of physical assets and perform comparison between a fleet of geographically distributed machines. Therefore, complex prognostics and intelligent maintenance system platforms can leverage the use of digital twins in finding the root cause of issues and possibly improve productivity.

Engineering, procurement, construction, and installation (EPCI) contractors, shipyards, and classification societies already routinely build finite element models of offshore plants and use them to assess initial design strength and suitability and to inform maintenance and life extension decisions. However, these models take time to build and have to be adapted for each purpose.

The digital transformation comes from the speed at which the model can now be built, and the need to build only one complete model that can be used for everything and kept up to date easily. The basic idea is to build a complete digital twin model of the actual asset and a systematic procedure that will keep it updated automatically so that it continuously reflects the actual condition of the asset and equipment.

Within the domain of offshore structures, the main computational engine for the digital twin seems to be based on the Reduced Basis Finite Element Analysis (RB-FEA) model which was developed at the Massachusetts Institute of Technology (see e.g. Grepl and Patera, 2005). This is now commercially available in the form of computer software. This computational engine enables very fast fully 3D structural analysis to be performed. This approach routinely produces structural models faster than FEA by orders of magnitude for industrial-scale simulations, and it also delivers models that are orders of magnitude larger. This speedup and level of detail is a key enabler for the digital twin technology and holds the promise to allow true condition-based modeling of large and critical assets. The relevant structural details can be included in the model, along with inspection-based condition data in relation to crack defects, corrosion, and damage due to impact or collision.

On the input side, the digital twin can interface with connected surveyors and inspection and testing data, and with live data from sensors on the equipment. On the output side, the digital twin will interface directly with structural calculation tools and with risk-based inspection (RBI) planning tools that will enable continual refinement and focusing of inspection effort. An interface with the operator’s display panels can also be established.

Cleary, the usefulness of a digital twin depends heavily on the feature that it really is a twin and not an incomplete or inadequate representation of the physical component, structure, or system.

4.3 Main factors influencing longevity

In the North Sea, offshore jacket structures have served the oil & gas industry conventionally under shallow waters with an average life expectancy of 20 years. Some offshore structures have also extended their uses beyond their life expectancy through proper servicing and maintenance to enable oil recovery under feasible economic conditions while emphasizing the importance of safety.

Structural longevity is most commonly concluded through specifications and safety practices of a specific design by the owner (Ersdal, 2005) and (Guedes Soares and Garbatov, 2015). Besides, a thorough safety inspection should be conducted if a structure is expected to be used exceeding its life expectancy. The process will include factors which contribute to structural deterioration such as fatigue, environmental conditions, and loading patterns affected by subsidence.

In Hess et al. (2015) it is stated that the essence of fatigue is confined and collective and it should be included when defining the longevity of an offshore structure. Therefore, the statement explains that the life span of an offshore structure at a particular point will be shortened through exposure to a given load. On the other hand, the longevity of an offshore structure does not necessarily mean the fatigue life of a specific point since local fatigue failure in a redundant structure does not constitute a threat to survival. Considering all factors which affect the longevity of a structure, a universal design and fatigue life larger than fatigue limit for specific points is produced. Nonetheless, in Hess et al. (2015) it is mentioned that “…a survey provided by May (2014), request for more guidance by the codes for managing short fatigue lives and handling corrosion and material degradation.” (p. 830).

4.3.1 Corrosion

A number of offshore installations worldwide are approaching or have already exceeded their original design life. Therefore, it is essential to check the feasibility of life extension by estimation of the remaining life and residual capacities. To address the above need, several degradation mechanisms and life extension issues are identified (Aeran et al., 2016). Corrosion is a major cause of structural deterioration in marine and offshore structures. It affects the life of process equipment and pipelines, and can result in structural failure, leakage, product loss, environmental pollution, and the loss of life.

Aeran et al. (2016) present various corrosion wastage models. A modal flexibility-based damage index is introduced to identify the damage state of the offshore jacket structures. Finally, the effect of ageing issues on life extension and significance of introduced damage index is highlighted through a case study.

Corrosion and fatigue are the main mechanisms of deterioration of wind power structures (OWS). The use of corrosion protection systems is essential to reach the expected service life for which a structure was designed. Different protection systems can be used to delay and mitigate corrosion initiation and its related consequences such as safety, structural integrity and service life. A passive approach to corrosion protection involves depositing a barrier layer that prevents contact of a material with the corrosive environment. Active approaches reduce the corrosion rate when the protective barrier is already damaged and corrosive agents come into contact with the metal substrate. Only the combination of both approaches can provide reliable protection against corrosion of metallic structures in harsh environments for the entire design life (Seth et al., 2017).

The application of coating systems is the most common method used to control corrosion. The coating process involves the application of organic coatings, metallic coatings, or the combination of these two types (generally named as a duplex system) on the steel surface. Coating offshore is more expensive than onshore due to several factors including the logistics of transporting manpower and materials to the job site and limited access to the offshore structures due to weather conditions. Expert judgment is of primary importance when coating systems are applied in very specific conditions such as the harsh offshore environment (Seth et al., 2017). Several studies have shown that bird droppings degrade the coating systems via chemical mechanisms (Rafiei et al., 2016; Ramezanzadeh et al., 2011, 2009). In order for offshore structure to maintain structural integrity over their design lives, the use of adequate and cost-effective coating systems will need to be employed in combination with adequate health monitoring and in-service inspection plans.

The paper by Lomasney et al. (2015) is focused on test results from applications of nanolaminated materials (Modumetal) for coating purposes. The aim is to improve the longevity of assets and support increased efficiency over the extended life. Applications for offshore rig maintenance and downhole production lift systems are described. Due to its low-cost, low-capex manufacturing process, this material can possibly provide improvements at comparable or lower cost to conventional metals.

Future work should involve an in-depth scientific study of the corrosion mechanism. Adequate engineering predictive models are recommended in order to assess failure, and thereby attempt to increase the remaining life of offshore assets. The present status of existing models is discussed in (Melchers, 2016), where also examples of developed models for corrosion of steel, aluminum, and copper-nickels are presented.

4.3.2 CP/Anode depletion / Coating deterioration

Fundamental corrosion protection measures for offshore wind power structures (OWS) include protective coatings and/or cathodic protection (CP), corrosion allowance, inspection/monitoring systems, material and weld design decisions, and control of environment for internal zones DNV-OS-J101 (DNV, 2014) and DNV-OS-C101 (DNV, 2017b). Corrosion protection of an OWS, typically consists of two or three epoxy-based coatings with a polyurethane top coat. However, this can vary according to exposure and location (Momber et al., 2008, 2015). CP is commonly used in submerged and tidal areas.

CP by sacrificial galvanic anodes for OWS is generally the preferential CP system used in industry nowadays. Impressed current cathodic protection (ICCP) is an alternative CP system option; however, it is uncommon today because it is more susceptible to environmental damage and third-party mechanical damage than galvanic anodes systems (DNV-OS-J101, 2014). ICCP typically requires more maintenance and inspection which is costly to provide for unmanned OWSs. Also, there are currently no industry design standards detailing requirements for impressed current systems as there currently are for the galvanic anode systems. Design considerations for impressed current systems were deleted from the scope of DNV-RP-B401 for the 2004 revision. (Seth et al., 2017)

Table 3 shows corrosion zones, methods for corrosion control and forms of corrosion in OWSs.

Undercoats are generally used to increase the overall thickness of the coating system. The top coat protects the layers below it from environmental agents such as UV light from the sun and provides primary abrasion resistance and decoration when necessary (Sahoo et al., 2017).

The two most common deterioration processes for coating are corrosion and fatigue. The most common non-destructive method (NDM) applied to old and new structures is visual inspection (Seth et al., 2017).

For corrosion protection coating systems, the research focus is on new environmentally friendly coatings systems with the ability to behave and adapt in response to environmental demands (Azemar et al., 2015; Carteau et al., 2014). The coatings should be effective in corrosion control for long service lives in a wide range of environments (Figueira, 2016). According to Gibson and Arun (2016) further improvements in the field of deep water construction using composite materials is necessary in order to improve the performance of the offshore industry.

4.3.3 Wear & tear

Assessment of aged offshore structures based on current and historical data is a critical issue for the life extension of offshore structures. The leak-before-break (LBB) approach can also be applied as a robust and cost-effective tool for structural integrity management of offshore structures that are either partly submerged (jackets, semi-submersible, ships), or contain fluids (pipes, pressure vessels). The core idea of LBB consists of guaranteeing that enough time is available between the moment a crack breaks through the hull or wall, causing a detectable leakage, and the moment when the crack becomes unstable, causing a structural failure. Ren et al. (2015) presents a case study of applying the LBB concept for a tether string that is part of the mooring system of an offshore structure.

4.3.4 Fatigue

Life extension of ageing assets is becoming increasingly important for the offshore oil and gas industry. Many pressure vessels in service have reached or are about to reach the end of their design lives, but their continued operation is required until the economic field life is exhausted. Many vessels in-service were designed over 30 years ago, when fatigue assessment was not required by the design standards. Therefore, fatigue reassessment is a critical part of the life extension process. Hutchison et al. (2015) presents reassessment of a benchmark vessel as a case study for life extension of other similar vessels. By determining the commonality between a vessel and the benchmark vessel, it may be possible with suitable on-going in-service inspection to justify life extension of the vessel without the need for a full fatigue life extension reassessment in every case.

Table 3. Corrosion zones, methods for corrosion control, and forms of corrosion in OWSs (from DNV-OS-J101, 2014)

Corrosion Zones	Corrosion Control	Form of corrosion
Atmospheric Zone		
External and internal areas of steel structures	Coating systems	Uniform and erosion-corrosion, stress corrosion cracking (SCC)
Internal surfaces without control of humidity	Corrosion allowance	Uniform and pitting corrosion, SCC
Internal surfaces of structural parts such as girders and columns	Corrosion allowance should be based on a corrosion rate ≥ 0.10 mm/year	
Critical components (e.g. bolting and other fastening devices)	Corrosion resistant materials are applicable such as stainless steel	Crevice, pitting and galvanic corrosion, SCC
Splash and Tidal Zones		
External and internal surfaces of steel structures	Coating systems	Uniform, crevice and pitting corrosion, microbial-induced corrosion (MIC)
Critical structures and components	Coating systems combined with corrosion allowance	
Internal surfaces of critical structures	Corrosion allowance and the use of coating systems is optional	Uniform, crevice and pitting corrosion
Structures and components below mean water level (MWL)	CP	
Structures and components below 1.0 m of the MWL	Coating systems	Uniform corrosion, MIC
External surfaces in the splash zone below MWL	CP	
Submerged zone		
External surfaces of steel structures	CP, the use of coating systems is optional and these should be compatible with the CP	Uniform corrosion and erosion-corrosion, MIC
Internal surfaces of steel structures	CP or corrosion allowance (with or without coating systems in combination)	Uniform, crevice and pitting corrosion, MIC
Critical structures and components	Corrosion allowance should be based on a corrosion rate ≥ 0.10 mm/year. Marine growth (bacteria) may cause a mean corrosion rate ≥ 0.10 mm/year, and the application of a coating system should be considered.	Uniform and/or pitting corrosion, MIC, SCC

Considering that offshore structures should stay fit for service during the remainder of the design and extended operating life of the field, a comprehensive methodology for the survey and inspection of the unit during this period was developed. Nezamian and Clarke (2014) provides an overall view in using the inspection and site specific characteristic data for calibrations/validations of the original design values to maintain the safety level by means of a maintenance and inspection program balancing the ageing mechanisms and improving the reliability of the collected platform conditions. Beganovic and Söffker (2016) introduce an approach to use operating conditions to control and extend a system's lifetime for larger wind turbine systems. The safety and reliability control engineering concept (SRCE), first discussed in Söffker and Raikowski (1997), introduces the idea of using knowledge about the current State-of-Health to predict remaining lifetime and integrate related information into the control loop targeting to adapt the control strategy to the current State-of-Health. The implementation leads to reliability-based (or health-state-based) system usage.

Reinforcement and repair of components using composite patches can be used for piping to reduce the stress intensity factors at the crack-front of a corrosion fatigue crack. For this purpose, an offshore pipe made of low-strength steel containing an initial fatigue corrosion crack repaired by glass/epoxy composite patch was considered. A parametric study was performed by numerical methods in order to find the effects of patch thickness on fatigue crack growth life extension and crack-front shape of the repaired pipes, (Ghaffari and Hosseini-Toudeshky, 2013). It was shown that repair of cracked pipes with glass/epoxy composite leads to significant life extension for both restarting crack growth and crack propagation period; even a repair with two layers of composite leads to a 65% life extension for restarting crack growth. It was also shown that the crack-front shape curvatures of the repaired pipes are more bent for increasing number of patch layers, but the crack-front shape changes are not significant for more than eight patch layers.

Haagensen et al. (2015) describe the original repair and strengthening program of a floating platform with extensive fatigue cracking, and the types of subsequent fatigue damage that necessitated new repairs. The recent life extension program has resulted in safe operation of the platform for an estimated additional period of 20 years.

The most common methods to improve fatigue life for offshore welded structures are grinding and peening.

4.3.5 Buckling

Buckling failures of offshore structures or sub-components of these structures are usually associated with extreme loading events. There are numerous different types of buckling, e.g. column buckling, plate buckling, local beam buckling, and stiffened plate buckling. Clearly, reduction of cross-sectional area caused by corrosion or local damage due to impact loading will generally tend to lower the buckling resistance.

Non-linear finite element approaches are now applied in the assessment of buckling resistance of complicated details. For such assessments it is very important that effect of local imperfections and residual stresses are included in the assessments. Guidance for how to carry out non-linear FE analyses can be found in DNV GL guideline "Determination of Structural Capacity by Non-Linear Finite Element Analysis Methods," DNV GL-RP-C208 (2016b).

Regarding very localized buckling, the effects of anti-symmetric buckling on the fracture and fatigue behavior of tension cracked plates was studied experimentally. Results showed that these effects can reduce the fracture capacity and the fatigue life by 35% and 59% respectively. (Seif and Kabir, 2017).

4.4 Methods ensuring safe operation

4.4.1 General

The aim of integrity management is in general to ensure management and continuous follow up for structures and marine systems from the safety, environmental, operational, maintenance, and quality management viewpoints. The process needs to include handling and understanding the effect of degradation, damage, changes in e.g. actions, organization, procedures and use, accidental overloading, and the development in offshore design and operational practices.

The objective of integrity management of structures and marine systems is further to document an acceptable level of safety and suitability of the relevant assets for their intended purposes during all phases of their life. This includes: implementation of integrity management activities that cover all aspects of the safety of the structures and marine systems, surveillance of parameters to detect changes which may affect as-is integrity assessment results, and initiation of timely and relevant responses to detected changes, which also includes assessments and compensating measures as necessary.

4.4.2 Structural Integrity Management (SIM)

The operator is required to manage integrity of the structures and marine systems in a systematic manner in order to determine with a reasonable level of confidence, the existence, extent, and consequence of changes affecting safety and performance.

Per NORSOK-N005 (NORSOK, 2016), structural integrity management will typically include the following:

- Definition of performance requirements for the structures and marine systems;
- Identification of performance limitations based on as-is condition and definition of operating limitations if found necessary (e.g. operating manual);
- Management and execution of the surveillance process;
- Contingency plans for emergency response;
- Mitigations, repairs, and other mitigating actions if systems, elements, components exceed their performance limitations;
- Requirements to personnel qualifications, competence, organization and availability;
- A strategy for acquiring and implementing best practices;
- New knowledge and techniques for improved surveillance and in-service structural and marine system integrity management;
- Continuous updating of the in-service integrity management process for structures and marine systems.

Interfaces between disciplines responsible for structures, penetrations in structures and supports (e.g. for piping, cables, ventilation ducts, riser, caissons, conductor, and equipment) also need to be defined.

Integrity management may provide a framework for:

- Understanding the hazards to and failure modes of structures and marine systems and their components;
- Understanding how the structures and marine systems are intended to withstand and be protected against these hazards;

- Understanding the context under which the evaluations are valid;
- Forming an integrity strategy and specific performance criteria for operation of the structures and marine systems;
- Operating in accordance with operational limitations, design basis, surveillance strategy, and performance criteria as formalized in operating procedures;
- Surveillance of the condition of structural and the marine systems, the metrological and oceanographic conditions, the actions and hazards, modifications and other changes in condition or use, including inspection planning and maintenance, data management and storage (including reports);
- Acting upon undesired conditions and changes to the basis for integrity assessment e.g. by defect evaluation/anomaly assessment and if necessary integrity analyses, emergency response preparedness, implementing repairs and mitigations;
- Measuring and verifying the performance of the structure and marine systems;
- Improving the structure and marine systems when deemed necessary;
- Quality assurance and verification of the integrity management work;
- Exception analysis.

4.4.3 Codes and guidelines covering structural integrity management

Codes and guidelines covering structural integrity management typically introduce a classification of structures and structural components. Such a classification makes it possible to establish the basis for risk screening and determination of what types of inspection and what methods to use.

The classification of structural components will typically consider the following issues: likelihood of corrosion, likelihood of overload, likelihood of fatigue cracks, consequence of component failure (the remaining structure's ability to withstand actions e.g. by damage tolerance or redundancy), possibility of progressive failure, deficiencies, misalignments and non-conformances reported in the design, fabrication, and installation (DFI) résumé, inspection history, presence of stress concentrations and critical load transfer connections, access and preparations to facilitate access for inspection, maintenance and repair, extent of monitoring for the structural component, and inspection method suitability (i.e. deployment, reliability, accuracy).

Classification of structural components according to design class is based on the complexity of the relevant joint, the consequences of failure, and the stress level. However, such classification may not be directly applicable for use in the classification of structural parts for in-service integrity management. This is due to the design classification society's classification not taking into account the exposure to deterioration, changes to the structure, and its variable loads. More comprehensive evaluation of likelihood and consequences of failure are frequently required.

Re-classification from classification society rule-based design to risk-based classification of members and components primarily used for fabrication, transport and installation phases may accordingly be necessary, see e.g. NORSOK N-005 (NORSOK, 2016).

With respect to the task of assessing residual fatigue lifetime, recent updates of the DNV GL rules are described in Lotsberg et. al. (2016). The recommended practice DNV GL-RP-C203 on fatigue design of offshore steel structures has been revised a number of times since it was first issued in 2001. The 2016 revision includes additional information on a number of items such as: residual stresses in tubular sections made from cold forming, S-N data for subsea application, change in validity of S-N curve in seawater with cathodic protection, relation between surface roughness and requirements for roughness for coating, S-N curves and stress concentration factors for fatigue assessment of pipelines, relation between fabrication tolerances and S-N curves in different types of structural details, and hot spot stress analysis for rainflow counting. The background for this is explained in the paper. In addition, the paper includes some information on recommendations for fatigue design of single-sided tubular joints that was included in the 2014 revision of the Recommended Practice.

4.4.4 Survey and inspection methods

Depending on how and where the execution is performed, several campaigns may be required that can be executed independently of one another, for example: onshore documentation surveillance, as-built weights and documentation (project surveillance), operational changes surveillance, offshore physical surveillance, condition above water/above cellar deck or freeboard deck (not wave dependent), condition above water/below cellar deck or freeboard deck (wave dependent), condition in wave zone (special access equipment), condition below water, ROV (executed by a marine contractor), condition below water, diver (executed by a diving contractor), as-is weight and layout control, level, distance, and freeboard surveys.

Campaign work packages

Planning the execution of surveillance tasks (i.e. structural monitoring and inspection) is facilitated by grouping similar tasks into Work packages. The organization of work packages is typically decided by a surveillance campaign planner.

The following are examples of criteria which may be used to sort tasks into work packages: facility ID (if there are several facilities), facility area (if the facility is divided into areas), method of inspection (if the campaign contains special inspections), types of structure (e.g. major structures, inventory structures).

Surveillance task execution description

The format of the task descriptions is inspection planning system dependent. Typically, a task description will refer to a general execution procedure, and in addition provide the following information: campaign name and ID, work package name and ID, task ID, surveillance type (planned inspection type and deployment method), location details, locations drawings/plots, task description, and special requirements.

Surveillance task reporting requirements

Predefined formats may be provided for the purpose of standardizing reporting of surveillance findings. These will typically contain the following reporting fields: inspection execution date, inspector name and company, inspection problems (yes/no), description of any inspection problems, inspection type(s) and deployment method used, inspection findings (yes/no), finding description and data, probable cause and possible consequence, corrective actions taken, recommended further action, and reference to separate reports/images/videos.

In the following, a summary of different inspection methods is given. Further details are found in the ISSC2015 V.7 report (Hess et al., 2015).

General visual inspection

General visual inspection (GVI) is the most commonly applied inspection method used to confirm general configurations and to detect large scale anomalies. GVI requires a satisfactory light level and visibility. Used subsea, GVI is normally performed without removal of marine growth.

Close visual inspection

Close visual inspection (CVI) is used for detailed examination of structural components or to provide further information on suspected anomalies. Used subsea, CVI requires removal of marine growth. When light color paint is used, small fatigue cracks may be detected by CVI due to paint cracking or rust staining. Close visual inspection should always be carried out before NDE work is started.

Non-destructive examination (NDE)

Thickness measurements are carried out by UT. Thickness measurements need not be carried out as long as the corrosion protection systems are maintained. Surface breaking defects for magnetic materials may be detected by means of dye penetration, ACFM, MPE, EC, or in some cases by UT. For non-magnetic materials, surface breaking defects may be detected by dye penetration, EC, or in some cases UT.

Pressure testing and tightness testing

Hydrostatic pressure testing may be used to verify structural integrity and water tightness of decks and bulkheads between adjacent tanks and compartments. Aerostatic pressure testing combined with soap water may be used for tightness testing of penetration closures and through thickness cracks in welds and base materials. The overpressure should not exceed the design pressure of the tank, and should be controlled by means of a water-tube. For personnel risk reasons the overpressure should not exceed 2,000 mm water column.

Flooded member detection

Flooded member detection can be used to detect through thickness cracks of air-filled submerged hollow members. The method should be used at the lower end to detect water in vertical and inclined members, and used vertically to detect water filling in horizontal members.

At the moment, there are ongoing efforts within the offshore industry related to development of fully autonomous subsea inspection systems based on application of AUVs and ROVs, see e.g. Offshore Energy Today (2017). This may comprise acoustic and laser sensor technology as well as artificial intelligence-based navigation software. The data from inspections can be uploaded into a platform that may include robust data ingestion, automatic defect recognition, predictive analytics, and a visualization portal for the operators and other users. Laser scanning can be repeated numerous times per second to generate coordinate values for millions of points on a surface. These points will provide highly accurate and intricate 3D models of subsea infrastructure. This may serve to expand capabilities for inspections of FPSO as well as ship hulls, underwater production fields, subsea pipelines and cables, and offshore wind farm assets.

4.4.5 Repair/mitigation

The type of repair method will typically depend on the type of offshore structure which is being considered, NORSOK-N005 (NORSOK, 2016):

For jackets:

Due to the long history of jacket structures there is considerable world-wide experience with respect to remedial measures. This comprises actions such as load reduction (marine growth removal, topside weight reduction, spider deck walkway removal), strengthening/repair/replacement (clamps, grouting, additional braces), application of insert piles and “piggy back” piles, conductor and caisson guide gap reduction, changes related to operational mode and procedures (operational restrictions), weld profiling, crack grinding, crack arrestor holes, repair welding, and intensified surveillance.

In Zhang et. al. (2016) and Zhu et. al. (2017), application of an expansive grouted clamp has been outlined with focus on verification of slip capacity and bolt prying. A typical jacket platform is employed for illustration of the analysis. A method to simulate the clamp on the FE model of the platform using line elements is proposed. The influence of bolt prestress load is also considered. Reference is also made to Li and Shi (2014) for a description of this method.

For concrete structures:

Corrective maintenance should be implemented on concrete structures to prevent escalation of minor damage into major damage. It is especially important to maintain steel reinforcements, pre-tension, and embedded pipes to secure their structural functionality during the whole lifetime of the structure.

Column stabilized unit hull structures (CSU), Ship shaped units, and Tension Leg Platforms

Temporary measures may include drilling of crack arrestors, temporary strengthening, temporary load reductions, operational limitations and changes (draft, trim, ballast, mooring pretension, etc.), increased inspection activities, and use of specific monitoring equipment. It is important that all temporary measures are subjected to a criticality and consequence evaluation.

4.4.6 Lifetime extension

Damaged structures and marine systems that, following as-is assurance assessments, cannot be shown to meet in-service integrity requirements must be corrected by appropriate permanent measures. These may involve the following: strengthening/repair/replace, physical modifications that reduce permanent and/or variable actions, modified operating procedures that reduce variable actions, modified operating procedures that reduce consequences of potential further escalation, and modified operating mode to meet the minimum facility requirements.

Activities leading to and concluding long-term compensating measures can include:

- Further detailed damage survey and evaluation;
- Full damaged integrity analysis of the structure or marine system;
- If necessary, the design of repairs, reinforcements, and/or other compensating measures;
- Revision of the defined safe operating sea-states, draft, trim, cog, pre-tension, etc.;
- Update of the as-is analysis model such as with a digital twin.

Integrity assessments of critical structures and marine systems normally require extensive numerical analyses, which simulate the effects of relevant actions. These analyses must be updated if their assessment premises are found to be significantly altered during the operation phase. Key Performance Indices (KPIs) also must be specified.

In Tang et. al. (2015) structural monitoring and early warning conditions of aging jacket platforms are considered. Characteristics of aging jacket offshore platforms are established, including the monitoring and early warning conditions in relation to displacements, pile end bearing loads, and platform subsidence. On the basis of pushover analysis, the curves of base shear force versus deck displacement are developed. Furthermore, the anticipated risks are classified into three levels due to different deformations in the collapse process. A set of three level early warning conditions are established accordingly. A method for monitoring the bearing loads of the pile end is proposed, based on calculation of the load transmission function. The early warning condition that the bearing loads of the pile end should not exceed half of the ultimate pile capacity based on API RP2A-WSD is provided. A long-term monitoring method of the platform subsidence is presented based on calculation of the difference between the elevations for any two pile tops. Early warning conditions considering the stress and tilt requirements are also established. The monitoring method has been applied to a jacket offshore platform located in the South China Sea, and the results illustrate the feasibility of the proposed method.

Andrews and Fecarotti (2017) address system design and maintenance modelling for safety in extended life operations in more general terms. The condition and performance of existing systems, which are operated beyond their originally intended design life, are typically controlled through maintenance. For new systems there is the option to simultaneously develop the design and the maintenance processes for best effect when a longer life expectancy is planned. The paper considers application of a combined Petri net and Bayesian network approach to investigate the effects of design and maintenance features on the system performance. For the assessment of aging systems, the method avoids the need to assume a constant failure rate over the lifetime duration. In addition, the assumption of independence between component failure events is relaxed. In comparison with the commonly applied system modelling techniques, this methodology is claimed to have the capability to represent the maintenance process in some detail. Accordingly, options for inspection and testing, servicing, reactive repair, and component replacement based on system condition, age or use are represented in the analysis. In considering system design options, levels of redundancy and diversity along with the component types selected can be investigated. The model has the possibility to evaluate different system failure modes. Application of the approach is demonstrated through assessment of a remote un-manned wellhead platform from the oil and gas industry.

4.5 Special items

4.5.1 Risers / pipelines

Timely detection of damage in deepwater risers is important to keep the consequence and economic loss due to damage to a minimum. Hence, continuous monitoring is needed. Vibration based monitoring is the most widely used method used in offshore structures.

Huang et. al. (2013) address time-frequency methods for structural health monitoring (SHM) of deepwater risers subjected to vortex induced vibrations (VIV). An approach based on a new damage index, distributed force change (WDFC) for monitoring the structural health of risers used for production in deepwater floating platforms, is presented. Experiments with a scaled pipe are carried out to validate the vibration-based damage identification method. The influences of multiple cracks on the WDFC damage index are studied. Furthermore, this paper illustrates the utility of wave propagation based structural health monitoring (SHM) strategies within the pipe model. This is realized based on the results of numerical investigation obtained by the use of the finite element method (FEM) together with application of a Time-of-Flight damage identification method. The damage severity is indicated by the root mean square of the damage-reflected wave. The influence of crack(s) in the riser/pipe on the wave propagation is studied by the authors. The results from the experiments and numerical analysis indicate that the investigated identification methods can provide information about the estimated crack location(s) and the possible crack extent. Hence the methods are believed to be suitable both for global and local monitoring of the structural health of deepwater risers.

4.5.2 Mooring lines

Life extension and asset integrity of floating production unit (FPU) moorings are issues of increasing importance for operators due to changing production requirements, the requirement to extend service life, and circumstances where the metocean basis of design (BOD) has increased significantly over the life of the field. Reliability methods are gaining wider acceptance as enhanced computing power allows large numbers of simulations to be undertaken using realistic fully coupled models that are validated against prior experiments. When applied to the re-qualification and life extension of FPU moorings, particularly with regard to requalification and life extension of in-place moorings, reliability analysis may offer considerable advantages over conventional deterministic return period design.

Life extension and asset integrity of mooring systems for FPUs are addressed in Rosen et. al. (2016). In Rosen et.al. (2016), application of a reliability approach is used for re-qualification and life extension of a turret-moored FPU for which design metocean conditions have increased significantly over the life of the field. The results of this study illustrate the significant advantages to the industry conferred by adopting reliability methods in the re-certification and life extension of existing FPU moorings. In particular, the study highlights that conventional mooring code deterministic design methods, while adequate for original design purposes, lack sufficient fidelity to address the multi-faceted issue of re-assessment of notionally marginal legacy systems. For a degraded existing mooring, an application of these methods can demonstrate that the level of reliability of the system is still acceptable, whereas a conventional approach may produce an overly conservative indication that the mooring is non-compliant.

4.5.3 Caisson

Caissons are an important part of offshore installations. The major design consideration for the hydrocarbon riser caisson is to protect the risers against external impact from vessels, hydrodynamic loading, and corrosion. However, this makes the inspection of the riser external wall and caisson internal wall very difficult (Schmidt, 2013).

A hydrocarbon riser caisson represents a safety critical item of an offshore platform installation. Loss of the riser caisson integrity compromised by corrosion can have a devastating impact on production capability. Corrosion can affect the riser external surface and the caisson internal surface if the caisson annulus is not well managed. The corrosion process will gradually reduce the wall thickness of the riser until failure resulting from pressure build-up of hydrocarbon within the caisson annulus. The likelihood of caisson failure is increased if the caisson itself has suffered from internal or external corrosion (Anunobi, 2010).

Hall (2012), describes the integrity management of caissons using a retrofit cathodic protection (CP) system. On the other hand, Schmidt (2013) reports on an alternative approach to managing corrosion problems in a caisson using composite materials for repair.

4.5.4 Conductors

Well integrity is typically understood as the required actions which imply reduction of the risks of release of formation fluids into the environment during the operating lifespan of the well. Frequently, a minimum requirement of a two-barrier well construction is applied in order to prevent any leaks to the environment. The conductor and casings fall into the category of the well structural barrier, along with the annuli cement. Typical wells are designed for 25 years of service life, and operators worldwide are beginning to encounter wells operating beyond 30 years and even up to 40 years in some areas.

Continued services are usually expected of these older wells for several reasons. The primary reason is due to the availability of a significant amount of reserves remaining in the reservoir, accompanied by excessive cost in replacement/abandonment activities. This implies that the integrity of the wells must be continuously assured if extended service life is expected. It is common for operators to carry out scheduled site inspections and surveys to monitor the integrity of their wells (Abdalla and Fahim, 2013). However, it is very likely that these data are not used or are misinterpreted in evaluating the integrity of ageing wells. This may potentially result in catastrophic failures such as casing collapse and wellhead and surface tree settlement.

In an ageing well, the heavy external corrosion on the conductor and outer side of the casing will result in loss in overall stiffness to resist the topside weights and environmental loads. In areas with large pits and holes, seawater ingress will cause internal corrosion on the inner side of the conductor, and to some extent also the surface of the casing. Continued corrosion of the inner surface of the conductor can result in rust flakes formation (Talabani et al., 2000). This will in turn diminish the annular cement capacity to bond with the pipes inside the annulus effectively. Over time, this may cause cement shortfall, i.e. the cementation losing its shear bond capacity and dropping further downhole.

As described by Balmer (2012), under potentially high loading from the well topsides equipment (axial) and the environment (bending), and from the reduced stiffness from the heavy wall loss and cement shortfall, possible collapse of the conductor/casing pipes can occur, resulting in the wellhead and tree dropping vertically (settlement).

4.5.5 Wind turbines

Research activities related to lifecycle design and monitoring of wind turbines (WT) are proliferating. In recent years, structural health monitoring of WT systems is significantly improved through automated on-line fault detection and health or condition monitoring (CM) system integration

Beganovic and Söffker (2016) consider Structural Health Monitoring (SHM) systems applied to WTs. Challenges resulting from contradictions between requirements related to efficient operation with respect to energy production costs and those related to lifetime and maintenance are discussed. Especially pronounced in larger WT systems, structural loads contribute to lifetime shortening due to damage accumulation and damage-caused effects influencing subsystems of the wind turbine. Continuous monitoring of the WT system concerning State-of-Health is necessitated to provide information about the condition of the system guaranteeing reliable and efficient operation, as well as efficient energy extraction. The focus is given to hardware components (mainly sensor technologies) and methods used for change evaluation, damage detection, and damage accumulation estimation. The paper comprises recent knowledge about methods and approaches of handling structural loads with emphasis on offshore wind turbine systems and applied sensing technologies (especially with respect to wind turbine blades, gearboxes, and bearings). A key idea of the introduced approach is to use the operating conditions to control and especially to extend system's lifetime. An actual state-of-the-art analysis and overview related to the use and application of SHM-related technologies and methods are presented.

In Ziegler, L. and Muskulus, M. (2016), fatigue reassessment in order to decide about lifetime extension of aging offshore wind farms is addressed. A methodology to identify important parameters to monitor during the operational phase of offshore wind turbines is presented. An elementary effects method is applied to analyze the global sensitivity of residual fatigue lifetimes to environmental, structural, and operational parameters. Renewed lifetime simulations are performed for a case study which consists of a 5 MW turbine with a monopile substructure in 20 m water depth. Results show that corrosion, turbine availability, and turbulence intensity are the most influential parameters. It is cautioned that this can vary strongly for other settings (water depth, turbine size, etc.) making case-specific assessments necessary.

Vera-Tudela, L. and Kühn, M. (2017) address lifetime evaluation with fatigue loads for wind turbines. This is usually done during the design phase, but rarely during operation due to the cost of extra measurements. Fatigue load prediction with neural networks, using existing supervisory control and data acquisition (SCADA) signals, is a potential cost-effective alternative to continuously monitoring lifetime consumption. The evaluations were limited to single cases and the implication for the design of a monitoring system was not discussed. Hence, metrics to evaluate prediction quality were proposed. Using one year of measurements at two wind turbines, predictions in six different flow conditions were evaluated. The quality of fatigue load predictions was assessed for bending moments of two blades, in edgewise and flapwise directions. Results based on 48 analyses demonstrated that prediction quality varies marginally with varying flow conditions. Predictions were accurate in all cases and had an average error below 1.5%, but their precision slightly deteriorated in wake flow conditions. In general, results demonstrated that a reasonable monitoring system can be based on a neural network model without the need to distinguish between inflow conditions.

4.6 Offshore Platform Longevity Processes

Many would define the longevity of a platform as the operational phase. However, the longevity of an offshore platform includes several phases, which all more or less affect the total lifetime of the platform. In offshore engineering, it is common to distinguish between seven main phases as outlined in Table 4 (definitions by Vugts, 2013). Included in the table are 1) main tasks involved in each phase, 2) main factors effecting the longevity, 3) tools required to obtain/maintain the desired longevity and 4) parties involved.

Table 4 Generic phase defining the full life cycle of a platform (based on definitions outlined by Vugts 2013).

Phases					
Planning (P)	Design (D)	Fabrication (F)	Transport (T) & installation (I)	Operation (O) (incl. lifetime extension)	Decommissioning / abandonment (A)
Main Tasks					
Design and operational philosophy is defined. Design specifications are made.	Preliminary design (FEED). Detailed design.	Procurement. Fabrication.	Load out & offshore tow. Lifting or Launching operations. Foundation.	Monitoring. Inspection. Maintenance. Repair. Lifetime extension.	
Main factors with effect on longevity					
Redundancy is defined in form of DFF* (minimum DFF* is code defined).	Platform is designed to meet the desired operational life time including desired contingency.	Quality of fabrication and NDT	Loads induced by tow and installation, e.g. driving of piles.	Quality of maintenance and repair. Correct response to survey findings. Modification of platforms, e.g. increased topsides weight. Lifetime extensions.	
Tools					
	Detailed fatigue life calculations using global/local FE models. Good environmental models/statistics Fatigue “friendly” designs.	Surveys at fabrication yard ensuring quality.	Sea transportation analyses. Pile driving analyses.	Inspections (can be Risk Based Inspection, RBI). Possible monitoring (e.g. online SHM Systems). Details SIM systems / digital twins.	Crane vessels, dive support vessels, ROVs.
Parties involved					
Consultants. Authorities. Intended owner.	Consultants. Certifying agencies. Contractors (EPC). Owners/possible future owners.	Contractors.	Contractors.	Owners. Consultants. Contractors.	Owners. Consultants. Contractors. Authorities.

* DFF: Design Fatigue Factor

4.7 Conclusions and Recommendations

Ongoing developments represent a trend towards integration of an extensive number of sensors with increasingly refined processing algorithms and decision support systems. Furthermore, robotic systems are entering the scene. These features pose challenges with respect to a good understanding of the structural behavior and also require that proper guidelines for operation of increasingly complex health monitoring systems are developed. Accordingly, it is also recommended that the multi-disciplinary nature of teams involved in design of such systems is properly acknowledged such that an adequate communication between different experts can be achieved.

5. SHIP STRUCTURAL LONGEVITY METHODS AND EXAMPLES

5.1 Introduction

In this chapter, a critical review of the literature has been conducted in relation to application of the principles discussed in Chapters 2 and 3 to ships.

5.2 Prediction of longevity

Due to increased competition and demanding economic conditions, owners and operators often want to continue exploiting ships and offshore platforms beyond their designed life instead of investing in a new asset.

The challenge in extending the life of an asset is to maintain adequate safety while continuing to operate cost effectively. In doing so, a level of technical assurance is required through approval by national and international statutory authorities. In Chapter 2, the approaches taken by classification societies to carry out a comprehensive re-appraisal of conditions of assets is discussed, which takes into account its past history and present condition of the structure. In this chapter, models for prediction of longevity based on first principles are discussed.

5.2.1 Models for prediction of longevity

Prediction of longevity is carried out using a combination of numerical, experimental, and full-scale measurement approaches. These predictions can either be deterministic or probabilistic.

Magoga et al. (2014; 2017) performed full scale measurements on board the Australian navy *Armidale* class patrol boats that were fitted with sensors used to predict slamming in a variety of ways. It was found that the most successful criterion for slam detection is based on whipping stress rate. Although the authors suggested a robust threshold value of whipping stress ratio for the class of vessel studies, they concluded that for individual ship types it is necessary to verify the appropriate criterion and sensor locations. Vincent et al. (2015) presented a program of work incorporating the design, installation, and performance of an integrated set of sensors capable of monitoring global as well as local structural response of an aluminum patrol craft of the Australian navy. Practical conclusions concerning their design, installation, and performance are discussed in the paper.

Clauss and Klein (2016) described an experimental study of the effect of freak waves on the total loading of the hull girder and in particular the relation of loading to the geometry of the forward structure of three types of ships. Sea conditions corresponding to the Draupner wave were generated in a test tank and the responses of a bulk carrier, a ro-ro, and a container ship were monitored. In general, it was found that the geometry of the bow structure on total loading is significant. Specifically, it was found that in the case of the containership, the addition of a freeboard extension in way of the bow area resulted in an increase in VBM amidships of around 20 percent.

A wireless system of sensors was developed in order to measure structural and motion response of free-running models or ships at full scale (Figure 6) as described in Bennet et al. (2014). The system can capture rigid body motions and three axis accelerations using a 9 d.o.f. sensor node while the structural deformation of the hull girder is obtained from three nodes in parallel. The output consists of time-synchronized inertial and magnetic data for ship models at an accuracy that is comparable to that of optical wired systems.

Shen et al. (2015) investigated the suitability of two types of fiber Bragg grating (FBG) strain gauges for use in long term hull health monitoring under conditions of corrosion and fatigue. Both gauge types were checked for signal linearity and stability in laboratory conditions simulating real conditions and also using finite element analysis.

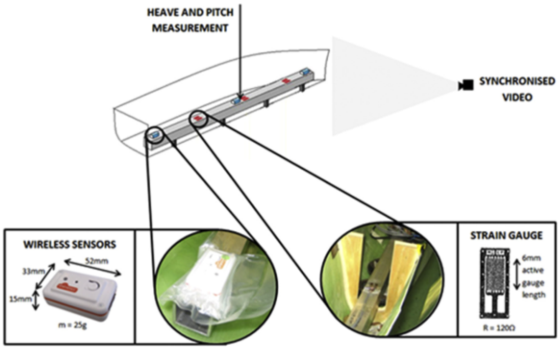
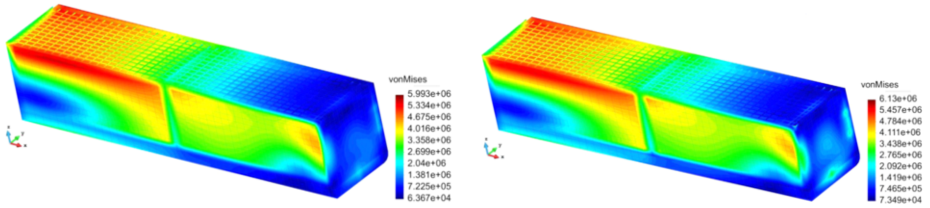


Figure 6. Locations of wireless sensors for structural and motion response (Bennett et al., 2014).

A computationally accurate, robust, and rapid algorithm named the inverse Finite Element Method (iFEM) was recently developed and applied to aerospace structures by Tessler and Spangler (2003, 2005). It was based on a three-node inverse shell element (iMIN3) using lowest order anisoparametric co-continuous functions and thus models in-plane displacements and bending rotations in a linear manner, introducing a quadratic constrained-type deflection. The iFEM methodology possesses a general applicability to complex structures subjected to complicated boundary conditions in real-time, and works on the principle that discrete strain data (shape and stress sensing) obtained from on board sensors are used to re-construct the displacement, strain, and stress fields using algorithms minimizing the weighted-least-squares functions. Kefal and Oterkus (2016) applied the iFEM methodology for the first time in the field of naval architecture for shape and stress sensing of a chemical tanker, and introduced a four-node inverse quadrilateral shell (iQS4) element, based on Mindlin's first-order plate theory. The steps followed in this study were: (a) Hydrodynamic analysis of the vessel to determine hydrodynamic forces; (b) FE analysis of the vessel using as input the hydrodynamic forces to determine the strain data to be used as input for the iFEM analysis; and (c) iFEM analysis using the strain data. Results are shown in Figure 7. The method appears to offer potential benefits in the sense that a very limited strain data obtained from several strain rosettes located at a deck stiffener, the centerline longitudinal bulkhead, and the centerline girder can be sufficient to reconstruct a precise global deformed shape and stress field in the entire structure. It is seen that the results are excellent although the practical challenge is to obtain robust and reliable results using a limited number of sensors.



(a) iFEM for one-to-one strain data *(b) Direct finite element stress distribution*

Figure 7. Von Mises stress distributions (Kefal and Oterkus, 2016).

A structural reliability assessment procedure is presented and its operation is illustrated for the case of a Capesize bulk carrier (Michala et al., 2017). The aim of the procedure is to identify weak points in the structure from the fatigue point of view and to assist in decision-making processes (planning of future repairs). It relies on hydrodynamic analysis, a finite element representation of the structure amidships, and structural reliability theory.

A series of extensive review papers were published by Ibrahim (2015a–d, 2016a–b) that deal with the application of structural reliability theory to structural longevity-related issues for naval ship structures. Consideration is given to fracture mechanics theory, corrosion, hydrogen embrittlement, impacts, and crack growth in joints. A detailed exposition of the theory is given in each case and recent developments are presented.

Lynch et al. (2012) proposed a strategy for the estimation of the remaining fatigue life of a naval structure. The strategy makes use of onboard sensors that provide raw data that is processed so that the current state of the hull girder can be assessed. The method is based on fatigue theory in conjunction with a statistical approach called the Dirlik procedure. The purpose of this is to use a limited number of parameters from the power spectrum thus avoiding the continuous processing that is necessary in rainflow counting. The method was validated by comparison with test data.

Zhu and Collette (2015) used Dynamic Bayesian Networks (DBNs) to model system behavior and update reliability and uncertainty analysis with data such as fatigue cracking. A fundamental difficulty arises when considering low probability failure events and the authors have presented an algorithm which dynamically partitions the discretization intervals at each iteration. The algorithm was validated using two crack growth models and it was concluded that it can achieve the same degree of accuracy as static discretization with less than half the number of intervals. Furthermore, it avoids the need to manually iterate through different static discretization methods and resolution levels to achieve convergence.

Das et al. (2015) performed reliability analyses of aluminum unstiffened and stiffened plates that resulted in the determination of partial safety factors for use in strength design. In the case of stiffened plates, use was made of Paik's two analytical formulations (Paik et al., 2008) that apply to T-bar and flatbar stiffened plates respectively. Sensitivity analyses were performed for model uncertainty, plate thickness, loading, breadth, material yield stresses, elasticity modulus, and corresponding partial safety factors with respect to ultimate strength obtained.

Akpan et al. (2014) illustrated application of structural assessment methodology incorporating advanced computational methods, damage models, probabilistic tools, and optimization techniques for redesign of a tanker structure for optimal performance and reliability.

5.2.2 Failure Modes Contributing to Longevity Assessment

Lifetime assessment of a vessel is typically based on particular failure modes at the component and system levels. The primary failure modes are: failure of the hull girder by reaching its ultimate strength capacity, failure of a stiffened panel by material yielding or instability, fatigue failure of structural details due to cyclic loading, fracture due to overload, and combinations of these. Consideration of deterioration due to corrosion should also be given in all the failure modes (for example in Ayyub et al., 2015).

Panel Yielding/Collapse Strength Buckling

The overall failure of ship structures is evaluated based on the buckling and elastic- plastic collapse of the plates and stiffened panels in the deck, bottom, and sometimes side shell. Therefore, the accurate assessment of the collapse strength of plates and stiffened panels is an important task in the structural design and safety assessment of ship. Application of the common structural rules (CSR) of the International Association of Classification Societies (IACS, 2014) for collapse strength of plates and stiffened panels can be used. Yielding on the other hand affects serviceability such as in connection with plate permanent set resulting from lateral pressure loading.

For the collapse strength of stiffened panels, the procedure proposed in CSR assumes that the ultimate compressive strength is the lowest of the three different buckling modes: beam column flexural buckling, stiffener torsional buckling, and local buckling of the stiffener web. More details of the procedure employed, including the comparison of the CSR procedure with the non-linear FE method is provided in Corak et al. (2010).

The increase of the deck stress due to the loss of hull girder section modulus (HGSM) was analyzed by Jurisic and Parunov (2015) and at the same time the reduction of the collapse strength of plates and stiffened panels of the main deck due to what the authors claim is a reduction in elastic modulus and yield strength due to corrosion was determined. This simple method shows the point in time as illustrated in Figure 8 when it is expected that the applied stress will exceed the strength of stiffened panels of the main deck. The solution is to replace the corroded plating with a new one to avoid an unsafe zone for the aging ships.

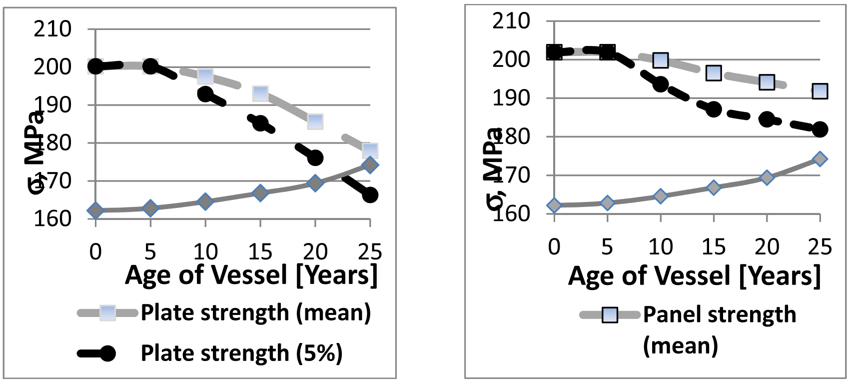


Figure 8. Safety margin of plates (left) and stiffener panels (right), cargo oil tanks of sample tanker (Jurisic and Parunov, 2015).

Ultimate Hull Girder Strength

Ship's structure in operation is exposed to the various loads such as hydrostatic pressure, static and dynamic pressure of cargo carried, the wave loads, and vibration loads such as whipping. During navigation the ship hull is deformed (sagging and hogging), and in these conditions the maximum stresses affect structural elements that are farthest from the neutral axis of the cross section of the ship (deck and bottom). Therefore, there is a danger that when the stress exceeds the strength in these elements, they are no longer able to carry all of the applied loads. Overstressed structural elements then collapse and may further cause global collapse of the main deck or the bottom. This could result in a loss of overall hull girder strength of the ship's hull. Therefore, the problem of the ultimate capacity of the cross section, also known as the ultimate strength of the ship hull, becomes an essential segment in the calculation of the ship strength (Harmonized Common Structural Rules for Bulk Carriers and Double Bottom Tankers, IACS, 2014).

Recently, based on some major ship accidents, numerous research studies, and public pressure, the approach for longitudinal strength assessment through hull girder section modulus (HGSM) of new-built ships started to be complemented by the hull girder ultimate strength (HGUS) assessment, as a more effective criterion by which to judge the capacity of the ship hull.

Fatigue

Fatigue is one of the main deterioration mechanisms that affect the longevity of ship structures. Fatigue cracks can appear at various locations along the ship structure and may occur at early stages in the service life of a ship. Large fatigue cracks may influence ship structural safety in two ways. Firstly, if a stress intensity factor at a fatigue-induced crack tip exceeds its critical value, then unstable crack propagation may take place. Secondly, even during stable crack propagation, the load-carrying area is reduced because of the presence of the crack, and consequently, the structural capacity of plates and stiffened panels is reduced (Paik et al., 2005).

Experimental studies are performed to analyze fatigue life of welded specimens corroded in real seawater conditions. Unexpectedly, it was found that cracks initiate at local pits, rather than at weld toes. Fatigue life of such specimens with pitting corrosion is much lower compared to uncorroded specimens (Garbatov et al., 2014a). Garbatov (2016) performed fatigue strength and reliability assessment of a complex double hull tanker structure, utilizing local structural finite element models, accounting for the uncertainties originating from the loads, nominal stresses, hot spot stress calculations, weld quality estimations and misalignments, and fatigue S-N parameters including the correlation between load cases and the coating life and corrosion degradation. Fatigue reliability during the service life was modelled as a system of correlated events. The analysis showed that the uncertainty in the fatigue stress estimation and fatigue damage were the most important variables.

Significant efforts have been spent to investigate the reliability of ship structures. However, there has been a lack of research that focuses on risk-based performance assessment of ship structures. The importance of risk as a performance indicator was emphasized by Dong and Frangopol (2015). Based on a probabilistic approach, optimum inspection and repair planning was solved as a multi-objective optimization problem for a VLCC structure considering corrosion and fatigue. The key findings of the research were that corrosion and fatigue have significant impact on the risk of structural failure of ships; the risk of structural failure increases rapidly with time due to corrosion and fatigue; and the risk of ship failure can be reduced significantly by optimum inspection and repair planning.

Degradation of hull structure due to loss of coating protection and corrosion

The marine environment is generally the most aggressive naturally occurring environment. The hull being constantly exposed to the seawater environment experiences general corrosion, which reduces the plate thickness, but it is also likely to experience pitting, galvanic corrosion, and others. The mechanism of corrosion wastage in marine environments on ship's structures is dependent on many different factors, such as: the type of cathodic protection, humidity, type of cargo and cargo operations, fluid flow, dissolved oxygen, temperature, and salinity (Ibrahim, 2015d; Jurisic and Parunov, 2015). Therefore, the corrosion wastage for different ship structural elements is defined based on the type of element and its location, and varies as a function of the corrosion environmental conditions.

Corrosion degradation needs to be modelled as a function of time in order to predict hull structural deterioration during the service life. In that way, the effect of corrosion degradation during its service life may be taken into account in the ship structural design and in repair planning. While such a model will allow changes in the environmental factors to be reflected in the corrosion rates, the historical data available do not contain that information.

Corrosion can interfere with the operation of ships and impose increasing stresses, accelerate deterioration of ship structures, and increase the hydrodynamic drag. Furthermore, it can cause degradation of coatings as shown by tests carried out under laboratory conditions. It was found that aging of marine organic coatings (due to raised temperature, in air or immersed in sea-water) has a negative impact on the coatings' mechanical properties and in particular the fracture strain can be reduced substantially.

Typical histograms of corrosion thickness measurements, based on which the mean value is calculated, are presented in Figure 9, where the corrosion wastage of the main deck plates in cargo tanks for a ship after 15 and 20 years in service are shown.

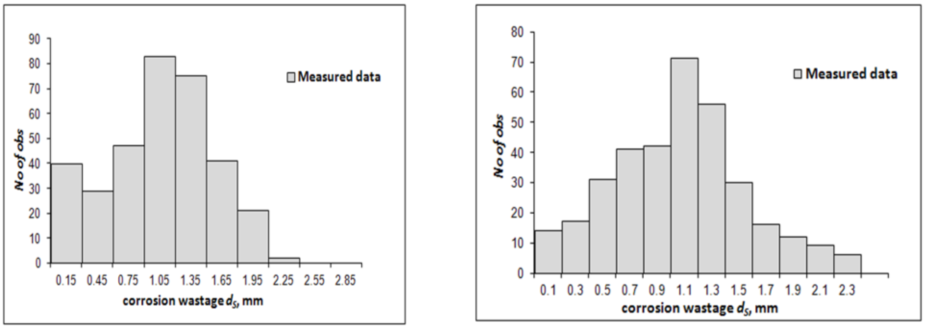


Figure 9. Corrosion wastage of main deck plates in the cargo tanks of sample oil tanker after 15 years (left) and 20 years (right) (Jurasic et al., 2014)

Corrosion progression models are used by classification societies and ship owners in order to predict long-term behavior of hull structure and to decide if the renewal of the hull structure is necessary and the optimal time for the repair. A typical model of the corrosion process consists of at least two phases: a phase without corrosion because of the durability or life of the protective coating and a phase of corrosion progression. Three widely used models for corrosion progression in ship structures are those originally developed by Melchers (2008), Yamamoto and Ikagaki (1998), and Guedes Soares and Garbatov (Garbatov et al., 2007). The model of corrosion degradation GS&G was proposed by Garbatov et al. (2007). The corrosion wastage model G&A was originally defined by Yamamoto and Ikagaki (1998) and later applied in the analysis by Guo et al. (2008). Comparison of these two prediction models with thickness measurements on three oil tankers is presented in Figure 10.

In order to quantify the uncertainty of the corrosion degradation models used, the complete results for the predicted and measured mean corrosion thicknesses are presented in Figure 10 and are statistically analyzed. It can be concluded that corrosion wastage in cargo tanks is larger than in ballast tanks, while deck stiffeners in cargo tanks experienced the largest corrosion wastage of all ship structural components analyzed (Jurisic and Parunov, 2015). This trend is well predicted by both methods. The phenomenon has already been observed in Garbatov et al. (2007) and was explained to be caused by sulphur from oil gases in combination with surface rust to the back face of an oil tanker deck. In such cases, corrosion mechanisms can create more damage in a cargo tank than from the sea water in the ballast tank.

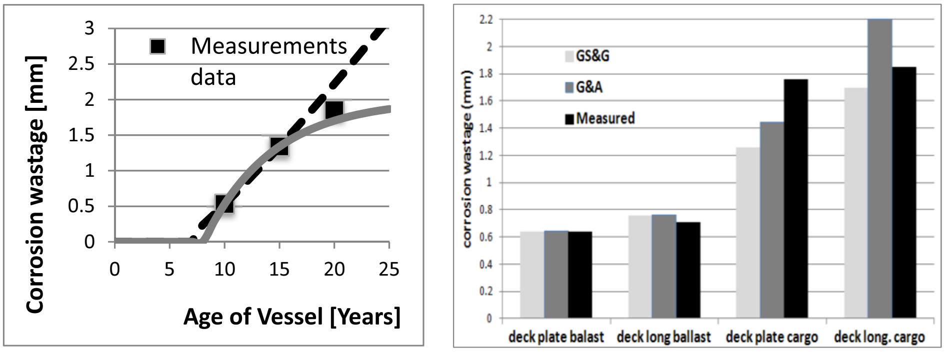


Figure 10. Measured and predicted mean annual corrosion wastage for main deck stiffeners in cargo oil tanks (COT) and complete corrosion wastage after 20 years of example tanker (Jurisic et al., 2014).

Combined factors e.g. strength, fatigue, and corrosion

For the assessment of structural longevity at the middle or near the end of the designed life of a vessel, long term prediction of corrosion effects on fatigue and ultimate strength becomes very important (Garbatov et al., 2014a; Garbatov et al., 2014b; Guo et al., 2008).

Corrosion wastage and fatigue cracks are recognized as the two most important long-term degradation mechanisms of ship structures. The consequences of age related damages can be catastrophic in some circumstances, requiring that experts in the maritime industry take into consideration degradation factors on ship structural safety. Aging effects need to be appropriately addressed (Jurisic et al., 2017). Due to these reasons, much research effort has been spent in the past few decades aiming to understand and model the degradation phenomena and to develop practically applicable models for long-term prediction of both these phenomena. The nature of corrosion and fatigue crack progression is extremely complex and unpredictable, and consequently large uncertainties are associated with computational models for their prediction, as both phenomena often occur at the same time and are mutually dependent.

Recently a comprehensive experimental work was performed in identifying the effect of corrosion on the mechanical properties of ageing marine structures. Corroded box girders have been tested for ultimate strength, showing an important reduction of mechanical properties. Further analyses have been performed using the tensile test specimens that have been cut from corroded box girders. The analysis of the results from specimens confirmed changes in mechanical properties of the corroded steel. It was shown that the modulus of elasticity and yield strength of corroded shipbuilding steel reduces with time. The phenomenon is quite unexpected and still unexplained, as the grain size and chemical composition of the steel are not expected to change due to corrosion (Garbatov et al., 2014b). To cause such corrosion degradation, accelerated anodic polarization of the metal surface was used. Anodic electric current was supplied by an external source. The highly accelerated test was done in 90 days as opposed to a more natural corrosion evolution and it is unclear if this aggressive technique was or was not the cause of the change in mechanical properties.

Further studies have been undertaken to investigate the consequence of corrosion-induced mechanical degradation on the local collapse strength of plates and stiffeners, and on the ultimate strength of an 88,000-t tanker structure. The losses in hull girder section modulus (HGSM) and hull girder ultimate strength (HGUS) for a corroded ship with and without degradation of mechanical properties of hull structure are obtained using single step method calculations proposed by CSR DH OT (Jurisic et al., 2017). These are shown in Figure 12.

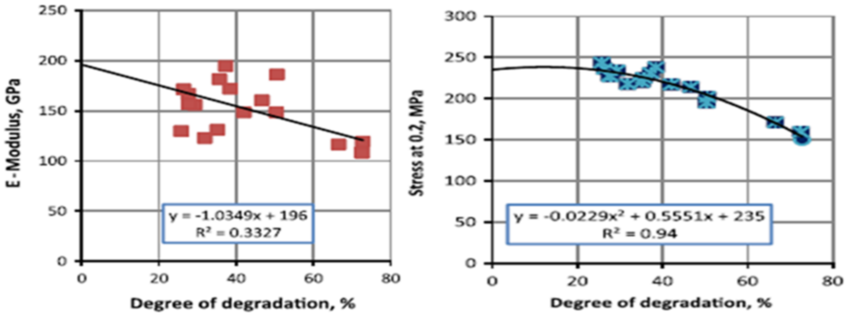


Figure 11. E-modulus, GPa (left) and yield strength 0.2 MPa (right) decreasing (Garbatov, 2016)

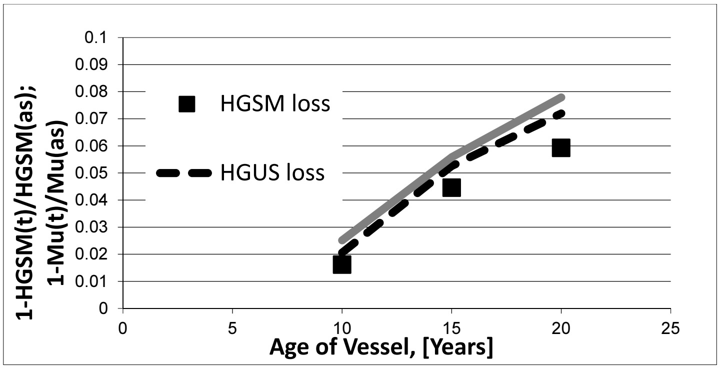


Figure 12. Measured HGSM losses and calculated HGUS losses for example oil tanker (Jurisic et al., 2017).

It can be seen from Figure 12 that the degradation of mechanical properties has a minor effect on the HGUS. The maximum difference in the reduction of hull girder ultimate strength by taking into account degradation of mechanical properties is about 1% of the initial HGUS. However, similar studies performed on plates and stiffened panels indicate that the influence of degradation on local collapse strength may be significant in certain cases (Jurisic and Parunov, 2015).

5.3 *Main factors influencing longevity*

The failure modes affecting longevity of surface ships, namely yielding, fatigue, and corrosion, have been discussed in section 5.2 of this chapter. In this section consideration will be given to related aspects and how they affect longevity.

Classification societies recognize that no ceiling ought to be imposed on a ship's lifetime, and thus periodical surveys are planned to ensure that with advancement in ship's age, a more thorough evaluation of condition is carried out and stricter requirements and related tests are in place prior to issuance of class certificates. Commercial pressures dictate that for many of the world's merchant ships, insufficient time is devoted to periodical surveys and related repairs. This is a situation that is much more serious in the case of larger ships (Figure 13).

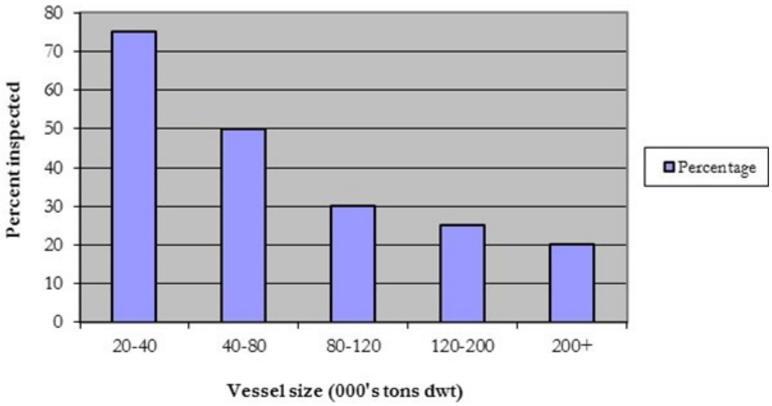


Figure 13. Proportion of hull structure inspected based on vessel size (Bell et al., 1989).

There are other types of ships that operate under much stricter regimes (LNG carriers, chemical carriers) so that this problem does not arise to the same extent. In addition to classification society requirements, there exist other bodies that perform ship surveys (OCIMF, the Oil Companies International Marine Forum, and vetting of oil tankers on behalf of the major oil companies). During vetting, emphasis is placed on safety and pollution prevention during cargo handling operations, although structural issues are also addressed (OCIMF, 2016).

Clearly, a well-designed and well-built ship will outlast a poorly designed and/or poorly built one and it is necessary to point out what characterizes good design and good practice. It is also necessary to point out that there exist different regimes that govern ship structural adequacy, depending on whether the vessels are merchant or naval ships, on the type of ship, and on their individual operating regimes. It may therefore not be possible to speak in terms of requirements to be imposed throughout the world fleet, although techniques developed may by universally applicable. For example, adequate design at the structural detail level is necessary to ensure the requisite fatigue life and the avoidance of yielding.

Although most commercial ship owners have a non-technical understanding of good construction quality they are nevertheless prepared to invest in it, the reason being that experience has shown that a high-quality ship will operate more efficiently from the investment point of view (shorter off-hire periods) and during later stages of its life it will be easier and less costly to maintain. Yard practice varies throughout the world's shipyards, with certain yards having a superior reputation to others. Owners are aware of this, and this knowledge is important when investment decisions are being made. Concomitant to yard practice is quality control, and this figures largely in quality of construction. It has to be understood that the vast majority of individual owners do not have the time or resources to perform in-depth studies of shipyard quality, and thus their decisions are based on past experience and knowledge.

Finally, it is important to distinguish between technical and economic obsolescence. The former has been discussed throughout this report. Of equal importance however is economic obsolescence, whose presence has indirect effects on technical obsolescence. We understand economic obsolescence to be the withdrawal of a ship from active trading despite the fact that it is not technically obsolete. This may arise as a result of market conditions, that is, very low freight rates over a long period of time. When a ship is likely to become economically obsolete, the owner will understandably be reluctant to invest in repairs that are costly and lengthy. In such a situation, repairs will be reduced to the minimum necessary to ensure that the ship can continue trading in the short term.

5.3.1 Role of Life Extension Programs

Aging of water transport represents a serious problem, with the cost of maintaining the safe state of vessels increasing while the vessels' operational qualities and competitiveness are steadily decreased. Certainly, new shipbuilding is the best cure of such problems, but the leading shipping companies that built many vessels in the past are reluctant or unable to build in a crisis market. Therefore, it is necessary to pay close attention to the compromised technical solutions for the prolongation of life of existing vessels. The types of approaches adopted for river-sea vessels are general modernization, renovation, overhaul, and conversion (vessel's construction with use of donor vessel's elements), as described in Egorov and Avtutov (2016):

1. Modernization of hulls: Existing hatch coamings / trunks are the most loaded elements and hence were critical for fatigue life. Use of highly continuous longitudinal hatch coamings or trunks would allow for significant section modulus increases to enhance the general strength of vessel's hull, cargo holds' / tanks' capacity, and deadweight in accordance with requirements of International Load Lines Convention.
2. Renovation: Renovation of a vessel's hull is the most known and widely used scheme for prolonging the vessel's life that is applied in commercial shipping. The main drawback of this procedure is that renovation concerns only an assessment of hull reliability. Engines, mechanisms, devices and systems remain without changes. As a general rule, this scheme does not allow a decrease in insurance rates and influences vessel's economy by little, since in general the risk of the vessel's operation depends not only on hull condition, but also on condition of the other vessel's elements.
3. Overhaul: Overhaul combines structural renovation with repair of the engines, mechanisms, devices, and systems. Average overhaul cost of a 5,000-t tanker is about 3.0 million U.S. dollars which is estimated to be around 20-24% of the new built cost.
4. Conversion: Conversion occupies a special place among different variants of essential modernizations; it means considerable, as a rule, dimensional modernization of the vessel with survey of all her parts as if new, i.e. in compliance with requirements of the international conventions and rules of the classification society for date of survey. Conversion allows remediating problems important to life extension and increasing the safety with less time and cost than that of new construction.

Conversion requires the accounting of the following defects which were accumulated during operation of the vessel pre-conversion:

- Corrosion and mechanical wear of hull constructions and welded joints, especially local thinning which are badly documented and not considered at the traditional strength calculations;
- Deformations of the inner bottom and inner side as a result of contact with cargo and cargo handling gauges in ports;
- Deformation of the outer shell as a result of contact with ground at shallow water, with walls of locks or channels, with berthing facilities or ice;
- Accumulated fatigue damage at the zone of stress concentration, especially microcrack and violations of crystal structure of material which cannot be found at surveys;
- Possible alternation of physical-mechanical properties of material of the hull (ageing).

Conversion is based on the following basic principles:

- The scientific-based approach to determine the need for new elements or use the old ones;

- The full compliance with the international and national requirements for the building date of the new vessel;
- Ensuring reliability for the set operational term of the vessel;
- Has the same quality as a new build from the point of view of the primary use;
- Uses modern calculation methods and technologies.

The most striking example of a vessel's building with usage of elements of the existing donor vessels is creation of a series of river-sea dry-cargo vessels with a deadweight about 6,000 tons of "Chelsea" type (Egorov and Avtutov, 2016).

River dry-cargo "Volga-Don" type vessels that were built in the 1960s, were used as donors. The scheme of vessel's construction with pointing the new (marked) elements is shown in Figure 14. The vessels construction consisted of keeping part of the existing structure (about 650 tons), adding about 650 tons of new construction (new coamings, second deck, forecastle and poop, new deck-house and hatch covers) and replacing about 550 tons of existing hull elements. Total cost for converting a single "Chelsea" type vessel was about 5.5-6.0 million U.S. dollars. In comparison, construction cost of a similar new build vessel is about 11-14 million U.S. dollars.

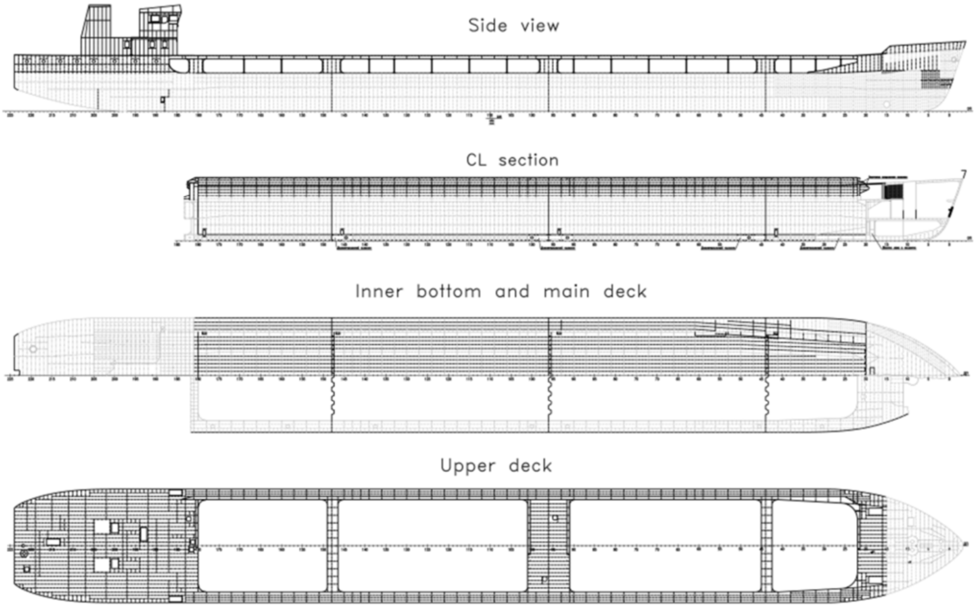


Figure 14. Scheme of construction of dry-cargo vessel of "Chelsea" type (Egorov and Avtutov, 2016).

It is necessary to understand clearly that a vessel's life prolongation schemes are not an alternative to new shipbuilding. These schemes allow provision of necessary transport needs during the next 10-15 years; offering a compromise solution between lowering fleet transportation rates and the rising demands of the economy while financial and industrial resourced are limited.

5.4 Methods for ensuring safe operation

5.4.1 Current practice and future directions

Chapter 3 of the previous committee report (Hess, et al., 2015) provided current practice three years ago. It was observed in preparing the current ISSC2018 Committee V.7 report that little has changed in practice in three years. The recent literature relevant to ensuring safe operation of ships has been presented in the following sub-sections.

5.4.2 Structure Monitoring, Inspection, Maintenance, and Repairs

Sanchez-Silva et al. (2016) discuss the main conceptual and theoretical principles involved in the maintenance and operation of infrastructure under uncertainty. The concepts discussed form the basis to build models that can be used for making better decisions for maintaining and operating infrastructure systems.

Structural health monitoring systems constitute effective tools for measuring the structural response and assessing the structural performance under actual operational conditions. Inspection, monitoring, and/or repair actions are applied to prevent sudden failures of structural components due to fatigue and their associated consequences. However, these actions increase the operational cost of the ship and should be optimally planned during its service life.

Magoga et al. (2015) reviewed the benefits and challenges of utilizing hull monitoring data with respect to naval high-speed light craft (HSLC). While full-scale data is obtained in the actual operational environment in real-time with non-linear loads taken into account implicitly, the measurements must be high-quality to be reliable, and it is relatively costly and time-consuming. Aksu et al. (2015) discussed the utilization of data collected from a hull monitoring system (HMS) onboard an aluminum patrol boat, to support sustainment of the fleet.

Soliman et al. (2016) argued that the planning of inspection, monitoring, and/or repair actions of a maritime asset should be performed probabilistically, given the presence of significant uncertainties associated with crack initiation and propagation, and proposed a probabilistic approach for inspection, monitoring, and maintenance optimization for ship details under fatigue effects. Based on the stress distribution and the crack geometry at the damaged location, a multi objective optimization problem, with the objective functions being the minimization of the life-cycle cost and maximizing the expected service life, was solved to determine intervention times and types.

An accurate, quantifiable means of assessing a structural damage condition are paramount for maintaining the structural integrity of ship hull forms. A non-contact approach to identifying and characterizing imperfections within the submerged bow section of a representative ship hull was developed (Reed and Earls, 2015) using simulated sonar pulses. The pressure field local to the acoustically excited hull section was monitored. It is shown that the resulting data can be used to identify the parameters describing the structural damage field. A Bayesian, reversible jump Markov chain Monte Carlo approach is then used to generate the imperfection parameter estimates and quantify the uncertainty in those estimates.

The idea of leak-before-break (LBB) is based principally on guaranteeing that enough time is available between the moment a crack breaks through the hull or wall, and the moment when the crack becomes unstable, causing a structural failure. The concept was originally developed and applied in the nuclear power industry and has recently been applied to the structural safety of a tether string that is part of the mooring system of an offshore structure (Ren et al., 2015). Application of the LBT concept to ship structural safety should be investigated.

Fatigue damage is proportional to the third power of stress range (Drummen, et al., 2017) and influenced by the operator avoiding heavy weather when possible. Furthermore, it is beneficial to monitor the fatigue damage accumulation. Drummen, et al. (2017) argued that this can be done with a simple system, calibrated to key locations using FEA. Such a simple system can enable long term cost effective monitoring approach for reducing uncertainties and risk in life-cycle and end of service life decisions.

Stambaugh et al. (2014) discussed a reliability-based fatigue life prediction approach, in relation to the U.S. Coast Guard's Fatigue Life Assessment Project (FLAP), along with how it may be used to evaluate options for life cycle management of fatigue and the return on investment (ROI) for considering fatigue early in the design. With the knowledge of the time varying structural fatigue reliability, it is possible to evaluate the cost of alternative design and maintenance strategies and the ROI of these alternatives. Example ROI estimates showing the benefits of considering structural fatigue analysis (SFA) early in the design process, prior to construction, during construction, and in the ship's service life is given in Table 5 (Stambaugh et al., 2014). In this example, ROI is defined as net cost savings (cost avoidance) divided by the cost invested by considering fatigue in preliminary design shown as base option in Table 5.

Various approaches have been adopted by researchers to determine the remaining useful life of structures: noisy gamma deterioration process by Le Son et al. (2016); and monitoring of corrosion damage using high frequency guided waves (Chew and Fromme, 2014).

Table 5. Example return on investment (ROI) of SFA in preliminary design as compared to incurred repair costs in service (after Stambaugh et al., 2104).

Life Phase	Relative Cost/Cutter	ROI of fatigue design	Lost Operation Days	Comments
Preliminary design	0.5	Base option	0	Essentially the cost of added steel
Detail design	1.0	1.5:1	85+	Including design rework
Construction	4	7:1	170	One-year delay in delivery
After delivery	20	39:1	85	Half year dry dock
Repair through 30-year service life	10-30	>19.5:1	340+	6 – 2-week EDS+ 2 – 1-month EDD

EDD: Emergency Dry Dock; EDS: Emergency Dock Side

5.4.3 At-sea damage response: measurement, analysis, repair, and/or change in operation

Incorporating life-cycle concepts in structural design and assessment codes is gaining momentum in recent years (Frangopol and Soliman, 2016). The main principles, concepts, methods, and strategies are discussed by Biondini and Frangopol (2014). The concepts of life-cycle performance assessment and maintenance planning are used to formulate the life-cycle reliability-based design problem in an optimization context.

Dong et al. (2016) presented a decision support system for mission-based ship routing considering multiple performance criteria. The generalized decision-making framework developed performs a variety of tasks such as the flexural and fatigue performance evaluation of ship structures and employs multi-attribute utility theory to evaluate ship mission performance. The expected repair cost, cumulative fatigue damage, total travel time, and carbon dioxide emissions associated with ship routing are considered as consequences within the risk assessment procedure.

Frangopol and Soliman (2016) presented aspects of life cycle management decisions such as the performance prediction under uncertainty and optimization of life-cycle cost and intervention activities, the role of structural health monitoring and non-destructive testing techniques as well as integration of risk, resilience, sustainability, and their integration into the life-cycle management.

Decò and Frangopol (2015) calculated the risk of a vessel integrating structural health monitoring data. Optimal short-range routing of ships was accomplished by solving two- and three-objective optimization problems with objectives being the estimated time of arrival, mean total risk, and fuel cost. It was found that optimizing three objectives provided a comprehensive set of optimal solutions.

Knowledge of the current structural state can be used to predict structural integrity at a future time and allows actions to be taken to improve safety, minimize ownership costs, and/or increase the operating envelope. Nichols et al. (2014) described a structured decision making (SDM) process for taking available information (loading data, model output, etc.) and producing a plan of action for maintaining the structure. It was demonstrated that SDM produced the optimal trip plan by minimizing transit time and probability of failure.

A self-powered, wireless system offers a versatile and powerful SHM tool to enhance the reliability and safety of avionics platforms, jet fighters, helicopters, and commercial aircraft that use lightweight composite material structures (Mendoza et al., 2012).

Saad-Eldeen et al. (2014) compared the behavior of three corroded box girders experimentally tested with respect to collapse modes, strain measurements, residual stresses, load-displacement relationship, moment-curvature relationship and the effect of different corrosion levels on structural integrity.

5.4.4 Remaining Service Life

The Structural Life Assessment of Ship Hulls (SLASH) methodology for the structural reliability analysis of marine vessels based on failure modes of their hull girders, stiffened panels including buckling, fatigue, and fracture and corresponding life predictions at the component and system levels was presented by Ayyub et al. (2015). It employs time-dependent reliability functions for hull girders, stiffened panels, fatigue details, and fracture at the component and system levels, but only considers time to first failure and does not consider additional failures or repair. The methodology was implemented as a web-enabled, cloud-computing-based tool with a database for managing vessels analyzed.

Soliman et al. (2015) quantified the accumulated fatigue damage and the fatigue reliability based on structural health monitoring data acquired from an aluminum naval vessel operating under different operational conditions (speed, sea states, and heading angles). The hot spot structural stress approach was used for the fatigue assessment. Estimates of target fatigue life for different operational profiles were performed for the reliability index, β, target values of 2.0 and 3.0.

5.5 Notional Examples of Longevity and Life Extension Decisions

5.5.1 Naval Ship

The navies are increasingly forced to extend the service life of aging ships due to budgetary and political constraints. In making such service life extension decisions, maintaining the seaworthiness of the platform is critical. On these grounds, interest in the utilization of in-service loads and strain data for through-life structural management of naval ships has recently grown. In the case of aluminum lightweight high speed naval craft, additional challenges are posed in extreme environments when sustaining significant wave induced impacts and slamming, resulting in a higher incidence of fatigue-related cracks (Magoga et al., 2014).

Modern high strength and ductile steels are a key element of U.S. Navy ship structural technology. Matic et al. (2015) reviewed the analytical and computational tools, driving simulation methods and experimental techniques that were developed to provide ongoing insights into the material, damage, and fracture characteristics of these alloys. Knowledge gained about fracture resistance was used to meet minimum fracture initiation, crack growth, and crack arrest characteristics as part of overall structural integrity considerations.

However, the emphasis of fatigue analysis research has tended to be on increasing the accuracy of numerical approaches by considering more parameters of influence and higher fidelity modelling. The approaches also tend to be validated via other numerical methods and experimental data. In comparison, use of in-service load and response data combined with survey reports to establish practicable methodologies and to update service life predictions has been limited (Soliman et al., 2015). A typical procedure for life of type assessment of a naval vessel covers the following steps:

- Determination of operational history;
- Areas of operation, speed profile, sea state information, loading changes (displacement increase due to mid-life upgrade and weapon and combat systems upgrades;
- Determination of long term loads;
- Using seakeeping codes or hull monitoring data;
- FE modelling and analysis for critical locations;
- Identification of critical joints for fatigue assessment;
- Incorporation of degradation (corrosion) into FEA;
- Determination of stress range histograms at critical locations;
- Fatigue damage estimation.

Magoga et al. (2016) applied the aforementioned methodology for Life of Type assessment of a generic patrol boat. Drummen et al. (2017) conducted structural fatigue life assessment and maintenance needs for a new class of U.S. Coast Guard Cutters using a very similar procedure.

5.5.2 Bulk carrier / Tanker/Container

The current trends in the global marine marketplace is that new building orders for bulk carriers, oil tankers, and container ships have significantly reduced, resulting in a more important need for life extension. (for example, Parunov et al., 2010).

Before purchase of existing ships, it is necessary to perform condition assessment of a vessel including determination of corrosion damage based on the hull thickness measurements (Jurisic et al. 2011). classification societies are currently developing software packages for ships in service that have an integrated corroded structure module within the finite element method (FEM) model allowing incorporation of hull inspection survey reports.

The nonlinear finite element method (NLFEM) is an important tool in the analysis of structures with the significant influence of geometric and material nonlinearities. Today NLFEM can be considered sufficiently developed for the use in the design of ship structures and in the assessment of the ultimate compressive strength of plates and stiffened panels. In the ultimate strength analysis of unstiffened plate and stiffened panel both types of nonlinearity appear: geometrical nonlinearity due to large deflection and material nonlinearity due to the nonlinear behavior of material in the plastic region.

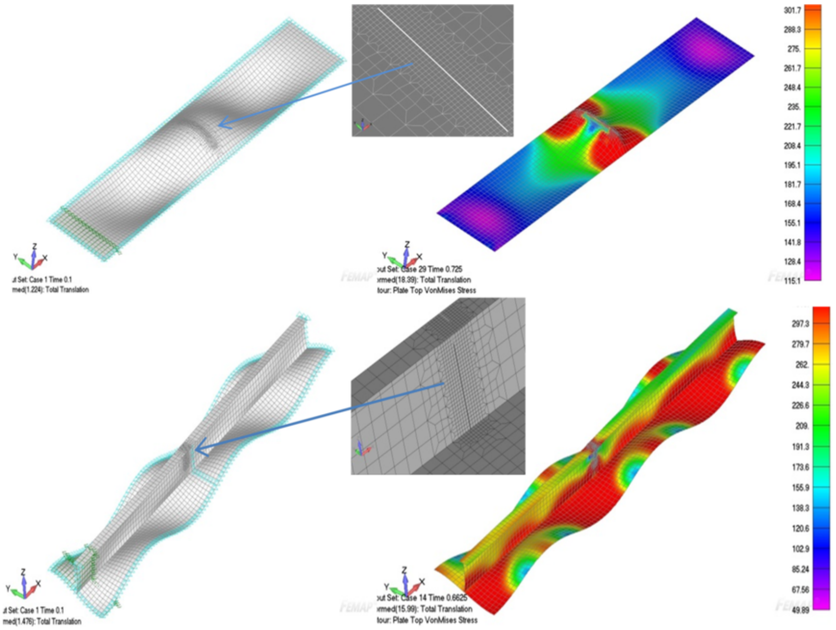


Figure 15. NFEM model of cracks of deck plate and stiffener panel for example oil tanker (Jurisic et al., 2017).

As an illustrative example, the model of the plate with a simulated fatigue crack has been shown on the upper left side of Figure 15. Cracks quite often appear in an aged structure after many years of ship in service, as shown in the lower left side of Figure 15. The resulting von Mises stresses at the plate collapse are presented on the upper right side, and for the stiffener panel on the lower right side of Figure 15. It can be noticed that the stress increases in the area of the crack, reaching limit condition values of 315 MPa, corresponding to steel AH 32 yield strength.

5.5.3 Inland Vessels

Reliability and failure analysis of river passenger vessels (RPV) hulls was made in (Egorov and Egorov, 2015). It was observed that RPVs operational conditions are less severe than for cargo vessels; they are operated with permanent qualified personnel, they have smaller draughts and correspondingly less probability for grounding, they have almost constant load conditions, they have seasonal operations which practically excludes ice damage risk, they include sideshell protection by crinolines so the level of side damage is lower than for cargo vessels despite large numbers of mooring locking through operations, and they have no aggressive cargoes and grab cargo-handling operations (Egorov and Egorov, 2015).

Corrosion damage accumulation for a RPV is 2–4 times smaller than that of cargo vessels. Investigations (Egorov and Egorov, 2015) showed that corrosion was, as follows: 2.4% for bottom shell, 2.1% for side shell, 6.3% for main deck shell, 2.1% for tank top shell, 2.8% for transverse bulkhead plating, 2.1% for bottom elements, 2.4% for side elements, 2.3% for deck elements. Increased corrosion damage was found on decks where the crew and passenger compartments are located (places of bilge waters) and at the sewage tanks.

Description of river and river-sea passenger vessel new construction was given by (Egorov and Kalugin, 2015). Analysis of inland vessels was made for Danube river barges. Typical non-propelled vessels are dry-cargo and tanker river sectional barges of “Europe-2B” type with cargo capacity of 1,600–2,000 t. Analysis of the operation of such vessels was conducted to identify the factors that make the greatest impact on the risk during the whole lifetime (Egorov and Egorova, 2016).

Due to the nature of the operations of inland vessels passing through locks, contacts with walls of the locks and canals are common, leading to the additional scuffing of sheer-strake and bilge strake of shell plating and strake stiffeners' deformation.

Analysis of repair documents, cargo operation books, and logbooks for 140 vessels was conducted to identify the typical defects and damages to their hulls after having undergone a long period of operation. The typical hull's damages are shown in Figure 16 and corresponding causes are shown in Figure 17. Most hull breakages occur during cargo loading and unloading.

The overwhelming majority of the inland vessel's hull failures (especially on the Rhine–Main–Danube Canal system, where there are no significant waves) are associated with buckling failure of the elements of the compressed strake of the hull girder which could be the result of widespread use of transverse framing system in European river shipbuilding.

Longitudinal strength improvements can be provided by the following measures (Egorov and Egorova, 2016):

- Increasing of thickness and sizes of hull members;
- Better estimation of loads due to longitudinal bending;
- Changing of the method of longitudinal strength calculation due to safety factor increase; checking hull strength while taking into account life-cycle degradation and damage;
- Changing of the transverse framing system of the hull girder extreme strakes to longitudinal stiffening;
- Increasing of buckling strength of longitudinal members of longitudinal framing system by reducing frame spacing and increasing the cross-sectional moment of inertia.

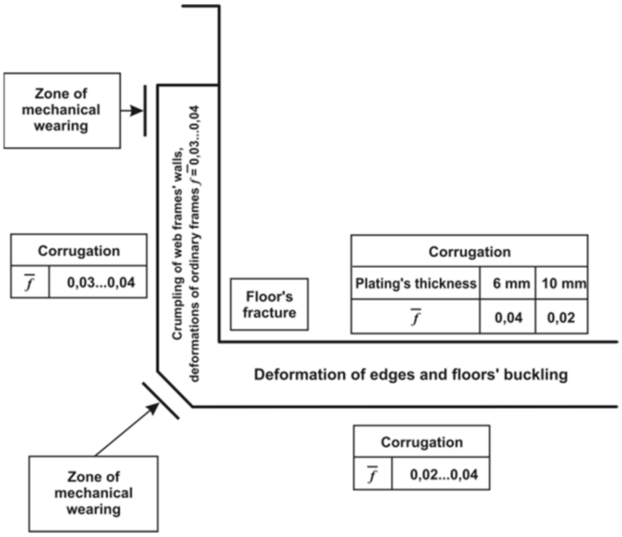


Figure 16. Hull damage in barge of "Europe-2B" type – relative deflection (Egorov and Egorova, 2016).

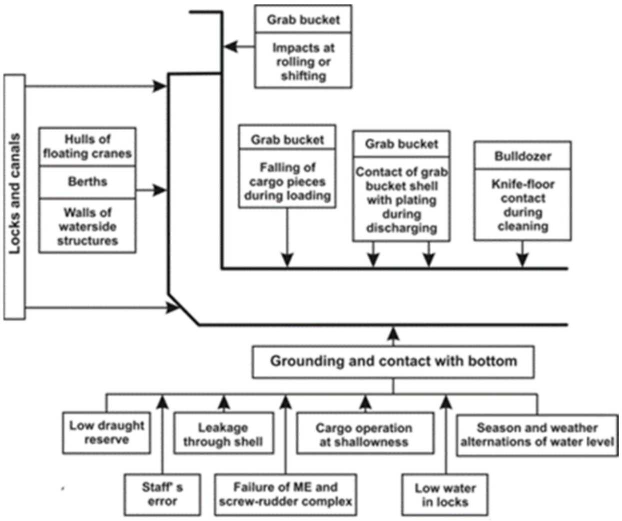


Figure 17. Sources of damage in sectional barge hulls (Egorov and Egorova, 2016).

5.6 Discussion and Conclusions

- First-principles based prediction of longevity is carried out using experimental, numerical, full scale measurements approaches. The current literature is reviewed in relation to the application of dominant longevity factors (yielding, ultimate strength, fatigue and corrosion) to ship structures.
- Wireless sensors and fiber Bragg grating strain gauges represent new technology that is applied to obtain hull response data for use in experimental predictions.
- The inverse finite element method is one of the methods used to analyze experimental sensor data to determine displacements, strains and stresses throughout the structure.
- Dynamic Bayesian Networks are being used to model system behavior and update reliability and uncertainty analysis with data such as fatigue cracking.
- The primary failure modes that affect structural longevity are: failure of the hull girder by reaching its ultimate strength capacity; failure of a stiffened panel by material yielding or instability; fatigue failure of structural details due to cyclic loading; fracture due to overload; and combinations of these. The dominant longevity factors for different types of vessels are presented in Table 6.
- Structural health monitoring systems constitute effective tools for measuring the structural response and assessing the structural performance under actual operational conditions. The planning of inspection, monitoring and/or repair actions of a maritime asset should be performed probabilistically to minimize life-cycle cost and maximize the expected service life.
- A reliability-based fatigue life prediction approach can be used to evaluate options for life cycle management of fatigue and the return on investment for considering fatigue early in design.

Table 6. Dominant longevity factors vs. ship/vessel type

Ship Type	Yielding	Ultimate Strength	Fatigue	Corrosion	General Comments
Naval Vessels	High		High	High	Extended operational life
Aluminium high-speed craft	High		High		High dynamic loading
Tanker		High	High	High	Relative importance of these depends on vessel size
Bulk Carrier		High	High	High	Relative importance of these depends on vessel size
Container ship		High	High	High	Open deck, reduced capacity, overloading above safe limits
Passenger ship			High		Large openings, extensive deckhouse
Inland ship			High		Accounting of local loadings (mooring operations, canal and locks passages, shallow water) on design stage
River-sea ship		High	High	High	Accounting of local loadings, flex hull as the result of metal consumption optimization, wave height restrictions

6. CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The high level mandate for this committee was to develop an understanding of structural longevity and the factors that shape this topic, both in importance and how it is managed or maintained. Chapters 2, and 3 describe the importance of structural longevity from different perspectives, as well as describe some of the methods used in life-cycle management such as monitoring and inspection. Chapters 4 and 5 describe the application of the methods of structural longevity to offshore structures and to ships.

It is clear that there is a growing concern for the structural longevity of ship, offshore and other marine structures, with systemized methods developed or under development to provide the owners with information to make a decision on the future of their assets, the lifetime assessment that is balanced by economic, structural, maintenance, systems, and resilience considerations. However, the development and approaches to life extension of assets for the marine industry has been driven by regulatory bodies, with little reporting in the literature by ship and offshore owners and operators of current or planned practice. Significant work has been done on life-cycle fatigue analysis, but there is little indication that the results of such studies have been integrated into life-cycle management plans or structural health monitoring systems other than identifying problem areas for inspections. For many owners, the concept of structural longevity is limited to following the requirements of classification societies and only performing the structural repairs and modifications that are necessary to last until the next five-year inspection. Specific conclusions are as follows:

- Since ISSC 2015 there has been increasing research on the incorporation of structural lifetime assessment of ship and offshore structures and a transfer of knowledge across industry sectors.
- Classification societies and other standards provide guidance for the assessment of the current state of an asset, but not for assessment of future conditions.
- There is a need to integrate structural hull/health monitoring with structural assessment to manage the structural longevity over the remaining life of ships' structures as has been increasingly done for offshore structures.
- Integrating an understanding of degradation propagation with the classification of inherent risks in inspection and the consequences of failure can be used to develop specific inspection plans (risk-based-inspection).
- Many non-destructive testing techniques are being used across a wide range of industries to identify damage and irregularities in materials.
- The probability of detection and probability of sizing defects are being improved through stringent codes, the use of complementary techniques, and the use of more focused and automated inspection and monitoring techniques.
- Non-destructive inspection techniques are being improved through methods such as signal digitizing, image processing, and machine-learning techniques.
- Increasing use of digitization, integration, and automation of inspection and monitoring data requires more attention to data management and cyber-risk management.
- The increase in the number of offshore wind turbines has led to research in the life-cycle design and monitoring to ensure the longevity of these structures.
- Structural integrity management systems are being developed to provide a framework for ensuring the longevity of marine structures.
- Advances continue to be made in the assessment of the current condition of ships' structure and the evaluation of the probability of future fatigue damage.

6.2 Recommendations

This committee report describes elements important to structural longevity, building upon past ISSC committee efforts. The following recommendations should be considered by the industry, regulatory bodies, and researchers.

- Develop structural prediction models capable of incorporating structural condition data (from sensors or inspection) that are able to predict remaining life, and continue support management of the asset over that life.
- Develop guidance for the use of digital twins to manage the structure of a marine asset over its entire life-cycle.
- Develop better corrosion rates from on-line monitoring.
- Conduct research to verify that corroded steel mechanical properties of steel either change or stay the same to ensure proper accounting in failure analyses and longevity assessments.
- Conduct research into practical applications of probabilistic methods for the assessment of aging, including risk-based inspection and risk-based maintenance.
- Industry design standards are needed for the impressed current systems used to reduce corrosion of offshore structures.

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