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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. Attention should be given to ongoing lifetime extension of existing structures. Focus shall be on methodologies for translating monitoring data into operational advice and lifecycle management. The research and development in passive, latent and active systems including their sensors and actuators should be addressed. Further, self-healing and smart materials should be addressed.

COMMITTEE MEMBERS

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KEYWORDS

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

CONTENTS

1. INTRODUCTION

1.1 Background & Mandate

Ships, offshore and other marine platform structures are designed with assumptions 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 actual condition, use, and performance of the platform structure changes over time, which requires updated maintenance requirements for scheduling and budgeting, decisions on limiting or expanding the operational use, and predicting remaining useful service life.

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 and fatigue cracking. 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 on-board structural monitoring systems, and research continues into means of translating the data collected from those systems into operational advice and lifecycle 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 lifecycle 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 lifecycle management scheme.

1.2 Relationship with other ISSC Committees

The following committees have areas in their mandates that overlap the work of this committee and were therefore not specifically addressed by this committee.

- Committee III.2 — Fatigue and Fracture
- Committee V.3 — Material and Fabrication Technology — the impact of corrosion protection techniques on structural performance.

Past ISSC Committees addressed areas contained within the work of this committee.

- Committee I.2, Loads, of ISSC 2012 — procedures for stress monitoring and for operational guidance
- Committee II.1, Quasi-Static Response, of ISSC 2012 — strain gauges embedded in a composite, reliability-based structural assessment, and reliability-based inspection, maintenance, and repair, including the use of real-time condition monitoring systems
- Committee II.2, Dynamic Response, of ISSC 2012 — monitoring of both ship structures and offshore structures
- Committee IV.2, Design Methods of ISSC 2012 — means to effectively use all of the data accumulated over the lifetime of a ship for more cost-effective management
- Committee V.2, Natural Gas Storage and Transportation, of ISSC 2012 — monitoring of hull structures and containment tanks
- Committee V.3, Materials and Fabrication Technology, of ISSC 2012 — structural health monitoring including a study of the time-varying reliability of ship structure due to corrosion
- Committee V.5, Naval Vessels, of ISSC 2012 — monitoring of structure
- Committee V.6, Arctic Technology, of ISSC 2012 — requirements by ABS for ice load monitoring (ABS, 2011)

Given this interest in structural longevity, this specialized committee, Structural Longevity, was formed for ISSC 2015. Because the technology is currently being applied to all marine structures and has the potential for improvement in the management of those structures, the mandate for this committee includes all ship, offshore, and other marine structures. As the primary causes of structural deterioration are fatigue and corrosion, with the two mechanisms sometimes assisting each other, the diagnosis and prognosis of structural health concentrates on these mechanisms. Assessment of structural health and structural rehabilitation is essential for the continued safety of a marine structure throughout its life, but is also important for the decision-making process for extending the service life of an existing structure and these topics have been dealt with in this report. As more ships and other marine structures are receiving more instrumentation to monitor the structure, including strain gauging, motion detectors, and fatigue and corrosion sensors, the data from these monitoring systems needs to be taken to full advantage. Therefore, this committee has had a focus on the methodology for translating that data into operational advice as well as lifecycle management of structures. Improvements in these monitoring systems, including passive, latent and active systems and their sensors and actuators were also addressed.

2. LIFECYCLE ASSESSMENT & MANAGEMENT FOR STRUCTURAL LONGEVITY

2.1 Introduction

This chapter will examine the need to assess the structural lifetime of vessels and floating offshore structures and the subsequent management for structural longevity.

Through-life assessment and appreciation of the full lifecycle costs are needed for the asset owner to make decisions on continuing operation and managing longevity. This requires accurate monitoring technologies, effective inspection methodologies, predictive tools for damage evolution and preventive methods (maintenance, repair and rehabilitation).

Structural assessment following a change in conditions, such as structural deterioration from corrosion or fatigue, structural damage, a change in loading, or an extension of the design working life qualifies an asset's (vessel or platform) instantaneous capability to function as intended by examining its residual capacity to withstand loads (Rucker et al., 2006). Design code updates or operator-led safety measures may also initiate structural assessment (Dier, 2004). Lifetime assessment 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. Nappi and Collette (2013) describe the complexity of the lifecycle performance predictions, and argue for a greater investment in improving design frameworks and structural assessment tools for new structures.

Structural codes that have been developed for new designs are often not appropriate for structural assessment since there are significant differences between design and assessment processes. There is a tendency to develop conservative, redundant designs to account for the uncertainties that arise from the prediction of load and resistance parameters of a new structure. Hence, whilst a conservative design does not result in a significant increase in structural cost, a conservative assessment on the other hand may result in unnecessary and costly repairs or replacement (Rucker et al., 2006). Kwon and Frangopol (2012a) reason that in order to account for uncertainty, a probabilistic methodology for lifetime structural performance assessment and management has to be developed in a rational way. In fact, Hess (2003) used the framework for structural reliability analysis coupled with performance goals of operational availability, capability, and dependability (Ao, Co, Do) metrics to link lifecycle guidance to structural assessment. Stacey et al. (2008) discuss the identification of uncertainty in structural performance as a major issue for any life extended facility, including the loss of corporate knowledge, increasing relevance of small defects, and structural condition and associated responses. It is therefore necessary to quantify residual structural capacity, but its definition at any instant in time is uncertain, so any decision on life extension and structural management comes with a risk from the costs associated with action or inaction. Recently, Stambaugh et al. (2014) presented a framework for evaluating a function of risk against total ownership costs and tested the framework against the lifecycle management of a US Coast Guard vessel. A Monte Carlo simulation is used to compute the time-varying structural fatigue reliability, which is then used to evaluate the effect of alternative design and maintenance strategies on total ownership cost.

With a large number of existing offshore installations reaching or close to reaching their nominal installation life, ageing and life extension (ALE) has been of particular interest. The practice of operation beyond design life is becoming more and more common because of obvious economic drivers such as lack of funds for decommissioning the original asset and installation of a replacement (Stacey et al., 2008). The development and approaches to life extension of assets for the marine industry has been driven by regulatory bodies such as the UK's Health and Safety Executive "Key Program 4" (KP4). This program examines the extent to which asset integrity risks associated with ALE are being managed effectively by asset owners/duty holders and how good practice is being promoted and developed.

2.2 The Need for Lifecycle Assessment and Management

As structures age, operational and organizational changes in strategy influence the way in which the structure should be managed. To provide the owners information to make a decision on the future of their asset such as scrapping the asset and building a new asset, the lifetime assessment is informed by Roberton, (2014):

- Economic: with or without intervention (based on condition), what is the cost of operating a vessel for X number of years?
- Structural: by assessing load input and structural response within material limits what's the life of the vessel?
- Maintenance: inspection techniques and condition based monitoring defining appropriate service scheduling and subsequent life extension after maintenance.
- Systems: system-focused life prediction: holistic approach using the combined influence of component reliability on the system's life prediction.
- Resilience: the capacity of the structure to withstand off-design variations and flexibility in operation role.

With ageing structures, the economic benefit of continuing to operate the asset may not balance with incumbent costs associated with maintenance, repair, or rehabilitation. The question remains: with or without intervention (based on condition), what is the cost of operating a vessel for a defined number of years? Extending the life of an asset is a complicated decision process which hinges on the lifecycle costs. The process of ageing isn't readily defined by the length of service the asset has already seen: poorly designed and maintained assets will fail faster than older, more conservatively designed assets with effective inspection and maintenance regimes. What is known about the condition, how to reduce or recognize the onset of degradation, how that degradation evolves, and what to do to mitigate the degradation is more important than the physical age. Economically a decision then centers on the possible actions of continued service, re-rating (for example, vessels looking at costly steel repair to make good minimum thickness limits following corrosion could operate under a limited service, reassessed by Class, affording a more generous corrosion allowance), repair, or scrapping in favor of a new build (HSE, 2014).

The attractions for life extension seem obvious: for example, Jean (2008) writes "to modernize a [US Navy] surface combatant costs a fifth of what it takes to build a new ship. A new destroyer costs about $1 billion. The price to upgrade a destroyer is about $180 million..." However, at what point does it become unfeasible to life extend? How are costs modeled? What is the total cost of ownership and how transparent is this?

Business economists Ntuen & Moore (1986) define lifecycle costs as capital acquisition costs, operating costs including maintenance, and end of life disposal costs. The authors include a classification of approaches to availability-based lifecycle cost analysis that covers established techniques in optimization, queuing, and simulation as applied to design, unavailability, and operation (availability) costs (earliest reference from 1946 up to 1985). More recently, well cited work by Umeda et al. (2000) explores lifecycle simulations (LCS) incorporating the aforementioned techniques. Physical deterioration of a product can be represented by a stochastic element in the simulation (Komoto et al., 2011). Well established methods and tools exist therefore to aid the decision process but the complexity of the asset itself as a system, the number of stakeholders, the supply chain, the length of service, diversity of the physical operating environment, and a fickle economic climate lead to an almost intractable simulation of every scenario.

Of the whole lifecycle cost, through the stages of requirements definition, design, production, operation, and disposal, it is expected that around 70% is consumed during the operational phase (BMT, 2006) and yet two-thirds of the budget has been fixed by the time that the requirements definition has been completed (Fabrycky, 2003). Decisions made in the early phases of a system's lifecycle therefore have significant cost impact during the operational phase of a system (Iyer, 1999, Swift and Brown, 2003). To avoid budget versus performance problems it's imperative to pay attention to lifecycle costs at the earliest of the design stage. Turan et al. (2009) present a design-oriented optimization study as an approach for analyzing lifecycle costs for a commercial vessel but again discuss this process' limitation in the breadth of the available cost information. Methods such as System Dynamics or Discrete Event Simulations following Brailsford and Hilton (2001) have been used by the UK's Royal National Lifeboat Institution (RNLI) in determining appropriate maintenance schedules and costs, at both boat and fleet level.

Maintenance activities are a significant portion of the operational costs. In the UK manufacturing industry, the impact of maintenance is between 12 and 23% (Cross, 1988) of the operating costs but for bulk carriers, average maintenance activities account for 40% of the operating costs (Alhouli et al., 2010). A logical goal therefore is for management to balance the lifecycle costs with system effectiveness or availability. As a significant amount of the annual operational costs are attributed to maintenance costs, an effective and efficient maintenance policy is preferable to investment in redundant capacity or reactive maintenance efforts.

It is unsustainable under increasing pressures and greater financial constraints to be investing in assets that cannot be flexible in their operational capability or designed to be easily maintained. Page (2002) shows that driving operating costs down is challenging, but for new assets there's an opportunity to appreciate the impact of design subtleties on lifecycle costs, allowing for greater flexibility into operational capability and extend the asset's useful life. Gratsos et al (2009) also reflect upon the impact of design decisions on the lifecycle costs of an asset, balancing steel corrosion allowances for more robust ship structures with lower maintenance burdens against through-life carbon foot-printing.

Stambaugh and Barry (2014) cite lifecycle cost and total ownership cost modeling undertaken by the US Navy, US Coast Guard and the US Government Accountability Office. In the UK, a similar convergence has been observed where the Royal National Lifeboat Institution (RNLI) has restructured the management of their mostly composite, 25-m or less boats' lifecycle, bringing their build in-house, adopting lean manufacturing, incorporating condition based monitoring of their vessels, and actively managing for future obsolescence of components. This has resulted in a strategy for existing vessels to have their life extended by 25 years and new builds being designed for a 50-year service life (Walshe et al., 2011). Currently there is a program of research to investigate the residual fatigue life remaining for their structures by continual strain gauge monitoring to better inform the maintenance scheduling and through-life costing (Roberton, 2014).

An otherwise general absence of a holistic methodology within the maritime industry was noted by Nappi and Collette (2013) who report on the limited investigations of time-based reliability of structures and the integration of this information into design and maintenance scheduling. Collette with co-researchers have subsequently worked on probabilistic models including Bayesian networks which aim to predict future structural capacity from structural health monitoring (SHM) data (Groden and Collette, 2013) and optimize the maintenance/inspection intervals considering costs imposed by maintenance, corrosion, fatigue damage and possible life extension (Temple and Collette, 2013). Frangopol and Soliman (2013) have used genetic algorithms to search for optimal through life decisions in the large problem space of component, system and network management levels simultaneously balancing financial, safety and environmental constraints.

2.3 Conclusions

In comparison to the aerospace, chemical processing, and nuclear power industries, the maritime industry is not as prolific in its uptake of lifecycle assessment and management. The organizers of the Condition Based Maintenance conference series, the Institute of Marine Engineering, Science and Technology, report that the industry is aware of the maturity of technology and methods supporting through life asset management but requires an organizational culture change for their general adoption. It is clear that the movement is towards integrated approaches and with goal based standards firmly rooted within the International Maritime Organization as the future for maritime design and operations, holistic approaches factoring in uncertainty, likelihood, reliability, consequence and risk can better inform the owner/operator of the asset's health and provide a route for managing that health efficiently and effectively.

3. CURRENT PRACTICE

3.1 Introduction

Current practice is dominated by owners and operators complying with the rules and other guidance of regulators and classification societies. This chapter briefly reviews that guidance and indicates how it is currently used for maintaining structural longevity primarily until the next required inspection in a cycle.

3.2 The Role of Regulators and Classification Societies

Classification societies can aid the unraveling of direct and indirect cost implications of life extension or scrapping. Det Norske Veritas (DNV) report that for some owners balancing income against maintenance and running costs is an art (DNV, 2006). But class societies can help with the engineering science to prepare, for example, different steel and coating deterioration predictions for different maintenance scenarios based upon current vessel condition. An appropriate maintenance scheme is then developed with the owner's/operator's input. In fact Paik and Melchers (2014) report that much of the shipbuilding industry is starting to follow the systematic risk-based approach seen in the offshore industry and it is more common that owners and operators are requesting vessel-specific inspection and maintenance guidance. As an example of where this can benefit and improve the transparency of some of the lifecycle costs, DNV (2010b) report that coating costs are a major factor in the dry-docking budget but only the very recent vessels are likely to have a 3D computer model leaving the yard little option but to overestimate the amount of blasting and coating required.

Ships and platforms are mandatorily inspected and surveyed under the requirements set out by IACS, the IMO, flag and port states, but the industry has also established recommended practices or standards to better manage its vessels (Paik and Melchers, 2014). MARPOL's Condition Assessment Scheme (CAS) exists for oil tankers but in response to broader asset owner pressure on driving down lifecycle costs and subsequently the life extension of their assets, class societies are actively responding to industry needs for managing all ageing structures. Many have introduced condition assessment programs aimed at hull condition and renovation and the American Bureau of Shipping, Lloyd's Register, and Bureau Veritas also have wider schemes looking at machinery and electrical systems, cargo, and ballast (Caridis, 2009).

Increased stakeholder involvement in the application of technology and research to lifecycle assessment and management is evidenced by a number of international projects in research and evaluation. Stakeholders in this process include owners, operators, shipyards, and classification societies. There are many examples in the European Community funded through the Framework Programmes that importantly look at the holistic problem of lifetime assessment and management (e.g. Condition Assessment Scheme for Ship Hull Maintenance, FLAGSHIP, HULLMON+, Inspection Capabilities for Enhanced Ship Safety (INCASS), OPTIMISE) and it is clear that the culture for lifecycle assessment and management for structural longevity is becoming not only increasingly recognized in its need but also in its adoption.

3.3 Classification Rules and Guidance

The vast majority of commercial ships and other mobile offshore units are built to and surveyed for compliance with the standards established by classification societies. The purpose of a classification society is to provide statutory services and assistance to the maritime and offshore industry with regard to maritime safety and pollution prevention, and allow for insurance of ship and cargo to be obtained. Classification Societies aim to achieve this objective through the development and application of their own rules and by verifying compliance with international and national statutory regulations on behalf of flag administrations (IACS, 2014a).

Table 1. Primary Classification Society References.

Author	Reference
American Bureau of Shipping (ABS)	• Guide for Hull Inspection and Maintenance Program (2013) • Guide for Nondestructive Inspection of Hull Welds (2014b) • Guidance Notes on the Inspection, Maintenance and Application of Marine Coating Systems (2007a) • Guide for Surveys using Risk-Based Inspection for the Offshore Industry (2003b) • Rules for Survey After Construction (2014c) • Guide for Hull Condition Monitoring Systems (2003a)
Bureau Veritas (BV)	• NR 467 Rules for the Classification of Steel Ships (2015) • NI 456 Harmonized condition assessment programme (1999) • NI 531 Guidelines for the application of the IMO performance standard for protective coatings (2007) • NI 422 Type Approval of Non Destructive Testing Equipment Dedicated to Underwater Inspection of Offshore Structures (1998) • NI 567 Risk Based Verification of Floating Offshore Units (2010)
Det Norske Veritas (DNV)*	• DNV Rules for Classification of Ships: part 7 Ships in Operation, Chapter 1, Survey Requirements (2013) • DNV-RP-G101 Risk Based Inspection of Offshore Topsides Static Mechanical Equipment (2010a) • DNV-RP-G103 Non-Intrusive Inspection (2011) • DNV Class Note 7 Non-destructive testing (2012b) • DNV Class Note 10.2 Guidance for Condition Monitoring (2008) • DNV Guideline 10 Guide for Ultrasonic Thickness Measurements of Ships Classed with DNV (2009)
Korean Register of Shipping (KR)	• Rules for the Classification of Steel Ships (2014)
Lloyds Register (LR)	• NSRC/14 Rules and Regulations for Classification of Naval Ships (2014b) • MTSTCG/14 Tank Coatings Condition Guide (2014c)
Nippon Kaiji Kyokai (ClassNK)	• Rules for the Survey and Construction of Steel Ships (2014b) • Rules for Hull Monitoring Systems (2014a)
Germanischer Lloyd*	• Rules for Classification and Construction. Ship Technology – Part 0 Classification and Surveys (2015)

*Det Norske Veritas and Germanischer Lloyd have recently merged but at the time of this writing their respective rules have not been harmonized.

A group comprising the largest classification societies are members of the International Association of Classification Societies (IACS), founded in 1968. With the aim of harmonizing the class rules of the respective classification societies, Common Structural Rules (CSR) for tankers and bulk carriers (IACS, 2014b) have been developed by the IACS members. Through the IACS membership the classification societies have undertaken to implement these rules to their own class rules. Today it is estimated that more than 90% of the world's cargo carrying tonnage is covered by the classification design, construction, and through-life compliance rules and standards set by the member societies of IACS. IACS is a non-governmental organization, but it also plays a role within the International Maritime Organization (IMO), for which IACS provides technical support and guidance and develops unified interpretations of the international statutory regulations developed by the member states of the IMO. The link between the international maritime regulations, developed by the IMO and the classification rule requirements for a ship is established though the International Convention for the Safety of Life at Sea (SOLAS)(IACS, 2011). Classification societies are required to implement requirements of IMO and/or Flag states to their rules.

Vessels not covered by the IACS Common Structural Rules include container ships, passenger ships, high-speed craft, and river and river-sea vessels. These are covered by specific rules developed by the individual classification societies. As a consequence of not being harmonized the rules may have less common features. International trading vessels are still subject to IMO regulations.

In addition to specifying rules and requirements to design and operation of vessels, classification societies also provide guidance and practical information on classification of ships and other objects in varying ways. Classification societies provide guidance on a wide range various topics ranging from design (fatigue, strength, buckling etc.) to operation (repair, non-destructive testing, monitoring, etc). Table 1 lists some of the primary references to some of the recognized classification societies.

3.4 Commercial shipping vessels

3.4.1 International trading vessels

Commercial shipping vessels are required to be designed according to class rule requirements as a minimum. Although a specific design life is not stated, a design life of 20 years is expected through adherence to class rules, yet there is limited emphasis on the total lifetime in the class rules because the class system for ships in operation is based on renewal programs carried out each fifth year. The vessel is approved for continued operation provided that all requirements are met.

The class rules state that a vessel shall be subjected to annual, intermediate, and renewal surveys. The purpose of an annual survey is to confirm that the general condition of the hull is maintained at a satisfactory level. The Intermediate Survey is to be held at or between either the 2nd or 3rd Annual Survey. Those items that are additional to the requirements of the Annual Surveys may be surveyed either at or, between the 2nd and 3rd Annual Survey. In addition to the requirements of the annual survey, the intermediate survey contains requirements for extended overall and close-up surveys including thickness measurements of cargo and ballast tanks. The renewal surveys are carried out in five-year intervals with the purpose of establishing the condition of the structure to confirm that the structural integrity is satisfactory in accordance with the classification requirements, and will remain fit for its intended purpose for another five-year period, subject to proper maintenance and operation of the ship. The renewal survey normally covers overall and close-up examination, thickness measurements, and testing, and is aimed at detecting fractures, buckling, corrosion, and other types of structural deterioration (IMO, 2004). A vessel can operate as long as requirements for class renewal are satisfied. Hence, provided that the technical condition is sufficient, then, in principal, there is no limitation for how long the vessel can operate. Vessels are however subject to more comprehensive surveys as the age increases.

The Harmonised System of Survey and Certification (HSSC) adopted by IMO entered into force in 2000 to simplify the survey and certification process. The HSSC seeks to standardize the period of validity and the intervals between surveys for the nine main convention certificates to a maximum period of validly for all certificates to five years. In practice, many administrations and classification societies already operated a form of harmonized survey and certification, but now all vessels under the jurisdiction of IMO are subject to a unified survey regime.

Since compliance with the class rules is required for ships to remain in class, the class survey system is an important starting point for how structural longevity is managed by the owner. There is however considerable variation among the owners on how this is handled. Some do not consider the longevity beyond the five-year class perspective. This is regarded as being sufficient as the satisfactory technical condition of the vessel is ensured through maintenance and repairs required during periodical surveys. A short time horizon may also fit well with the economical perspective that is limited by the contracts they work under. Costly maintenance and repairs that are not required may therefore be postponed, but from a long term structural integrity point of view these actions would be reasonable to undertake. Alternately, other vessel owners may have implemented a quality and safety philosophy that extends beyond the time horizon of renewal surveys.

Besides the mandatory inspection regime specified by class and additional measures taken by the owner, other requirements may be invoked by relevant national regulations, port authorities etc.

3.4.2 High-speed Craft (HSC)

Design and operation of high-speed craft is governed by the International Code of Safety for High-Speed Craft (HSC code) adopted by IMO in 1994 and updated in 2000 (IMO, 2000). In 1994, IMO adopted a new SOLAS Chapter X — Safety measures for high-speed craft, which makes the HSC Code mandatory for high-speed craft built on or after 1 January 1996 (IMO, 2014). With the development of many new types of HSC in the 1980s and 1990s, IMO found it necessary to adopt new international regulations dealing with the special needs of this type of vessel. The regulations take into account that a high-speed craft is of a light displacement compared with a conventional ship, and consequently the regulations allow for use of non-conventional shipbuilding materials, provided that a safety standard at least equivalent to conventional ships is achieved (Hoppe, 2005).

Due to the special characteristics of high-speed craft all major classification societies have developed specific rules for this vessel type where the HSC code requirements are implemented. The code does not provide specific requirements related to materials, structural strength, cyclic loads, and design criteria. The requirements implemented by the respective classification societies may therefore vary for these topics.

Renewal surveys in five year intervals are specified by the HSC code. Moreover, the HSC also applies for high-speed craft meaning that classed vessels are subject to annual, intermediate, and renewal surveys. ABS Rules for Survey After Construction (2014c) requires annual drydocking and survey of passenger vessels and high-speed craft.

3.4.3 Vessels operating in inland waterways

Inland vessels operating within one geographical zone (e.g. USA, Europe, or Russia) are not subject to IMO regulations. These are subject to either national requirements or regional requirements such as e.g. the European Code for Inland Waterways (CEVNI) issued by United Nations Economic Commission for Europe (UNECE). Similar to international trading vessels, inland operating vessels are required to be classed by a recognized classification society. Besides classifications societies operating globally, inland operating vessels also receive class from local actors such as The Shipping Register in Ukraine (RU) and Russian River Register (RRR). Classification rules of global actors like GL, BV, ABS, and Lloyds Register have implemented a survey regime that is identical or very similar to that of IACS. Annual, intermediate, and renewal surveys as described for international trading vessels are therefore often practiced for vessels operating in inland waterways unless regulations enforced by the authorities indicate otherwise.

3.5 Offshore structures

There is a large variety in offshore units both in terms of functionality and design. This ranges from drilling units that operate on a global scale at multiple locations to floating or fixed units that are designed for operation at one specific field their entire operational life. How the structural longevity aspect is handled varies significantly and a description of the practice of the most common offshore units will be given in the following.

3.5.1 Offshore drilling units

Typical mobile offshore drilling units are semisubmersibles, drillships, and jack-ups. The code for Mobile Offshore Drilling Units (MODU) (MODU, 2001) has been set to be the governing code by the IMO. Offshore drilling units are, according to the MODU code, required to be classed, and are hence subject to a five year renewal survey regime similar to that of commercial trading vessels with annual, intermediate, and renewal surveys.

Class rules require offshore drilling units to be designed for at least twenty years of operation. The unit is however allowed to operate further provided that it undergoes more comprehensive surveys. The use of Risk Based Inspection (RBI) planning has by some classification societies been accepted as an alternative to the extended surveys specified in the class rules. Inspection plans based on RBI assessments are often less comprehensive than the standard extended class surveys for ageing rigs, and is a service that increasingly is being used by rig owners.

Operation of offshore drilling units is very cost intensive, thus the industry is very focused on having the unit in operation as much as possible. Operation offshore is therefore planned for long periods before it is scheduled for dry docking at a yard for maintenance and inspection, when the necessary repairs, often required by the classification society, are made in order to be able to operate the next five years without interruption. The time horizon seldom extends beyond the five year cycle, and repairs not required by the classification society are often postponed until the next renewal survey.

3.5.2 Floating Production Storage and Offloading (FPSO) units

An FPSO is a floating vessel used for the processing of hydrocarbons and for storage of oil, receiving hydrocarbons produced from nearby platforms or subsea templates, processing them, and storing oil until they can be offloaded. FPSOs can be a conversion of an oil tanker or can be a vessel built specially for the application. It is the owner's decision whether vessel is classed or not. It is quite common that construction or conversion is carried out under a class regime. However, some choose to take the FPSO out of class afterwards when it enters operation.

The FPSO is often planned to operate continuously at the field. A situation where the unit must enter a shipyard for repairs or other modifications would be disastrous from an economic point of view. The incentive for having a structural integrity perspective that covers the entire time in operation is thus strong. This is especially evident in harsh environments like the North Sea where structures are prone to fatigue. Inspections and repairs are often part of a long-term strategy to ensure the structural integrity of the unit during operation.

3.5.3 Fixed production platforms

Fixed production platforms, mostly jacket structures but also concrete deepwater (or “Condeep”) platforms, are designed to operate at a specific location in a predefined period. Governing standards for design and operation are specified by the national authority responsible for the petroleum activities of the Coastal state.

Operators of fixed platforms have often a long term perspective when planning for safe operation during the lifetime of the field, with additional measures which go beyond the requirements of the governing design standards commonly implemented. Typically, more strict safety factors are used in fatigue analysis, even for details where this is not required, and additional corrosion tolerances are implemented in the design. Inspection and maintenance is also often part of long term plans. If a situation should occur where a critical damage is found, e.g. fatigue crack, it may take significant time before a repair can be carried out. This will depend on how long it takes to mobilize and plan for the repair. Furthermore, difficult accessibility and harsh weather conditions, such as during winter season, can lead to a repair being be postponed until the season is over. This represents a significant risk for the operator compared to mobile offshore units or commercial trading vessels that can be transported to a yard for repair in a relatively short time.

Many platforms set into production during the seventies and eighties were typically designed for an operational life of twenty years but improved subsea and drilling technology has permitted operators to take more resources from the reservoirs, leading to longer periods of operation. In order to justify operation beyond original design, comprehensive lifetime extension projects that document that the structure is fit for extended operation and specify areas that need reinforcement have been quite common the last couple of decades. Furthermore, through complete structural analyses with updated metocean data and state of the art computational tools inspection plans of structural details that do not fulfill requirements related to fatigue or corrosion tolerances are established. The NORSOK standard N-006 (NORSOK, 2009) was developed and published in 2009 to provide guidance to life extension assessments at the Norwegian Continental Shelf.

Extending the lifetime is a relatively costly process that may include comprehensive inspection and maintenance plans in the additional years of operation. There is now a tendency to design structures for a structural life beyond that of the planned operation with a structural design that is more flexible with regard to possible extension of field production.

3.6 Naval vessels

Larger navies have from a historical perspective had extensive national standards covering all aspects of shipbuilding and operation. Smaller navies on the other hand have not necessarily had the resources or competence to develop a complete set of standards, and have built vessels based on standards they have accessed through cooperation with other navies. This practice has gradually changed since the Cold War ended, as naval budgets have decreased, making it a challenge to maintain and develop internal standards. Smaller navies are especially vulnerable for this development as it may take several decades between when a naval vessel is placed in service and when it is replaced. This is challenging because the experience and knowledge gained from earlier projects may no longer be available.

Over the past couple of decades there has been an increasing tendency that navies choose to use the services of classification societies. In a traditional naval regime, the roles and responsibilities have been more unclear, and it could be difficult to distinguish the different roles, as many of these were undertaken by different units within the navy (Fredriksen, 2012). Navies that choose to class naval vessels also take the benefit from both civilian and naval shipbuilding knowledge. As navies are increasingly using class services, classification societies have begun developing rules adapted for naval vessels. Some examples are; DNV rules for High Speed, Light Craft and Naval Surface Craft (DNV, 2005), ABS International Naval Ships (ABS, 2014a) (ABS, 2010), Lloyds Register Rules and Regulations for the Classification of Naval Ships (Lloyds Register, 2014a), GL Rules and Guidelines III, Naval Ship Technology (Germanischer Lloyd, 2012), and BV Rules for the Classification of Naval Ships (Bureau Veritas, 2014). Reference is made to ISSC Committee V.5 Naval Vessels for discussion and comparison of naval rules of classification societies.

Naval vessels that are classed undergo the same survey regime as classed civilian vessels, and the navies have the same obligations as owners of civilian vessels to comply with maintenance and repairs required by classification society. Naval vessels outside class undergo a maintenance and inspection regime specified by the standard used by the individual navy. Instead of involving a third party (class), the process is of execution and control managed by the navy. It is still common, especially among the larger navies, to have their vessels outside the class regime.

3.7 Conclusions

All vessels operating internationally are subject to IMO regulations. These regulations are enforced though the rules of classification societies which are required to implement relevant IMO requirements. Today the class survey system is nearly identical for vessels operating internationally regardless of vessel type and classification society. Vessels not bound by IMO regulations also tend to be working under a similar regime because these are classed by the same classification societies. The survey system is the main basis for how structural longevity is handled by vessel owners. This may be due to both economical and competence reasons. However, the most important reason is believed to be that safe operation during the renewal cycle of five years is ensured by following the class requirements, though owners may have a longer time horizon.

4. PREDICTION OF LONGEVITY

4.1 Introduction

Failures in marine structures are prevented from occurring by implementing measures throughout their lifetime and beyond, from the concept design stage to their final disposition. Failure prevention is of fundamental importance in the drafting of codes and regulations related to ship construction. In fact, it could be said to be their raison d'être. The complete cycle includes feedback from ship operation, the processing of information and the concomitant use of research results in the drafting of codes and regulations. Failure prevention measures are implemented at the design stage, the fabrication stage, and throughout the lifetime of the structure. In order to be able to introduce failure prevention measures it is necessary to have an accurate picture of the behavior of a structure in its operating environment. In this way it is possible to predict the effects that individual factors that influence the behavior of a structure have, so that the required longevity is achieved. The prediction of response is therefore a necessary step before the development of rules and regulations, and is therefore carried out on a continuous basis. It may also be carried out at the design stage of an individual structure, especially if it is a novel design. During the operating life of a structure it may also be necessary in certain cases to predict the remaining lifetime, or longevity, of a structure. In this, different requirements lead to different approaches being followed in the maritime and the offshore industries.

4.2 Prediction of longevity of merchant ships

In the maritime industry, in the overwhelming majority of cases no specific calculation is made of the remaining lifetime of the structure. This is for historical reasons and also because of the economic environment within which merchant ships operate. The actual lifetime of a ship thus does not depend exclusively on technical factors and so a calculation on this basis is not of much practical value. This is discussed in the next paragraph.

With regard to economic factors, it is expected that the investment in a newbuilding will be amortized well before the expected lifetime of the structure is reached. It is market conditions and the condition of the structure that determine whether a ship will continue trading or not. When freight rates are high, overage ships find employment so that necessary repairs are carried out and these ships continue trading. When freight rates are low, only newer ships find employment, so that older vessels are condemned to the scrap yards. The fluctuation in scrap prices around the world is thus market-dependent and is recorded and reported daily in the shipping press. Other data reported include the average age at scrapping for each vessel type by organizations such as Clarksons shipbrokers.

A classic, extreme example of a modern fleet being condemned to the scrapyard is that of oil tankers in the oil crisis of the early 1970s. New VLCCs that could not find employment sailed directly to the breakers from construction yards. More recently, during the 2004–2008 period when freight rates were exceptionally high, a large number of overage vessels were employed, thereby leading to a significant increase in the average age at scrapping. A further, slightly different example is that of the Russian inland waterways vessels. In this case, older vessels cannot always be scrapped because of limited private investments in the river fleet and slow fleet renewal. These river ships do not operate for four to five months each year due to ice conditions and closed locks on rivers. So charterers employ older vessels in spite of the risks involved to their cargo and to the vessels themselves.

For these reasons, the actual determination of the longevity of the hull structure on the basis of technical factors is not always an overriding priority. Classification society rules and statutory regulations do not include any limitations on the operating lives of ships, and limit themselves to ensuring that the condition is satisfactory for the period between successive Special Surveys as described in Chapter 3.

Having said that, in addition to market conditions, technical factors also play an important role in the lifetime, or longevity, of a ship. The most important of these factors is fatigue, and because operating a ship with unreliable structure can result in damaged cargo, underwriters are reluctant to or refuse to insure cargoes carried in overage ships. As a result, these ships no longer find employment, are fraught with damages that are costly to repair, and so are scrapped.

An example of a use of fatigue analysis for planning life extension of ship structure is provided by Braidwood (2013). A single-hull tanker that had been converted to a floating storage and offloading platform was examined in 2007 for a 6-year extension of service life. In addition to an extensive structural survey, a detailed fatigue analysis of the unit was conducted that considered the previous 20 year of service and the projected six additional years of service. As a result of that analysis, modifications were made to the structure, which when surveyed in 2013 was found to be in good condition. The structural surveys and fatigue analyses were repeated in 2013 to develop the measures needed to ensure an additional eight years of service without drydocking.

In the sections that follow the technical factors that affect structural longevity will be considered individually. These are corrosion, fatigue and buckling.

4.2.1 Prediction of corrosion

In the case of surface ships, the statistical approach is used to assess the current condition of the hull structure vis-à-vis corrosion and also to predict the condition at some future point in time. This is based on the rate of corrosion concept, which is in effect the diminution of thickness that takes place during a specific period. The extensive data that have been obtained have shown that it depends on the type of structural member, the type of compartment, the arrangement of compartments as well as the type of ship. In order to avoid any loss of strength that may jeopardize structural integrity, classification societies have introduced the net thickness and the corrosion allowance concepts, both of which are expressed in absolute terms. The net thickness required by classification societies is the original thickness minus a corrosion allowance added to the calculated thickness during design and is thus the thickness required to ensure sufficient strength throughout the lifetime of the ship. It therefore represents the minimum value permitted under any circumstances. Rates of corrosion for different ship types have been obtained by IACS and other international organizations. Since ocean-going ships undergo Special Surveys at 5-year intervals, it is necessary to allow for the expected loss of thickness that will occur over this period. The total expected diminution is added to the net thickness and thus the total member thickness is obtained.

The methods used to ensure structural integrity during a ship's lifetime are permanent measures (such as the use of protective coatings and cathodic protection) and occasional measures, which relate to inspection, maintenance and repairs, including replacement of corroded members. Corrosion prevention is discussed further in Chapter 5.

4.2.2 Fatigue strength prediction

Fatigue design has been introduced relatively recently and has been undergoing significant developments in recent years. ISSC has maintained Technical Committee III.2 on Fatigue and Fracture, whose past and newest reports should be considered an important resource in understanding this technical area. The rules of different societies give different predictions of fatigue life partly because of the sensitivity of results to the underlying assumptions made. Broadly speaking, fatigue design may be carried out at different levels of increasing complexity and sophistication. The basic approach involves following rule guidelines on local detail design. Elementary fatigue life calculations can be carried out using methods such as Miner's rule whereas the more sophisticated approaches involve finite element modeling of the hull girder with particular attention to structural details. In general the remaining fatigue life of a vessel that has been in operation for some years is not usually calculated, although such information, as discussed above and in section 8.1.2 below, can be of benefit in forecasting maintenance costs.

4.2.3 Buckling prediction

The question of strength (yielding, buckling) has been addressed using the principles of mechanics since the development of large tankers during the 1970s. The problems that arose at that time made it clear that it was necessary to abandon empirical formulations and make use of engineering principles to determine strength. Later on, when high tensile steel was introduced, the problem of fatigue came to the fore and fatigue design methods started to be introduced. The most recent development in structural design concerns the determination of the ultimate strength of the hull girder in vertical bending. The recently introduced International Association of Classification Societies' Harmonized Common Structural Rules for oil tankers and bulk carriers include a step-by-step procedure to calculate ultimate strength that is based on beam theory, but which allows for progressive collapse of the hull girder. It is important to realize that failure does not occur instantaneously throughout the section but in a progressive manner. As the hull girder bending load increases, individual stiffened plate elements fail incrementally and thus have reduced effectiveness in contributing to the overall hull girder resistance to the bending loads. The method can also be applied to predict the ultimate strength throughout the lifetime of a ship, provided data concerning scantlings are maintained and updated. It can also be used to determine residual strength following accidents such as grounding and thus enables classification societies to provide advice as to the handling of the vessel and the necessary repairs. The ISSC Technical Committee III.1 on Ultimate Strength should be referenced for greater insight into the methods appropriate for capturing this failure mechanism.

4.3 Prediction of longevity of fixed offshore structures

When discussing the prediction of longevity of a structure including the fatigue life, it should be recognized that the nature of fatigue is cumulative and local. Hence, the only thing that can meaningfully be stated is that the fatigue life at a specific location in a structure has been consumed when exposed to a given load history. Local fatigue failure will in a redundant structure generally not pose an immediate danger to its survival, Vugts (2013). Hence, the longevity of a structure is not necessarily equal to the minimum fatigue life of a given component.

The design life (expected longevity) is normally defined by the platform operator/owner at the design stage. A general approach is then to design the structure so that it can sustain all design loads for the service, ultimate, accidental and fatigue limit states for the given design life, which includes that all hotspots have a fatigue life which is larger than the target fatigue life at the given location. The safety against fatigue put into the design depends on the subsequent inspection philosophy defined by the operator and the minimum safety defined by the design codes such as the guidelines in ISO 19902 (Din, 2007) or API and DNV-GL rules. In general the approaches are well established. However, a survey presented by May (2014) showed a request for more guidance by the codes for managing short fatigue lives and handling corrosion and material degradation.

4.4 Conclusions

Prediction of structural longevity requires the estimation of the time-varying probability of failure from fatigue, buckling, or corrosion, but examples of the systematic application of the principles required to do this are lacking. Failures in marine structures are prevented from occurring by implementing measures throughout their lifetime and beyond, from the concept design stage to their final disposition. The ISSC Technical Committees explore the key elements essential to prediction of structural behaviors that affect longevity, including fatigue failure, buckling and degradation such as corrosion that might lead to failure. Prevention of failure is of fundamental importance in the drafting and implementation of codes and regulations related to ship construction. Failure prevention measures are implemented at the design stage, the fabrication stage, and throughout the lifetime of the structure, based upon an understanding of failure mechanisms and modes and their prediction.

5. PREVENTION & REPAIR OF STRUCTURAL FAILURES

5.1 Introduction

This chapter presents a general overview of the latest methods applied in the offshore and naval societies for repair, and even more importantly, the prevention of structural failures with the aim of providing input to the operators for safe operation of their assets. Prevention of structural failure is a manifold task, which starts at the design stage and continues during operation of the asset by proper inspection and maintenance. Naturally, the owners of both ship and offshore structures aim to avoid failures. But, the approaches differ for the two communities throughout the life-time of the structures.

5.2 Prevention of failure - Design stage

The design phase is the optimal time to incorporate measures for minimizing the risk of failure. Hence, it is important that the right basis and tools are available for design considering the full service life of the structure. In the following sections some of the key issues for the prevention of structural failure in the design phase are discussed.

5.2.1 Corrosion protection

Experience from the shipping industry including mobile offshore units shows that corrosion accounts for more than half of the total damage and that damage from corrosion builds up with the age of the vessel, (Ayyub et al., 2000). Hence, in a corrosive environment to which most ship and offshore structures are exposed it is of major importance that the risk of corrosion is dealt with throughout the lifetime of the structure. At the design stage, corrosion allowance combined with coating can be included in certain areas such as the splash zones for offshore platforms and tank areas for ships. Proper coating and/or cathodic systems are normally selected for the protection of the rest of structure.

The correct coating system should be applied at the fabrication yards, as the cost of repair can be relatively expensive, e.g. a new build FPSO can be delivered with coating cost in the order of \$10 per coated m^2 while the cost for offshore repair is in the range of \$500 to \$3,000 per coated m^2 depending on the cause, extent, and location of failure (Kattan et al., 2013). Kattan et al. presented some of the aspects which should be focused on in the selection and application of coating systems. These include: surface preparation, application of coating, correct specification accounting for condition under which the coating is applied, and the design of the structure. Kattan et al. state that, as a rule of thumb, coating failure on edges are 7 times more likely than on a flat plate. Hence, from a coating point of view, simple designs with few sharp edges and corners are very beneficial.

An important input for the design of coating systems is the expected coating breakdown process and timeline. Material has been published in the past concerning average annual corrosion rates of ship and offshore structures, which should be accounted for in assessing the structural longevity of these assets. However, those average corrosion rates need to be considered in view of the increased ability of coating systems to completely protect structure for long periods. In one study by Slebodnick et al. (2013), high-solids coatings applied to the ballast tanks of a US Navy ship were observed to be in excellent condition after 15 years of service, with strong indications that they would remain so for the projected 20-year service life of the coatings. A new coating system in the ballast tank may effectively increase the lifetime when the quality is better than standard (De Baere et al., 2013a, De Baere et al., 2013b). In these economic evaluations, coating is seen as superior lifetime extension option over added steel thickness or steel with reduced corrosion. Improving the impact resistance will enhance the effect further.

Taking the development of coatings even further, it is very desirable to develop coatings that can provide corrosion protection but also include possible early detection of corrosion. A tremendous amount of research focuses on smart coatings that can sense corrosion and respond. An overview of recent work within this area is presented by Wheat (2012). In the development of smart coatings some of the main challenges are that indicators must be incorporated without reducing the protectiveness of the coating and that indicators must be active/sensitive over a prolonged period of time. The ultimate goal is to have coatings that can provide prolonged corrosion protection and at the same time monitor damage and detect and/or repair damaged coatings.

Despite the efforts mentioned above, it is not is not always economically possible to fully avoid corrosion. Hence it is necessary at the design stage to consider inspectability and repairability. For ships, special problems arise in relation to the particular conditions in various compartments such as ballast spaces, cargo tanks and holds. In order to develop a comprehensive and effective anti-corrosion plan, it is necessary to consider the whole lifecycle of a ship and to simulate the conditions that develop in various types of compartments under the environmental, cargo and hull structure conditions that prevail.

5.2.2 Material selection

The selection of material is of importance when failure due to brittle fracture is to be avoided. Within the offshore industry, normally relatively ductile materials are used in cyclically loaded structures with strict requirements on the test temperature relative to the operation temperature. This ensures ductile redundant structures. Additional safety can be built into the designs by the selection of SUF materials (Surface layer with Ultra-Fine grained microstructure). These materials, which introduce possible crack arrest by the material itself, are now commonly applied in the building of large container ships. Hence, effective guidelines/procedures for the determination of crack arrestability for SUF materials are needed. Ishikawa et al. (2012) worked on a test method based on small scale specimens for the determination of crack arrestability (K_{ca}). The method revealed good results when applied for EH47-class steel.

An alternative or a supplement to the use of corrosion protective coatings is the use of Corrosion Resistant Steels (CRS). Such steels have been developed for many purposes including protection of ballast tanks for cargo oil tankers, as described in Yamaguchi and Terashima (2011). Focus has been on steels which: a) have chemical compositions and mechanical properties that fulfill the existing requirements from the classification societies; b) have elements added to the steels for corrosion protection that are to within 1% of the full batch in order to ensure sufficient weldability; and c) do not initiate problematic galvanic corrosion with conventional steel applied in the cargo oil tankers. Pitting corrosion is one of the major forms of corrosion found in the crude oil tanks. Ito et al. (2012) developed methods for laboratory testing of pitting corrosion and conducted on-board evaluation of Corrosion Resistant Steel applied for bottom plates in VLCCs. Comparing conventional coated bottom plates with bottom plates constructed from CRS, it was found that pitting corrosion is significantly reduced using CRS and the overall corrosion rate was lower than when using conventional coated steel.

5.2.3 Structural design

The key to avoiding failures is a proper design which considers the full lifecycle of the structures, i.e. service, fatigue and ultimate limit states and in some cases also abnormal events. Additional safety put into the structure at the design stage can come manifold back at a later stage, i.e. if you think safety is expensive, try an accident.

One of the main causes of failures is fatigue induced cracks. The stresses that lead to fatigue failures in the structure are cyclic and normally initiate at singular points of the structure, i.e. at stress concentrations. As a consequence, the immediate measures that can be taken against fatigue cracks are either to reduce the cyclic stress loading or to release the stress concentrations. Generally, this can be obtained by smooth transitions and limited offsets in the design. As an example for a ship structure, this can be accomplished in the following ways (see also Figure 1.):

- Increase the dimensions in order to reduce the nominal stresses
- Use symmetrical stiffener cross-sections (e.g. T-sections) to avoid the development of bending stresses due to torsion that arises in asymmetrical sections
- Use larger transitional sections and limitations to geometrical discontinuities in order to reduce stress concentrations
- Add supporting brackets on the opposite side of existing tripping brackets. Their use can bring about a reduction in stresses of up to 35 per cent
- Replace the existing bracket with one whose toe has been suitably shaped and add counter-supporting brackets. This can bring about reductions in the local stresses of up to 65 per cent
- The grinding of the weld at the bracket toes also contributes to reductions in the stress concentrations and can increase the useful life of the structure by up to 100 per cent.

In recent years extensive catalogues of design improvements in order to reduce fatigue failures have been made available for standard details. Such guidelines are included in documents issued by the Ship Structure Committee, Lloyd's Register of Shipping, and the Tanker Structures Co-operative Forum for bulk carriers and tankers, see e.g. SSC-405 (Glenn, 1999).

Finally it should be noted that experience shows that gross errors are more likely for new types of structures or details than if well proven designs and fabrication methodologies are used (Lotsberg and Sigurdsson, 2014), i.e. conservative designs are less likely to fail. Hence, special focus shall be made when nonstandard approaches are applied such as excessive use of high strength steel.

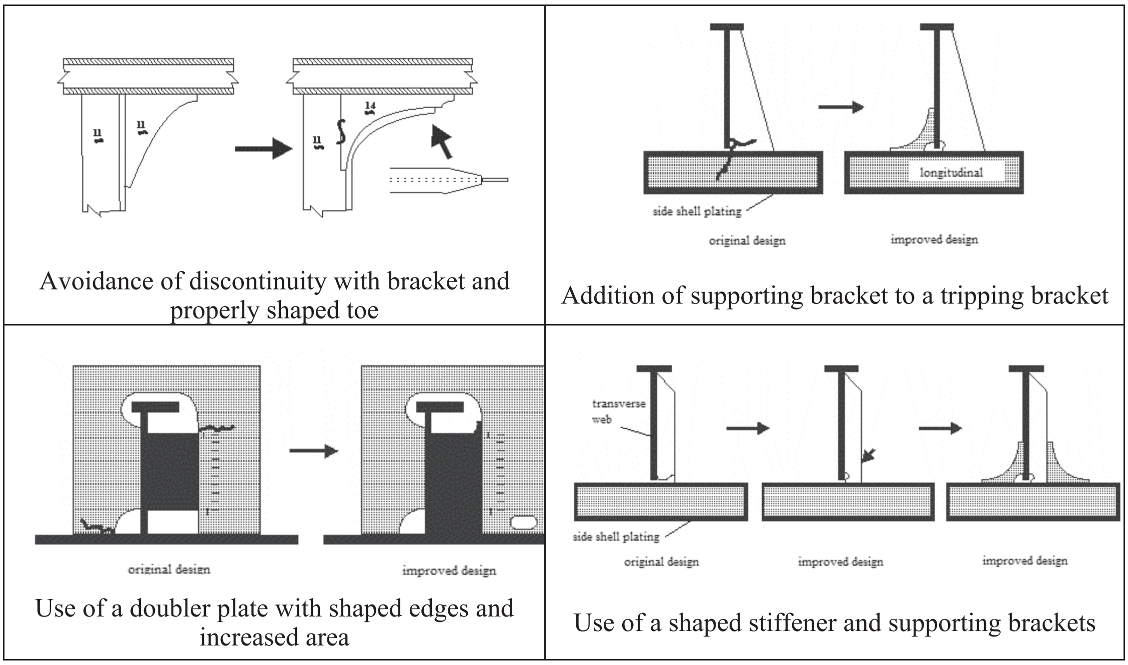

Figure 1. Methods of improving the structure at a local level.

5.3 Prevention of failure - Operation

5.3.1 Maintenance & inspection

Inspections play a major role in the prevention of structural failures. Ocean going merchant ships undergo regular inspections including special surveys every 5th year following an inspection program. Repairs and maintenance are carried out including reestablishment of coating and cathodic protections as required following guidelines such as those produced by IACS. 3D software can be used for the storing of information and assist in optimization of the inspection plans, see e.g. Witte et al. (2011).

With a focus on ship structures, the subject of corrosion is reviewed in the MegaRust symposia held annually by the American Society of Naval Engineers, see e.g. González Núñez et al. (2013) who investigated detection of corrosion using acoustic emissions, where the emissions occur as a result of stress-corrosion cracking in the corroded areas. The technique was demonstrated in a number of situations, including laboratory experiments and in a railroad tank car. Underwater inspection to detect corrosion through thickness readings using remotely operated vehicles was described by LeHardy and Walters (2013). In one test case on a naval vessel, internal inspectors identified five regions of reduced hull thickness, but subsequent inspection with an underwater apparatus found sixteen regions of reduced thickness, and a final internal inspection verified 10 of those 16 regions, with the remaining six regions not readily assessable internally. The cost of inspections can be relatively high due to the cost of preparation for inspection. Nelson et al. (2012) presented some experience on the use of a corrosion sensor-based tank monitoring system combined with an Insertable Stalk Inspection System (ISIS) as a means to reduce requirements for manned entry into tanks and voids during their inspections. These systems are so promising that they are now implemented in several US Navy vessels including new ship constructions.

For offshore structures, the level of inspection and maintenance can be determined at the design stage. The requirement for inspection (inspection intervals) will depend on the fatigue resistance of the platform and the safety put into the design. Often, a Risk Based Inspection (RBI) plan will be established and updated as the conditions of the platforms change due to modifications, unplanned events or extension of the service life. The RBI is a cost efficient way to establish an inspection strategy that legislative and operator requirements for safety and environmental risk are fulfilled and documented. The RBI approach is a condition-based approach by which the inspection effort is adapted to the condition of the item and prioritized in accordance with the importance of the individual items. The objective to the RBI methodology is to give feedback on where to inspect, what to inspect, how to inspect and when to inspect. Inspections, inspection techniques and structural integrity management systems are further discussed in chapters 6 to 8.

5.3.2 Repair and rehabilitation

During operation many ships and offshore structures will experience the need for strengthening, repair, or modification to ensure safe operation. Typically, damage will be detected during inspection of the structures. When a structural failure is detected, a decision must be made as to the most cost effective repair. This includes an assessment stage for the structure before deciding which, if any, Structural Modification and Repair (SMR) techniques are to be used. An overview of possible repair methods is outlined in the following starting with methods for offshore structure. Many of the techniques for repair and rehabilitation apply to both offshore and ship structures.

5.3.2.1 Fixed offshore structures

For fixed offshore installations, the initiator of SMR can be divided into the following categories: 1) change of platform operation, 2) lifetime extension 3) code updates or 4) damage including vessel collision, dropped objects, fatigue, corrosion, fabrication faults or unintended operations. A large number of SMR techniques exist. The most common industry adopted methods in the offshore industry are welded, clamped, and grouted repairs/modifications. A very thorough discussion on SMR techniques can be found in MSL (Dier, 2004) including a table with pros and cons for the different techniques, as reproduced in Table 2. An evaluation of requirements in terms of offshore equipment and timescale, costs, and loading penalties is included in MSL (Dier, 2004).

From the work presented in MSL (Dier, 2004), it can be concluded that grouted clamps offer both technically and economically attractive solutions for SMR work. Consequently, grouted repairs are used widely to provide additional strength, prevent propagation of dents or buckling, strengthening of legs, and clamped repairs for load transfer. Grouted connections have the major advantage that these can be utilized to accommodate geometrical imperfections and installation tolerances. With focus on structural integrity control of ageing structures, the current developments of grouted connections is evaluated by Samarakoon et al. (2013).

Table 2. Pros and cons for different SMR techniques, reproduction from MSL (Dier, 2004).

Technique	Defect							
	Fatigue crack	Non-fatigue crack	Dent	Corrosion	Inadequate static strength		Inadequate fatigue strength	
					Member	Joint	High loads	Fabr. Fault
Dry welding	yes(1)	yes	yes(3)	yes(3)	yes(1)	yes(1)	no	yes
Wet welding	no(2)	yes	yes(3)	yes(3)	yes(1)	yes(1)	no	yes
Toe grinding	no	no	no	no	no	no	yes	no
Remedial grinding	yes	yes(1)	no	no	no	no	no	no
Hammer peening	no	no	no	no	no	no	yes	no
Stressed mechanical clamp	yes	yes	no	yes	yes	no	yes	yes
Unstressed grouted clamp	yes	yes	yes	yes	yes	yes	yes	yes
Stressed grouted clamp	yes	yes	yes	yes	yes	yes	yes	yes
Neoprene-lined clamp	no	yes	no	yes	no	no	no	no
Grout-filling of members	no	no	yes	yes	yes	yes(4)	yes(4)	no
Grout filling of joints	no	no	yes	no	yes	yes(4)	yes(4)	no
Bolting	no	yes	no	no	no	no	no	no
Member removal	yes(5)	yes(5)	yes(5)	yes(5)	no	no	yes(5)	yes(5)
Composites	yes	yes	yes	yes	yes	yes	yes	yes

(1) Usually in conjunction with additional strengthening measures
(2) Except to apply weld beads in unstressed grouted connection/clamp repairs
(3) To apply patch plates
(4) Applicability depends on type and sense of loading
(5) If member is redundant (otherwise replace it)

5.3.2.2 Repair methods - ships

For ships the repair methods also vary widely. They can range from temporary cold patches to stop leaks to complete re-design of the structural detail and replacement of steel nearby the detail. Welding cracks is a popular repair, but the detail frequently fails again within a short time. Drilling the ends of the cracks is another frequently used temporary repair measure that is used until the ship is dry-docked.

For a fatigue crack in a particular structural detail, there are several methods to repair it. The expected repair life and repair cost of each repair method varies. Ship owners usually choose the most cost- and time-effective method. A robust, but extremely expensive repair method may not be the best alternative. A less robust and cheaper repair may not be favored either, because later the repair may fail again. It will cost even more money to repair the detail again and again. Selecting a repair alternative requires a large measure of judgment and engineering insight. The general strategies for crack repair of critical structural details can be classified as follows:

- *Re-weld* the cracks to the original construction: Gouging and re-welding is an easy and common way of repair. However, the repaired weld can/will create new crack potentials and thus fail again in a shorter time interval.
- *Re-weld the cracks plus post weld improvement:* This repair is basically the same as the previous one, but the life extension effect of post weld improvement can be significant.
- *Replace the cracked plate*: The existing plate is replaced with an identical new plate. However, if the loading history and dimensions are identical to those of the failed plate, its fatigue life should be about the same as the failed time of the crack.
- *Modify design* by adding a bracket, stiffener, lug, or other plate: The more robust way of repair is to modify the local geometry to reduce the stress concentration (see Figure 1). While adding a detail component and not cropping a large section, this repair may be one of the best. It can reduce the stress concentration and therefore increase the repair life significantly.
- *Change configuration* by applying a soft toe, increasing radius, trimming face plate, enlarging drain holes, etc. This is another way to modify the local geometry to reduce the stress concentration. If a longer life continuance is expected for the ship, a more robust repair such as this should be considered.
- *Enhance scantlings in size or thickness*: Increasing the size of a detail like a bracket is good. If discontinuity in thickness is introduced this should be carefully located outside the high stress area.

It is difficult to define which repair method is most reliable and cost effective for a particular crack. The selection of a particular repair alternative depends on the location of the crack and the expected life of the ship. Comprehensive lists of recommendations are nowadays available for most types of ship structures, see e.g. IACS (2007b), IACS (2005) and IACS (2007a) which cover double hull oil tankers, container ships and bulk carriers respectively.

5.3.2.3 Bonded patch repairs

A relatively new attractive efficient method for repair of corroded or cracked metal structures is bonded patch repairs. This type of repair is based on restoring the strength of the component by adding a bonded patch to the damage area. As an example, several ships of the US Navy CG47 Class have experienced sensitization of the 5456-H116 aluminum plate in their superstructures, which leads to stress corrosion cracking that cannot be repaired by welding because the stresses caused by shrinking associated with welding results in cracking of adjacent plate. Initial design and testing of a glass reinforced plastic (GRP) composite patch repair system for sensitized aluminum plate was performed, which was followed by shipboard repair with a system that was simple to install with minimal investment in specialized equipment, time, and technical expertise, with more than 120 m^2 (1,300 ft^2) of composite laminate laid down on the upper levels of aluminum superstructures of ten ships (Noland et al., 2013). In-service composite patch performance and results of reinforced aluminum center-cracked tension specimens testing to date provide confidence and data supporting the long term use of composite patches. The results of some of this testing and analysis were presented by Hart et al. (2014).

A European project on composite reinforcement of ship structures was the CO-PATCH project which involved 15 organizations representing eight countries. The primary goal of the project was to define and demonstrate composite patches as an effective repair or reinforcement method for ships and bridges with defects that can be environmentally stable and permanent. Areas investigated included the business and regulatory requirements and application cases for composite patch repairs and development of guidelines for the analysis and design of composite patch reinforcement and repair.

Another European project was BONDSHIP (Weitzenböck and McGeorge, 2005) which focused on the introduction of adhesive bonding into shipbuilding as an industrial process for joining of lightweight and dissimilar materials and structures. The project resulted in guidelines for design, modeling, testing, production, fire protection, inspection, and repair of bonded joints; acceptance tests and criteria; test and inspection methods for bonded joints; material data; documented application cases and joint designs; and documented production and assembly procedures and practical experience and skills from using adhesives in a shipyard. The project resulted in about twelve technical papers published by project participants, but the culminating document was the project guideline for the design, fabrication, operation and qualification of bonded repair of steel structures issued by DNVGL, Det Norske Veritas AS (2012a). This guideline also outlines some of the challenges with the use of bonded repairs, e.g. the provision of correct surface preparation for the patch repair, the fact that the repair makes inspection very difficult, and the insufficient long-term experience with patch repairs. Hence, these repairs are recommended to be limited to noncritical components or on critical components with noncritical defects (Echtermeyer et al., 2014). The patch repairs can also be used to postpone critical repairs until the next planned maintenance.

5.4 Conclusions and Recommendations

Prevention of structural failures is a manifold task, which starts at the design stage and continues during operation of the asset by proper inspection and maintenance. Some of the key issues and new developments are listed below:

- The design phase is the optimal time to incorporate measures that ensure the desired longevity of the structure. Additional cost spent at the design/construction stage can come manifold back, as the cost of repair can be very high compared to original fabrication cost
- Use of Corrosion Resistant Steels (CRSs) which can be applied directly using existing codes looks promising. Full scale testing shows that, relative to conventional coated steel, pitting corrosion is significantly reduced using CRS and the overall corrosion rate was lower
- A tremendous amount of research is focusing on smart coatings that can sense corrosion and respond. The ultimate goal is to have coatings that can provide prolonged corrosion protection and at the same time monitor damage and detect and/or repair damaged coatings.
- Cold patch repairs are becoming an attractive alternative to welding based repairs – A guideline has been established (DNV-RP-C301). Due to limited lifetime experience, the technique is recommended to be applied for noncritical components or on critical components with noncritical defects. Research is recommended to extend the lifetime of these repairs so that they may become permanent.

6. INSPECTION METHODS & TECHNIQUES

6.1 Introduction

This chapter describes current practices and trends in structural inspection approaches and execution to evaluate the state of the structure from inception to end of life, including deployed methodologies and techniques, and their inherent capabilities and limitations.

From the perspective of classification, legal requirements and proper asset integrity management, structural inspections are a necessity to safeguard structural longevity. In general, the outcome of periodical and event-driven asset inspections provide input for the determination of the components' (compiled) probability of failure, which is 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. Hence, in essence, current practices (still) 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 posterior analysis on correlation and causality of usage, external influences, and costs to improve the knowledge on physical system degradation, predict the future behaviour, and further refine the measures accordingly (Tammer and Kaminski, 2013). By linking this understanding of degradation propagation with the classification of the inherent risks of this process and the consequences of failure, a 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 on which practices such as Risk Based Inspection are based (Tammer and Kaminski, 2013).

The highly stochastic nature of the aging process has provided a multitude of models and inherent uncertainties that emphasize a probabilistic foundation. However, despite considerable developments in both structural reliability theory and computational methods, the probabilistic approach has gained little ground on the deterministic practices. 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. As a consequence, most operators of ship and offshore structures base decisions regarding inspection, repair and maintenance 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 guidelines (Berg et al., 2014). With this in mind, the general perspective of inspections is logically based on empirical findings.

6.2 Inspection execution

At this time, close visual inspection is deployed as the de-facto and dominant standard for initial inspection, and is the first step used to detect damage before a more refined assessment takes place with a suitable testing methodology. In general, the criterion and scope includes:

- Overall high-level inspection on component level
- Close-up visual inspections of selected and prescribed details
- Suspect areas examination
- Critical area inspection including fatigue hotspots
- Corrosion measures inspection (coating condition and anode inspection)

The execution is guided by asset-specific checklists, which are constructed as an execution guideline and used to collect textual descriptions and empirical evidence (such as photographic material) of the asset state. The inspector(s) assess the condition based on prescriptive instructions from these checklists, additional (class) guidelines and experiences gained combined with their judgement and experience. The recording of the findings differs per situation (and industry), but is often qualified by terms as ‘good’, ‘fair’ or ‘poor’ for general cases and in more refined and quantifiable parameters in the case of critical details or the extent of the damage found. Note that classification societies often require an approval of service suppliers for performing surveys, NDT/NDE tasks etc. In addition, Kalghatgi et al. (2009) presented a universally adaptable Hull Inspection and Maintenance Program (HIMP) devised by the American Bureau of Shipping (ABS), which aims to improve the structural and maintenance efficiency through the implementation of zone-based assessment and grading scheme based on six inspections criterions: the state of the coating, general corrosion, pitting and grooving, deformation, fatigue and cracks and general housekeeping and cleanliness.

6.3 Inspection techniques

Table 3 refers to the current dominant inspection methods categorized in visual, acoustic and magnetic techniques.

Table 3. Primary Inspection Techniques.

(Enhanced) Visual and Radiographic	
Strain Monitoring	Surface strain (material deformation) gauges are bonded to reference points on the evaluated structure to measure loads through elongation between these points. Traditionally, relatively low sensitivity and drift properties limited the operational monitoring time. However, more advanced and durable applications emerge, such as deployed in the Monitas II project (Kaminski and Aalberts, 2010) and through embedded (in-situ) gauges, which are often used in composite materials like carbon-reinforced structures (Okuhara and Matsubara, 2005).
Thermography	Constitutes the thermal mapping of a material surface to investigate its facial and/or its subsurface status that may affect its performance. This is done using photonic or bolometric arrays sensitive in the (1–13mm) band of the electromagnetic spectrum (Maldague, 2001). It has effectively been used to detect latent corrosion in different steel structures (Morel et al., 2001).
Liquid (Dye) Penetrant	Is employed for the detection of open-to-surface discontinuities in a non-porous material and widely used for the testing of non-magnetic materials. In this method a liquid penetrant (either visible dye penetrant or fluorescent variant) is applied to the surface. The penetrant remains in the discontinuity and indicates the presence as well as the location, size and nature of the discontinuity (IAEA, 2000), e.g. lack of fusion or porosity in welding and also for leak testing applications.
X-Ray Radiography	X-Ray radiography (sometimes abbreviated XR) is the most commonly used radiographic NDT-method. X-Rays are used to take a shadowgraph image of the sample, and shades in the shadowgraph show the attenuation to the signal while it has passed through the corresponding spot in the sample. In the X-Ray backscatter method (XB) both the X-Ray source and the detector are on the same side of the sample (Vaara and Leinonen, 2012). The method is very suitable and widely used to detect cracks and voids in steel structures and welding and also to detect delamination and porosity in composites.
Acoustic Techniques	

Ultrasonic Inspection	The basic principle of ultrasonic testing is that an ultrasonic sound wave (0.5 - 20 MHz) is introduced in the concerned material and when a discontinuity is present in the wave path, part of the sound energy will be reflected back from the flaw surface. The location of the flaw can be easily determined since the direction of the wave and the signal travel time are known. Sometimes other flaw properties like its size and orientation can be retrieved from the reflected signal. Advantages consist of the sensitivity to both surface and subsurface discontinuities, the depth of penetration, and high accuracy in determining location and size of flaws whilst providing instantaneous results. The primary drawback consists of the necessity of a coupling medium to promote the transfer of sound energy into the test specimen (van der Horst et al., 2013). Guided Wave Ultrasound (GWUT) employs mechanical stress waves that propagate along an elongated structure, guided by the dimensional boundaries of the structure. This permits the ultrasonic waves to travel a long distance with minimum loss of energy and has the potential to achieve very long range inspection by a single scan at a single sensor location (an entire hull plate) compared to the point-by-point scanning of conventional ultrasonic inspection methods. Due to the low wave frequency (10-100kHz), the operational principles of GWUT are fundamentally different from conventional. Despite seemingly superior performance, there are a few known disadvantages/issues, of which are a high dependency on the operator skills, difficulty in detecting very small pitting defects, and the lack of sound procedural protocols. Finally, the method is ineffective in thick material structures due to the very low frequency wave. Phased Array Ultrasound (PAUT) is very effective for wall thickness measurements combined with corrosion testing as the phased arrays in a variety of frequencies allows for more specific steering of the measurements in many angles and depths.
Acoustic Emission	One of the most reliable ways to detect the early stages of stress corrosion cracking and is commonly deployed for the inspection of storage tanks, pipelines and offshore structures. However, widespread adaptation/application in the shipping industry still has not been seen, although several on board trials have been conducted in the recent years by ABS (2007b) and MISTRAS (2009), Tscheliesnig (2006) and as described by Baran et al. (2012) on fatigue estimation and corrosion assessment of ships.
Magnetic Techniques	
Eddy Current	Is widely used to detect surface flaws, to measure thin walls from one surface only and to measure thin coatings in electrically conductive materials. Electric currents are produced in the structure by bringing it close to an alternating current carrying coil. The alternating magnetic field of the coil is modified by the magnetic fields of the eddy currents. This modification, which depends on the condition of the part near to the coil, is then shown as a meter reading or cathode ray tube presentation. Besides surface probes, internal probes can be used for the in-service testing of e.g. heat exchanger tubes and encircling probes for the testing of rods and tubes during manufacturing (IAEA, 2000).
Magnetic Particle Inspection (MPI)	This method is capable of detecting open-to-surface and just below the surface flaws. In this method the test specimen is first magnetized, either by using a permanent or an electromagnet, or by passing electric current through or around the specimen. The magnetic field thus introduced into the specimen is composed of magnetic lines of force. Whenever there is a flaw, which interrupts the flow of magnetic lines of force, some of these lines must exit and re-enter the specimen. These points of exit and re-entry form opposite magnetic poles. Whenever minute magnetic particles are sprinkled onto the surface of such a specimen, these particles are attracted by these magnetic poles to create a visual indication approximating the size and shape of the flaw (IAEA, 2000). A major disadvantage of the MPI-method is that it does not allow a quantitative measurement of the leakage field in the vicinity of a flaw.
Magnetic Flux Leakage (MFL)	The magnetic flux leakage (MFL) method that is derived from the MPI method resolves this problem by using a magnetometer instead of magnetic particles to detect the perturbed flux lines (Jiles, 1990). With the magnetometer, which is most often a Hall probe, it is even possible to measure the field components in three directions, perpendicular and parallel to the flaw and normal to the surface (van der Horst et al., 2013).
Alternating Current Field Measurement (ACFM)	Is a non-contact electromagnetic technique used for identifying, localising and sizing surface defects on metallic surfaces without the need for further evaluation by techniques, such as ultrasonic. It is based on the quantification of magnetic field disturbances, which arise when an electric current is disturbed by the presence of a surface breaking crack or a defect. The ACFM is a relatively recent technology widely used for structural weld inspection of offshore structures; however several initiatives are being pursued to incorporate ACFM in modern ship hull inspection schemes. The technique has the ability to detect defects through several millimetres of surface coatings on both (non)ferritic metals and up to 25mm with a high degree of accuracy.

6.4 Limitations

The outcome of the inspections and hence quality of the data and information gained is limited by the Probability of Detection (PoD), which is influenced by the deployed methodology and technology, circumstances during inspection execution, human factors, and the inspectability of details due to limitations such as accessibility or technological constraints. There are several references, which denote specific

PoD-curves for different inspection methods and -scenario's such as the HSE Offshore Technology Report 2000/018 – PoD/PoS curves for non-destructive examination (HSE, 2002) and the ICON database (HSE, 1996) or other references and experiences gained. The work by Demsetz and Cabrera (1999) for the report SSC-408 — Detection probability assessment for visual inspection of ships — shows the factors and limitations of human inspection and the PoD (Tammer and Kaminski, 2013). In addition, it is important to note that the PoD-curves are often based on technical constraints and it should be considered that:

- Inspections are performed by qualified and trained inspectors. Note that the framework for both competency/qualification and execution is often limited
- If qualified, intrinsic human limitations and external factors have a significant influence
- Inspection outcomes often have an inherent subjective element of subjectivity due to interpretation
- Non-ideal conditions due to confined spaces, accessibility, weather etc. also pose significant influences on the inspection outcomes.

A review from the SSC-355 (Shinozuka, 1990) showed that there is very little information available to assess the reliability of inspection techniques, as a performed case review delivered only one (1) reliable PoD-curve.

6.5 Conclusions and Recommendations

There are many options available to the inspection practitioner, each with its own detectable phenomena, probability of detection and cost of employment. Guidance on inspection techniques trade-space is provided in this chapter, but it is important to emphasize the significance of the inspection paradigm. Inspections are 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 safety, health and environmental risks. Hence, best-practices should be deployed to approximate the optimum of efforts to limit these risks and safeguard structural longevity.

7. SENSING TECHNOLOGIES

7.1 Introduction

Sensing systems provide primary information for the purpose of assessing the state of structural health. Systems can directly measure strain, acceleration, temperature, acoustic emission, pressure and so on, and indirectly measure such things as the location and extent of some kind of damage. Progress in electronics, optronics, mechatronics, material sciences, and processing technology and fusion of them (e.g. microelectromechanical systems, MEMS) has been continuously developing various aspects of sensors. A measurand is detected by sensors in the sensing system. The varieties of technologies for detecting a measurand have been expanded and many sensor options are available for a sensing system design. For instance, strain can be measured by not only conventional electrical-resistance strain gauges but also PZT (lead zirconium titanate ceramics) and PVDF (polyvinylidene fluoride) sensors, fiber-optic sensors, and so on. Sensors can be multiplexed with wireless sensor networks and distributed fiber-optic sensor technologies to increase measurement area/density or multifunctional capability.

If the sensing system is monitoring changes in physical parameters of a structure only by sensors that the structure is equipped with, using structural responses and behaviors resulting from operation, we can call this action "passive" sensing (Balageas et al., 2006). Most field-deployed structural health monitoring strategies for civil engineering structures are using a passive sensing system (Farrar and Worden, 2012). On the other hand, the "active" sensing approach is similar with that taken by non-destructive evaluation (NDE) methodologies, since this approach is concerned with directly assessing the state of structure by trying to detect the presence and extent of structural damage as a result of signals initiated in the structure by the sensing system (Giurgiutiu, 2007). In the active sensing system the structure is equipped with both actuators such as piezoelectric materials, including PZT, which generate perturbations in the structure, and then PZT or similar patches, which are used as dynamic strain gauge sensors.

In a conventional non-destructive inspection, as described in Chapter 6 (NDI) a portion of the sensing system, such as sensor probes or interrogator, has to be brought and set in the structure and therefore can be applied only to periodic inspection and not to real-time monitoring, which requires small, non-intrusive, low power, and robust systems.

7.2 Passive systems

Passive sensing systems are mainly concerned with identifying the operational and environmental loads acting on a structure and the structural responses caused by these loads based on measurement data (Adams, 2007), inferring the state of structural health.

7.2.1 Strain

Strain measurement, which often holds a prominent position for structural health monitoring systems, determines the stress and loading regime in part of a structure (Atkins, 2009) using point sensors, long-gauge sensors, and distributed sensors (Glisic and Inaudi, 2008).

Conventional bondable or weldable foil resistance strain gauges are most famous. Short base strain gauges (SBSGs) have a shorter gauge length and are generally more suitable for naval ships, which have much more complex structures and have less clear deck areas than tankers and bulk carriers (Phelps and Morris, 2013). Among fiber-optic sensors fiber Bragg gratings (FBGs) (Rao, 1997) and extrinsic Fabry-Perot interferometers (EFPIs) (Rao, 2006) are used as SBSGs in a manner similar to the foil strain gauges. For dynamic strain measurements PZT and PVDF bonded on surfaces are employed (Sirohi and Chopra, 2000). Fiber-optic and piezoelectric strain sensors can form strain gauge rosettes to measure individual components of strain tensors (Nichols et al., 2008, Zhao et al., 2011). Fiber-optic strain sensors survive in harsh environment and provide high sensitivity measurements (Rao, 2006, Martinez et al., 2011).

Long-base strain gauges (LBSGs), such as linear variable differential transformers (LVDTs), which measure the relative displacement between two points based on the inductive principle are designed for uniaxial strain measurement and are relatively insensitive to local stress concentrations. LBSGs are generally suitable for weather deck applications on large ships, such as tankers and bulk carriers where space in more readily available (Phelps and Morris, 2013). LBSGs based on different types of fiber-optic sensors are also available (Li and Wu, 2007, Rodrigues et al., 2013).

Fiber-optic sensors offer new and unique sensing topologies, including in-line multiplexing (quasi-distributed) and fully distributed sensing, offering novel monitoring opportunities (Murayama et al., 2012). Brillouin based sensing systems can measure strain at an arbitrary position along an optical fiber (Bao and Chen, 2012, Galindez-Jamioy and López-Higuera, 2012), and the spatial resolution, which used to be more than one meter but has been recently enhanced to cm-order or sub-cm-order (Song et al., 2006, Zhang and Wu, 2012). Strain sensing systems using optical frequency domain reflectometry (OFDR) have achieved the sub-mm-order resolution, so strain distributions with steep stress gradients can be measured accurately (Duncan et al., 2007, Murayama et al., 2013).

Full scale measurements using point or long-gauge strain sensors provide real time quantitative data about stresses, fatigue and extreme loading in commercial ships (Barhoumi and Storhaug, 2014, Li et al., 2014), naval vessels (Wang et al., 2001, Okasha et al., 2011), sailing boats (Micron, 2013), and offshore and marine structures (Bang et al., 2011, Inaudi, 2011). Although there are a number of examples of full scale measurements by in-line multiplexing and fully distributed sensing for civil infrastructures (Wan et al., 2013, Ye et al., 2014), those for ship structures are almost unexplored and expected fields (Murayama et al., 2003, Ivce et al., 2009).

7.2.2 Acoustic Emission

Acoustic emission (AE) monitoring is the process of monitoring a structure for the release of transient elastic waves that can result from yielding, fracture, debonding, or corrosion. A system with AE sensors can effectively monitor for crack initiation and growth and corrosion in metal structures as well as delamination and debonding in composite ones. AE frequencies used to detect fatigue cracks in marine steel structures are usually between 50 and 300 kHz. Due to attenuation of the AE signal, this method is generally suitable for local monitoring over several meters in the structure (Atkins, 2009).

Most AE sensors are of the resonance type. Finding the right frequency range for a specific application has to consider factors such as material, specimen size, and background noise. AE sensors with lower resonant frequency can extend the sensor spacing (Vallen, 2012).

Generally, PZT is used as the detection element in AE sensors. Although the resonance type of piezoelectric transducers have high sensitivity to signals within the bandwidth of interest, they have to be located in close proximity of the interrogation equipment if a preamplifier is not used. They also tend not to be used in harsh environments, in the presence of corrosive agents, under exposure to high temperatures, or in hazardous and explosive areas. In contrast, fiber-optic sensors don't suffer from the drawbacks that limit the use of conventional electrical-based sensors. The most common configurations in fiber-optic acoustic sensors are the Mach-Zehnder interferometers. Michelson interferometers, EFPI, and FBG are also used for AE detection (Burns, 2012). An ultra-wide frequency interrogation system allows a distributed array of in-line FBGs to act as strain, vibration and AE sensors (Mendoza et al., 2013).

AE has been commonly used in onshore storage tanks, pipelines, and offshore structures to detect cracks and corrosion but the widespread adaptation and application in the shipping industry still has not been seen, although several on board trials have been conducted in recent years. A recent pilot research program initiated by the Alaska Tanker Company, ABS and MISTRAS group ventures into evaluating commercial application of AE technologies in the marine industry. The sea trial was conducted to detect crack initiation on a double hull TAPS trade tanker (ABS, 2007b, MISTRAS, 2009). Tscheliesnig (2006) notes a European Commission (EC) funded research project was conducted by a consortium of R&D organizations to assess the feasibility of adapting AE to detect corrosion on ship hulls at the start of 2002. The main focus was to establish the feasibility of both a permanent on-board AE monitoring system and a discontinuous spot testing system. Tscheliesnig noted that environmental noise could be a vulnerability with a permanent on-board AE monitoring system. Baran et al. (2012) describe a recent development in AE technology for fatigue estimation and corrosion assessment of ships. This initiative was focused on preventative maintenance through reliable, cost effective NDT methods. On-board trials were conducted on the ICARUS III oil tanker and a database of structural response measurements was established. The ability to localize significant corrosion and extreme fatigue areas utilizing AE was also discussed.

7.2.3 Vibrations

Detection of defects in structure can also be made using the vibration of the structure when excited by natural sources of ship operation. Sabra and Houston (2011) describe a system using Diffuse Vibration Interferometry (DVI), in which the cross-correlation of vibration from separated sensors in a network is analyzed to form a coherent waveform of local structural response. The method was used to analyze strain gauge data from an instrumented high-speed aluminum vessel, but there were no known defects, so the trial was inconclusive, although DVI was successful in laboratory tests of small structures with known defects.

7.2.4 Crack

Crack propagation on a component is remotely determined by repeated or continuous measurements with gauges consisting of conductor tracks connected in parallel, which will tear if the crack extends under the crack propagation gauge, or electrically separated resistances, in which individual circuits are interrupted as the crack extends. Changes in resistances of such gauges can be measured using a conventional resistance meter or a strain gauge amplifier. A wireless crack propagation monitoring system can deliver timely data without the need for constant visual inspections and equipment downtime (Gahbauer, 2012).

Some indirect techniques can serve to monitor various parameters such as hydrogen, corrosion potential, pH, conductivity, dissolved oxygen on-line in real-time.

7.2.5 Corrosion

The marine environment is generally the most corrosive of naturally occurring environments. The hull being constantly exposed to the corrosive seawater environment experiences general corrosion that reduces the plate thickness uniformly but it is also likely to experience pitting, galvanic corrosion, and other types. Corrosion can interfere with the operation of ship and impose increased loading stress, accelerate deterioration of structure, and increase the hydrodynamic drag (Babu et al., 2014). Corrosion monitoring techniques may be broadly classified into direct corrosion measurement techniques, which measure parameters directly affected by the corrosion processes, and indirect corrosion measurement techniques, which provide data on parameters that either affect, or are affected by the corrosivity of the environment or by the products of the corrosion process (Roberge, 2007).

7.2.6 Acceleration

Accelerometers are used for motion monitoring in hull monitoring systems and vibration monitoring in condition monitoring of rotating machinery. Servo accelerometers are designed with low frequency sensitivity (DC-300 Hz), whereas piezoelectric sensors have higher frequency sensitivities (several Hz to several dozen kHz). Most MEMS accelerometers measure static as well as transient accelerations (DC to 1kHz). A number of FBG-based accelerometers are recently commercially available and they show different characteristics in terms of sensitivity, frequency range and maximum allowable acceleration (Baldwin et al., 2005).

7.2.7 Metocean information

The environment is an important element to measure and quantify to understand the loading on and response of the ship or offshore structure. Environmental measurement is typically undertaken via in situ wave-measurement buoys, air-borne or satellite devices, or mounted sensors on the ship or offshore structure itself. Wind speed is handled by use of an anemometer, with a growing range of technologies being employed beyond the original form of small cups driven by wind to rotate around a central axis. X-band wave radars (such as WaMoS® by OceanWaves or Wavex® by MIROS) have proven increasingly popular to map the water surface and determine wave heights, direction and periods, typically in the frequency domain.

Local wave behavior close to the hull may be measured with other devices such as the TSK Shipborn Wave Height Meter which measures wave elevation beneath the sensor. Further exploration and description of environmental sensors and their capabilities is the domain of the ISSC Committee I.1, Environment, and the reader is directed there to read past reports as well as the newest report.

7.3 Active systems

Excitation sources such as strain, acceleration, and AE, caused by the ambient load and environment as an excitation are often not stationary. This means that robustness and long-term stability in measured data and normalization procedures are required to determine if the change in the structural response is the result of damage or deterioration as opposed to changing operational and environmental conditions.

As an alternative, the active sensing system can be designed to provide a local excitation tailored to the damage detection process. The use of a known and repeatable input makes it easier to process the response signals for damage detection in a designated area. For instance, by exciting the structure in an ultrasonic frequency range, the sensing system can focus on monitoring changes of structural properties with minimum interference from operational and environmental variability, which tend to be low-frequency in nature.

Examples of the active sensing system for damage detection include impedance-based methods (Park et al., 2003) and Lamb wave-propagation methods (Raghavan and Cesnik, 2007). Active sensing systems are concerned with detecting the presence and extent of structural damage, while passive systems are concerned with measuring various structural responses as well as loads and environments.

7.3.1 Impedance-based methods

The electromechanical impedance (EMI) technique uses swept-sine, high-frequency excitations, typically higher than 30 KHz, applied through surface-bonded piezoelectric patches to identify changes in the structure's mechanical impedance, which can be considered an indication of a change in the mechanical impedance of the host structure due to damage such as the formation of a crack or the loosening of a bolted connection (Farrar and Worden, 2012).

In order to ensure high sensitivity to damage, the electrical impedance is measured at high frequencies in the range of 30 – 400 kHz. A frequency range higher than 200 kHz is found to be favorable in localizing the sensing, while a frequency range lower than 70 kHz covers a larger sensing area. It has been estimated that the sensing area of a single patch can vary anywhere from 0.4 m (sensing radius) on composite structures to 2 m on simple metal beams (Park et al., 2003).

The impedance method usually utilizes PZT sensors/actuators as well as macro-fiber composite (MFC) to acquire dynamic responses of a structure. Typical SHM applications based on EMI generally use commercial impedance analyzers or alternative systems based on frequency response function (FRF) or other methods. Such analyzers are often bulky, expensive and not suited for permanent placement on a structure. As a promising alternative, a new microcontrolled SHM system based on the EMI principle has been proposed to be small and low-cost (Park et al., 2007, Cortez et al., 2013, Grisso, 2013).

Using the impedance method, damage and deterioration, such as cracking, bolt loosening, composite delamination, and corrosion have been successfully detected on a variety of structures from simple beams and plates to bridge truss structures and composite patch repairs. Developed prototypes are still only in the laboratory verification stage (Park et al., 2007). Grisso (2013) provides details of development of a structural health monitoring prototype for aluminum ship structures using an impedance-based method in a highly complex ship sub-structure in the laboratory environment. Encouraged by the results of the laboratory tests, the initial investigations into miniaturized impedance hardware that could be used in actual naval settings show great promise.

In order to handle real-life applications, extensive efforts are being devoted to study the issues that include developing miniaturized and portable impedance measurement equipment, packaging of the sensors to facilitate installation, integrating this method with other NDE techniques, such as wave propagation methods, acoustic emissions and ultrasonics, and investigating the possibility of wireless communication between the sensor and the signal processing equipment (Park and Inman, 2007).

7.3.2 Lamb wave-propagation methods

The term guided-wave (GW) refers to elastic waves that propagate along a path defined by the structure's boundaries (Worden, 2001). GWs can travel at large distances in structures with only little energy loss, so they enable the SHM of large areas from a single location. Among GWs, Lamb waves are usually analyzed in the SHM field. Lamb waves are guided between two parallel free surfaces, such as the upper and lower surfaces of a plate. The symmetric Lamb waves (S_0, S_1, S_2, …) resemble the axial waves, whereas the antisymmetric Lamb waves (A_0, A_1, A_2, …) resemble the flexural waves. Lamb waves are highly dispersive, and their speed depends on the product between frequency and the plate thickness (Giurgiutiu, 2007).

To be able to distinguish between damage and structural features, prior information forming a baseline signal is required about the intact structure. To allow the receiving sensors to record the response with a minimal interference, it is essential to choose a driving frequency (Raghavan and Cesnik, 2007). With the appropriate drive signal chosen, the approaches to SHM involve some form of either a pitch-catch actuation-sensing scheme or a pulse-echo scheme. In the pitch-catch scheme a Lamb wave is launched from an actuator and received by a sensor at another location. From various characteristics of the received signal, such as delay in time of transit, amplitude, frequency content, etc., information about the damage can be obtained. With the pulse-echo approach the signal is generated at one location and the reflections of these waves off the free surfaces such as crack boundaries are measured at this same location. Defects can be located using the wave speed. In either approach, damage-sensitive features are extracted from the signal using some signal-processing algorithm, and a pattern recognition technique is required to classify the damage and estimate its severity. The choice of the threshold to decide whether damage is present in the structure or not is usually application-dependent (Giurgiutiu, 2007, Raghavan and Cesnik, 2007).

GW testing can offer an effective method to estimate the location, severity, and type of damage and it is a well-established practice in the NDE/NDT industry. The most commonly used transducers are angle piezoelectric wedge transducers, comb transducers and electromagnetic acoustic transducers (EMATs). Other options, such as Hertzian contact transducers and lasers, have been explored in recent years. However, while these types of transducers function well for maintenance checks when the structure is offline for service, they are not compact enough to be permanently onboard the structure during its operation. PZT is one of the most popular choices in the field of GW SHM (Raghavan and Cesnik, 2007). In order to overcome the disadvantage of PZT in terms of brittleness and flexibility, different types of piezocomposite transducers, such as the active fiber composite (AFC) (Bent and Hagood, 1997) and the macro fiber composite (MFC) (Williams et al., 2002), have been investigated. Fiber-optic sensors, which have flexibility, immunity to electromagnetic interference, and corrosive resistance can be also used as sensor elements (Li et al., 2010).

Variations of Lamb wave propagation reflect some changes in effective thickness and material properties caused by such structural flaws as fatigue cracks, corrosion and disbonding. Yeo and Fromme (2006) and Fromme (2008) investigated application of guided ultrasonic wave inspection for detecting corrosion in ship hull structures. A stiffened aluminum plate fatigue specimen which was constructed with typical naval ship details was instrumented with PZT to allow for GW SHM implementation during fatigue testing and structural changes due to fatigue were identified using Lamb waves prior to any visually observed cracking (Grisso et al., 2011). Corrosion damage in a thin aluminum plate was detected and monitored by the pitch-catch approach and a tomographic algorithm using damage index information produced by a signal processing method (Grisso et al., 2011). Delamination or disbonding in composites are also detected by the pitch-catch approach (Balasubramaniam, 2014, Ricci et al., 2014). Packaging of the transducers, as well as ensuring reliable mechanical and electrical connections for them, is an important element in *in situ* SHM applications. The packaging design should account for the demands of harsh environments, load conditions and cycling fatigue experienced by the structure. Some systems including sensors, hardware, and damage detection algorithms have been developed (Alcaide et al., 2012, Bergman et al., 2014). Several projects have been carried out to validate the system for aircraft structures in flight tests (Dragan et al., 2013, Eckstein et al., 2013), but more full field testing of the system need to be addressed.

7.4 Data acquisition and processing

In order to identify data features that allow one to correctly distinguish between the undamaged and damaged structure, the acquisition of necessary and sufficient data is needed as well as the normalization and cleansing process (Farrar and Worden, 2007).

The data acquisition portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware. Economic considerations and the interval at which the data should be collected will play a major role in making these decisions. The data normalization process is separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. One of the most common procedures is to normalize the measured responses by the measured inputs. Since strain sensors show cross-sensitive to temperature, temperature compensation is required as the normalization to obtain reliable strain or stress information. The data cleansing process is choosing data selectively to pass on to or reject from the feature selection process. If a sensor is loosely mounted and that fact is found, the data from this particular sensor may be selectively deleted. Filtering and resampling can also be thought of as data cleansing procedures.

7.5 Sensor network, wired and wireless

A sensor network integrates sensors, data processors, network controllers, and data links. The capability of a given sensor network can far exceed the sum of the capability of individual components (Balageas et al., 2006). For example, in the case of bridge or a ship hull regarded as a beam, point strain sensors provide just local strains and stresses individually, whereas the sensor network dealing with perfectly-synchronized strain data from point or distributed strain sensors along the beam structure can provide not only local strains from each components but also vertical displacements or deformation modes through double integration of curvature (Rodrigues et al., 2013).

In wired sensor networks data acquisition, storage, and analysis all occur at the one central location. Such systems have the advantage that recordings from multiple channels are more easily time-synchronized, which is important when damage sensitive features are based on relative information between sensors. In a fiber-optic sensor network one can reduce costs for the measurement system by using sensor multiplexing technique (Perez-Herrera and Lopez-Amo, 2013). The Norwegian Defense Research Establishment (FFI) developed an extended ship hull monitoring system (ESHHM) including a fiber-optic sensor network which had 36 strain sensors and 6 temperature sensors based on FBG. They installed it on a mine countermeasure vessel and measured the extreme sagging/hogging moment induced by slamming (Torkildsen et al., 2005). A significant limitation of such systems, however, is the deployment, since over 75% of the installation time is attributable to the laying of wires in a structure with installation costs representing up to 25% of the system total cost for larger-scale structures, such as long-span bridges (Lynch et al., 2004). Furthermore, wires installed in a combat vessel are vulnerable to detriments such as heat, moisture, and toxic chemicals common in harsh military operational environments (Swartz et al., 2012).

The integration of wireless communication technologies into SHM methods has been widely investigated in order to overcome the limitation of wired sensing networks (Farrar et al., 2006). The efficacy of the wireless hull monitoring system in a realistic marine environment was demonstrated in a high-speed littoral combat vessel (FSF-1 Sea Fighter). A multi-tiered, hybrid wired/wireless network with 3 wireless sub-networks was installed and tested for strain sensing as well as modal analysis using accelerometers (Swartz et al., 2012). A four AE channels platform with a self-powered wireless node has been developed (Godínez-Azcuaga et al., 2011). Wireless sensor networks using active sensing approaches have been studied for simple structures, such as an aluminum beam or sandwich plate (Dürager et al., 2013, Cortez et al., 2014). In a European project, a complete embedded sensor system (FBG sensor and interrogator) for composite structures has been developed so that any fragile external connection between the sensor fiber and the interrogator is avoided. The measured data is transmitted to an external read-out unit through the wireless channel, and the external unit, in addition, provides the wireless power supply to the embedded interrogator (SmartFiber, 2014).

7.6 Maturity of Structural Hull Monitoring Systems

The level of maturity of different SHM systems differs significantly for each type and area of application. Table 4 presents maturity of the SHM systems against the area of application.

Table 4. The Level of Maturity of SHM Systems Against the Area of Application.

Type of SHM or sensors	Application Area	Goals	Level of Maturity
Accelerometers, motion sensor units	Slam avoidance	Detecting a slam before it occurs	Sensor technology is mature; however it is not easy to detect a slam before it occurs. Hence, slam detection algorithms are not mature yet.
Accelerometers, motion sensor units to provide rigid body ship motions, strain gauges	Whipping and Springing	Quantifying whipping and springing responses, their contribution to fatigue and design loads.	Sensors and technology are mature. However, analysis may require effort by specialists.
Accelerometers, motion sensor units to provide rigid body ship motions	Motion Based Monitoring	Determining short and long term loads and avoidance of excessive motions.	Sensors and technology are mature. Commercial off the shelf tools are available.
Accelerometers, motion sensor units to provide rigid body ship motions	Weather Routing	Voyage optimisation for fuel efficiency and improved ship safety	Sensors and technology are mature. Commercial off the shelf tools are available.
Motion sensor units to provide rigid body ship motions, load cells, strain gauges, wave height sensors	Loads monitoring	Determination of bending moments and hydrodynamic loads for short term (voyage) and long term (design) analysis	Sensors and technology are mature. Commercial off the shelf tools are available.
Motion sensor units to provide rigid body ship motions, strain gauges, wave height sensors, weather hindcast data	Fatigue monitoring	Determination of speed, seaway and stress ranges over a long term monitoring	Sensors and technology are mature. However, analysis may require effort by specialists.
Acoustic Emission	Crack detection	Detecting crack before visually seen or before they occur.	Technology has been demonstrated in a laboratory or a small scale experiment. Widespread application is not available yet.
Impedance based detection methods	Crack detection	Detecting cracks before visually seen or before they occur	Technology has been demonstrated in a laboratory or on a small scale experiment. Application of it onboard a ship is yet to be successfully demonstrated.
	Corrosion detection	Detecting corrosion under insulation or in areas difficult to inspect	Small scale experiments have been shown. Widespread application is not available yet.
Fibre optic sensors	Failure detection	Detecting failure in marine composite structures	It is still in research phase in laboratory environments.

8. METHODOLOGIES FOR USING INSPECTION & SENSED DATA

8.1 Introduction

Effective inspection, Structural Health Monitoring (SHM) and operational guidance techniques allow the detecting, locating, and quantifying of potential damage situations in order to ensure the proper operational performance of the existing ship and offshore structures. It also ensures the ability to minimize maintenance and lifecycle cost by taking correctional measures in a timely manner. The current SHM systems have contributed to a significant improvement in the operational safety of ships, and will continue to play a critical role in ensuring structural and operational performance of commercial ships and naval vessels, including lightweight high performance ships. In the case of high performance ship design, construction includes novel lightweight structure which warrants the utilization of composite materials, aluminum alloys, or high strength steel with innovative application techniques to maximize the vessel performance (Sabra and Huston, 2011). At the same time, high performance vessels are subjected to significant wave induced impacts and slamming while operating in heavy/extreme environments which contribute to accumulation of fatigue damage. Thus, the development and application of new and innovative SHM systems are necessary for assessing the structural reliability of such high performance vessels.

8.2 Operational Advice

The implementation of SHM on vessels may lead to potentially effective and efficient ways to:

- Provide a real-time feedback system equipped with real time loading information and trends, and inform of the possibility of extreme loading events so that the risk of structural overload/ failure may be avoided, and
- Obtain actual in-service information of the extreme and long term fatigue loads to which the vessels are exposed, so that this information can be utilized to improve both the design and lifecycle management of ship and offshore structures (Phelps and Morris, 2013).

Operational decision-making also plays a key role in ensuring the safety of the vessel and the crew at sea. Most operational decisions require the assessment of both the ship conditions and environmental conditions by the ship operator. Operational risks governed by the seaway conditions are made at all stages of decision-making. Pre-operation decisions include considerations taken before the voyage. In term of passenger ships, the question might be whether to sail or to stay at quay. Preventative decision making becomes more important during the operation in order to avoid situations that might be uncomfortable or hazardous. It includes weather routing, and could also be a question of extra lashing or ballasting before entering heavy seas.

Within the last decade the on-board and post-voyage analysis of ship structures have become a common theme for the maritime industry. The analysis and recommendations developed through the implementation has improved both the design and operational aspects within the shipping industry. The combinational diagnostic and prognostic approach through SHM can significantly improve the vessel operation capabilities and lead to a significantly more optimized design methodology with a quantifiable increase in structural reliability.

8.2.1 Identifying loading to stay within safe operating envelope

8.2.1.1 Motion Based Monitoring

The roll, pitch, and heave response of a ship to a sea state are generally of the most concern from either a synchronous motion aspect or extreme motion aspect and whose limitations will bring operational benefits. Ship motion monitoring systems are primarily installed to warn the operating personnel that the vessel motions are approaching intensities where selected motion threshold limits are likely occurrence to be exceeded. Ship motions themselves are often not a problem for the vessel's integrity, but they are often the reason that a Master reacts to deteriorating environmental conditions. However, the limiting motions will sometimes be established on the basis of computed structural limits.

Topics to be discussed next such as slam avoidance, whipping and springing, weather routing are all related to motion based monitoring.

8.2.1.2 Slam Avoidance

Slam avoidance systems can predict the possibility of a vessel experiencing wave slams that may lead to either localized or hull girder structural damage. Structural damage warning levels on displays and alarm levels are set taking into account the approved scantlings and their conditions of approval. The criteria to judge the occurrence of slams is derived from calculations, model tests or full-scale trial results, which should be updated based on the actual experience. Methods of identifying slam impacts include:

Accelerometers and strain gauges: The recognition of a decaying vibratory shape on the acceleration or strain (converted to stress) signals (Magoga et al., 2014) at the frequency of the 2-node mode of vibration of the vessel which can be determined using spectral analysis or other techniques. The severity of the impact is indicated by the amplitude of the vibration. For the applications that have utilized multiple accelerometers to identify the presence of slamming through the detection of vibratory bow acceleration, the placement of accelerometers as close as possible to the extreme ends of the ship is noted to be particularly important for this system to maximize the two-node vibration detection (Moe et al., 2005).

Pressure Transducers: Pressure sensors at the bow of the vessel initiate a warning when a zero pressure state is recorded as a result of bow emergence. The severity of impact can be indicated by the re-entry pressure (Drummen et al., 2014). Also the strain gauge data from the bow panels may be used to calculate the mean pressures across the bow panels due to slamming.

Wave-induced hull girder vibrations are normally described by the terms springing and whipping. The resonant vibrations induced are termed springing, whilst transient vibrations which increase rapidly due to wave loads is termed whipping. The normal cause of whipping is attributed to the impact of loads generated from bottom slamming, bow flare slamming, or stern slamming. Full scale measurements on board a number of vessel types indicate the effect of vibrations on the structural fatigue damage is comparable to the conventional wave loading effects. The whipping contributes to extreme loading scenarios which may also exceed the classification society rule wave bending moment (Moe et al., 2005, Storhaug, 2012).

Barhoumi and Storhaug (2014) extensively studied the whipping and springing responses on a large 8,600TEU container vessel equipped with a hull monitoring system, based on fiber-optic sensors. The study indicated that the higher fatigue rates are limited in occurrence but contribute significantly to fatigue damage.

Sheinberg et al. (2011) investigated the effects of wave impact and whipping response on fatigue life and ultimate strength of a semi-displacement patrol boat based on model tests conducted on a segmented structural model. Stambaugh et al. (2014) strongly suggested onboard structural hull monitoring systems to provide life fatigue damage accumulation and guidance to the operator for heavy weather avoidance since fatigue damage is proportional to the third power of stress range.

Developments in detection of slamming events and understanding their contribution to localized stresses and fatigue life of the hull structure have significantly improved ship design and maintenance through post voyage analysis. New methods are being proposed to implement onboard monitoring and analysis of slam induced fatigue. At the same time, extensive data collection systems are installed for monitoring of engine and hull performance and for voyage performance evaluation, etc. Such systems are expanded to encompass procedures for stress monitoring and for decision support. Nielsen et al. (2011) outlines a conceptual calculation procedure for fatigue damage rate prediction in hull girders taking into account whipping stresses, proposing a method to automatically estimate hypothetical changes in ship course and speed in a wave environment to assess the accumulated fatigue damage in the hull girder.

8.2.1.3 Weather Routing

Weather related incidents have been a significant cause of maritime casualties/incidents all throughout the past. Therefore it is critical that effective weather routing technologies and systems are developed, in order to mitigate the effect of weather routing induced structural stresses. The main objective of weather routing systems for high-speed craft is to reduce the risk of crew injuries and to avoid significant hull damage. Weather routing systems provide decision support for the navigator regarding optimum speed and course based on limit values for relevant ship response (Rathje, 2009). Table 5 highlights several commercially available weather routing systems and services.

Table 5. Commercially Available Weather Routing Systems and Services (list is not exhaustive).

System	Vendor	System Details
Navi – Sailor 4000 ECDIS: Premium+	TRANSAS Headquarters St Petersburg, Russia	• AIS, Dual ARPA and Target Management • Provide information on the tides and currents • Compliance approved by 1. US Coast Guard Certificate of Approval 2. Russian Maritime Register of Shipping 3. DNV EC 4. China Classification Society Certification
Bon Voyage System	AWT Worldwide Headquarters California, USA	• Severe motion alerts • Graphical depiction of Weather, Route and Currents • High resolution data availability • Claims to be able to provide 16 day forecast and four time a day
Jeppesen Vessel Voyage Optimisation Solution	A Boeing Company Headquarters	• Automatic generation of a full range of optimized routes • Optimize to minimum fuel speed plan for required arrival time • VVOS optimal speed management • Simulation tools facilitate analysis of any route using high-resolution forecast weather to weigh trade-offs among ETA, fuel consumption, ship motions, hull stresses, and weather and sea conditions.

One of the leading voyage optimization tools offered by Jeppesen (2014) provides commercial benefits by enabling every vessel in the fleet to attain higher efficiency, as well as improved operating margins and operating risk mitigation. The Vessel Voyage Optimization Solution (VVOS) utilizes advanced routing algorithms to accurately optimize each route for on-time arrival while minimizing fuel consumption. The guidance system recommends speed and heading changes to manage ship motions and help minimize heavy weather damage. Krata and Szlapczynska (2012) explored the possibility of adapting pre-voyage Multi-criteria Evolutionary Weather Routing Algorithm (MEWRA). The authors calculated a safety index for dangerous dynamic phenomena (such as reduction of intact ship stability when riding a wave crest amidships or parametric roll phenomena) and suggested a similar safety index could potentially be applied regarding the structural condition of the vessel. Szlapczynska (2013) provided possible practical applications of MEWRA. Mao et al (2012) presented a ship fatigue routing procedure, using a simple spectral method developed by the authors, and the analysis of long-term fatigue assessment of a typical container vessel. The potential benefits of using the proposed ship fatigue routing procedure was demonstrated by a case study of a 2,800TEU container ship and the authors stipulated that the fatigue life of the vessel can be extended by at least 50% by choosing more well-suited ship routings.

8.2.2 Quantifying operational loading and changes

Researchers in China have made significant progress in various aspects of SHM for quantifying and tracking operational loads and responses. Ou and Li (2010) reported that almost 100 bridges, offshore platforms, tall buildings, spatial structures, underground infrastructures, and pavement have been implemented with SHM systems in China in an attempt to quantify loadings and the associated responses.

The VALID Joint Industry Project (JIP) resulted in SHM systems being deployed in new USCG ships and vessels. The project incorporated numerical analysis of the USCG National Security Cutter, segmented model tests and full scale sea trials to find insight into actual fatigue life vs. as-designed (Stambaugh et al., 2014).

Murawski et al. (2012) provide examples of marine safety improvements by the application of SHM systems. Li et al (2006) describe a methodology for the health monitoring of composite marine joint structures based on strain measurements under operational loading using embedded fiber Bragg grating sensors, which enables the sensor measurements to be used for damage detection without reference to a high-fidelity numerical model of the structure. The technique is shown to provide successful damage diagnoses with an acceptable level of accuracy.

Effective damage detection utilizing smart sensor technologies offer new opportunities and possibilities for structural health prognostics, with the results that include actual damage used in the prognostic models for accurate, real-time prediction of future trends. A prognostic model can be continually updated over time as the damage develops (Herszberg et al., 2007).

The (remaining) fatigue life estimation has been the topic of many research papers recently. New onboard hull monitoring systems are expanded to encompass procedures for stress monitoring and for decision support, where critical wave-induced ship responses and fatigue damage accumulation can be accurately estimated for hypothetical changes in ship course and speed in the automatically estimated wave environment. Nielsen et al. (2011) outline a conceptual calculation procedure for fatigue damage rate prediction in hull girders taking into account whipping stresses and a fast and reliable stress calculation procedure for the derivation of spectral properties at specific structural details for given environmental data, as the final step in developing a decision support system for accumulated fatigue damage. Considering only the contributions from vertical bending moments, Jensen et al. (2008) have described a simplified calculation procedure for the long term probability distribution of the combined wave and whipping induced stresses and Neilson et al. (2011) highlights that reasonable agreement with full-scale measurements were found, provided the pertinent parameters related to the estimation of the impulsive slamming load are chosen with care. Sheinberg et al. (2011) and Stambaugh et al. (2014) investigated the fatigue life of US Coast Guard patrol boats; Storhaug (2012) studied the effect of extreme responses to fatigue life of a container vessel; Temple and Collette (2013) discussed fatigue of naval vessels; Moe et al. (2005) conducted full scale measurements on a bulk carrier, and Kwon and Frangopol (2012a) investigated the fatigue life of aluminum ships.

Wagstaff et al. (2013) presented a case study where corrosion under insulation could be detected using the Asset Integrity Management (AIM) process working with measured data. An example test result is illustrated for sensing the crevice corrosion of nickel-aluminum bronze using a boron-doped diamond sensor array.

8.3 Lifecycle Management Advice

In order to ensure the safety of ships and prevent catastrophic effects of maritime accidents, reliable efforts are required through inspection, maintenance and repair to ensure the safety of the ship and its crew. As the current shipping fleets age, and due to the growing budgetary restrictions governments and operators are forced to extend the service life of marine vessels, including naval vessels, long past their acceptable operational lifecycles.

The European Union's Condition Assessment Scheme for Ship Hull Maintenance (Cabos et al., 2008) defined a standard ship electronic model into which the measurements of on-board thickness measurements, cracks and coating condition would be recorded. A computerized analysis of the ship electronic model (with measurements recorded inside) was developed to enable the triggering of automatic alarms if the condition of the vessel is degrading dangerously.

The approaches available to the navies for determining the assessed structural condition of an aged warship are similar to those used by commercial agencies for merchant ships. The US is very active in driving holistic treatments to manage and ensure structural longevity. Hecht and An (2004) sponsored by the US Naval Sea Systems Command showed how non-destructive evaluation methods can be justified in their uptake by integrating structural component level strength probabilities with system level descriptions and economic evaluations. The US Navy and the American Bureau of Shipping (ABS) embarked on a program which resulted in the Surface Ship Life Cycle Management (SSLCM) activity (Eccles et al., 2010). The main tool behind the program is to build a finite element model for the as-built configuration of the warship and apply projected operational loadings envisioned for the ship to identify the inherent structural margins, inherent corrosion allowances, critical inspection plans, plate renewal criteria and expected fatigue life for the ship.

The Naval Sea Systems Command and ABS are partnered in the Achieving Service Life Program (ASLP) for the US Navy. ASLP provides a structured, third-party periodic condition assessment process for selected systems and structures on a number of US surface combatants. ABS extended the ASLP to the Service Life Evaluation Program (SLEP) so that it can be employed by other navies (Anderson et al., 2013). SLEP has three principal components: survey reporting, strength analysis, and fatigue analysis. In a SLEP program the assessment cycle is defined with Baseline Service Life Assessment, Continual Service Life Assessment, and two Intermediate Service Life Assessments in between the two. For strength and fatigue analyses, and remaining fatigue life estimation, SLEP provides specific methods to apply with risk based assessment criteria and recommended fatigue inspection intervals. For more in-depth discussion on the topic of lifecycle management of naval ships, the readers are encouraged to refer to ISSC 2015 Committee V.5 Naval Ships, report.

General maintenance schedules for the large majority of marine vessels are largely based on their availability, usually calling for repairs on fixed intervals that are not chosen with the specifics of the ship's structure in mind. It is desirable to optimize the vessel lifecycle management/ maintenance systems based on the specific design of physical structure of the ship to improve safety and lifecycle management (Collette, 2011). An extensive study by Temple and Collette (2013) proposes a framework to determine the maintenance cycles for a naval vessel to be specific to the vessel itself, and take into account the potential for an extension to the original service life in order to minimize the lifetime maintenance cost for the ship in the face of operational uncertainty. Lee et al. (2006) presented the evolution of inspection and maintenance strategies as shown in Figure 2.

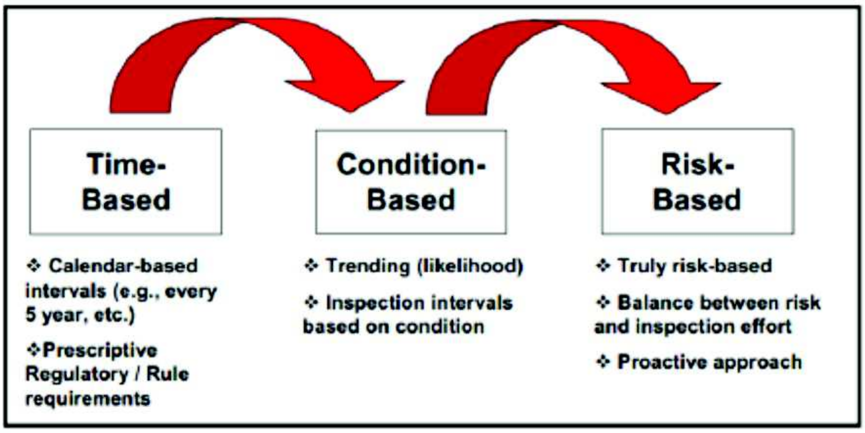

Figure 2. Evolution of Inspection and Maintenance Strategies (Lee, 2006).

Time-based maintenance where maintenance activities are carried out periodically is the traditional maintenance technique. It assumes that the failure behavior (characteristic) of the equipment is predictable based on hazards or failure rate trends, known as bathtub curves, as shown in Figure 3. As can be seen from the figure, failure rate trends can be divided into three phases: burn-in, useful life, and wear-out. It is expected that a high failure rate will be experienced at the start of the operational life of a complex structure. During the burn-in phase, the structure or equipment experiences decreasing failure rates early in its lifecycle, followed by a near constant failure rate (useful life). At the end of their lifecycles (wear-out), structure or equipment experience increasing failure rates (Ahmad and Kamaruddin, 2012).

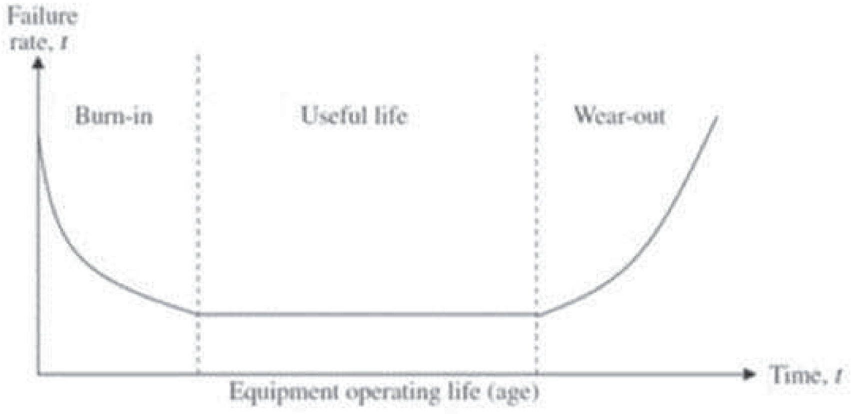

Figure 3. Typical bathtub curve.

8.3.1 Condition Based Maintenance (CBM)

Condition based maintenance (CBM), also known as predictive maintenance, is the modern and popular maintenance technique which, according to Jardine and Tsang (2013), recommends maintenance actions (decisions) based on the information collected through condition monitoring (CM) process. CM, performed either periodically or continuously enables the collection of the condition data (information) of the equipment or the structure or increases knowledge of the failure causes and effects and the deterioration patterns of equipment or structure. Applications to vibration monitoring, sound and acoustic monitoring, and lubricant monitoring using CBM are provided by Ahmad and Kamaruddin (2012).

CBM has become an integral part of many vessel monitoring sectors in the marine industry. Gudze and Melchers (2007) discussed the necessity for the CBM requirements (usually performed on board) for Australian Navy ships. Usually the major issues faced with condition based maintenance arise from the poor structural design or operational tactics of the vessel.

8.3.2 Reliability Centered Maintenance

Reliability Centered Maintenance is used to develop scheduled maintenance plans that will provide an acceptable level of operability, with an acceptable level of risk in an efficient and cost-effective manner. Camara and Cyrino (2012) presented reliability applications in design and maintenance planning of ships subjected to fatigue and corrosion. Based on a target reliability index, a comparative study was carried out considering fatigue of a critical joint based on S-N and fracture mechanics approaches. The fracture mechanics-based model presented slightly shorter inspection periods (5–10%) than that of the model based on a S-N curve. Camara and Cyrino (2012) reasoned this difference resulted from the crack initiation period not being taken into account in the model of fracture mechanics.

8.3.3 Reliability Based Inspections

Reliability based inspection relies on gaining experience from the initial and subsequent inspections. In this way, degradation patterns for probabilistic models can be constructed. These models are able to produce estimations and predictions about asset degradation and structural integrity at a specific time in the future. At the same time, the models are linked with the classification of the risks of this process and the consequences of failure to determine a more specific assessment and risk ranking. This practice is referred to as Risk Based Inspection (RBI) (Tammer and Kaminski, 2013). Tammer and Kaminski (2013) argue that the RBI methodology is a more comprehensive successor of Reliability Centered Maintenance methodology. The fundamental difference between the two methods is that reliability centered approach strives towards minimal loss of functional integrity of (mostly) dynamic equipment, while RBI deploys a directed inspection effort to the most critical components. It is important to recognize that seeking ways to relax inspection practices is not the goal of establishing an RBI program (ABS, 2003b).

There has been a body of research found in the literature discussing the applications of RBIs to ship and offshore structures (Lee et al., 2006, Bharadwaj and Wintle, 2011, Ku et al., 2012). Using the minimization of expected fatigue damage detection delay as the objective function, optimum inspection planning of ship hull structures subjected to fatigue was determined by Kim and Frangopol (2011). The study highlighted that an increase in the number of inspections and/or inspection quality can lead to reduction of the expected damage detection delay. Therefore, cost-effective inspection planning is important based on the Pareto solution front of the optimization problem. Kwon and Frangopol (2012a) applied the probabilistic approach to estimate fatigue reliability of aluminum ship structures and thus suggested life-time optimum inspection/repair. System reliability of a very large crude carrier structure under corrosion and fatigue was investigated by Kwon and Frangopol (2012b). Perisic and Tygesen (2014) investigated two cost effective load monitoring methods for fatigue life estimation of offshore platforms.

8.4 Design update based on lessons learned from analysis of failures

Lifecycle experience is an important factor in the updating and improvement of design codes. Update effectiveness is highly dependent upon an understanding of the operation and failure of earlier designs.

After a full scale experimental and numerical study, design pressures for fatigue of bilge keels of a class of naval vessels were found incompatible with those provided by the classification rules (Flockhart et al., 2010), which led to relevant class societies updating their rule set.

Another example is the United States Coast Guard's (USCG) project to assess fatigue design approaches for its new National Security Cutters (NSCs), known as the Fatigue Life Assessment Project (FLAP) (Stambaugh et al., 2014). To support the FLAP program, VALID Joint Industry Project (JIP) was formed by MARIN with multiple partners. The aim of the VALID project is to further improve the confidence in determining the wave loading leading to fatigue damage on a naval frigate type hull form and structure. This was achieved through the use of numerical predictive model for fatigue predictions (Hageman et al., 2014) and a model test program supported by dedicated full-scale trials (Drummen et al., 2014).

The key findings from the FLAP and VALID JIP projects relevant to the USCG that may have implications to design of future vessels are (Stambaugh et al., 2014):

- Fatigue life predictions using the traditional approach under-predict wave-induced fatigue loading by approximately 7%. Improvements are recommended to the traditional approach to fatigue damage from impact loading and whipping response.
- Uncertainties in the SFA process have been quantified on a sufficient level required for use in time varying fatigue reliability based assessments and sustainment evaluations.
- Conservative fatigue life estimates based on the standard S-N design curves are useful in fatigue design; however, forecasts of fatigue life must consider the large uncertainties in the operational environment, influence of the operator and the wide scatter of S-N data.

8.5 Discussion

Despite the above mentioned wide-spread application and use of Structural Health Monitoring data, it is important to recognize that there is still a considerable amount of effort required in the storage and handling of data. The analysis of such data presents significant challenges in the sense it requires steps such as filtering to remove noise, separation of high and low frequency responses, sampling techniques, statistical analysis. A typical SHM system will record in excess of hundred channels of data with sampling rates in the kHz range (Kiddy et al., 2002, Grassman and Hildstrom, 2003). For example, a sampling rate of 2 kHz is typically used if slamming associated data is required (Grassman and Hildstrom, 2003, Drummen et al., 2014). Drummen et al. (2014) reported that SHM data collected onboard NSC USCGC BERTHOLF is at a rate of 600 gigabytes per month and collected for a period of a full year.

L'Hostis et al. (2013) discussed the development of a fully automated advisory monitoring system for the fatigue of FPSO hulls as part of MONITAS II JIP. MONITAS I and II JIPS have demonstrated the need for detailed integration of the hull designer into the SHM design (Kaminski and Aalberts, 2010, L'Hostis et al., 2010). Understanding the FPSO hull design assumptions and embedding them into the data analysis tool is the only way to provide tools for fatigue management. It is argued that failing to do so during the project design phase (newbuilding or conversion) will lead into gigabytes of measured data that will probably remain untouched by and therefore useless to the operator (L'Hostis et al., 2013).

8.6 Conclusions

As was shown in Chapter 7, there are varying levels of maturity of different structural hull monitoring systems, varying from the conceptual design stage to proof-of-concept laboratory tests to wide-spread industrial applications. Use of the collected data is still limited but a wide range of efforts have been undertaken to develop and implement systems that take advantage of monitored data to guide operation and lifecycle management of the structure.

9. LIFE TIME EXTENSION, COMPARISON OUTSIDE & WITHIN THE MARITIME INDUSTRY

9.1 Introduction

This chapter describes the issues not specifically considered in the preceding sections. It covers the areas related to lifetime extension of existing structures, not meaning the repair actions. The second section covers the lessons that can be learnt from the other industries and the last section is devoted to the differences that exist between the approaches for ships, offshore structures and other marine applications, ranging from navy to renewable energies.

9.2 Lifetime Extension of Existing Structures

Lifetime extension is required when vessels or offshore structures need to remain longer in service than considered in their initial design. For this reason, HSE UK (Stacey et al., 2008, Stacey, 2011, Stacey and Sharp, 2011) and Norway's PSA (Ersdal et al., 2011) started projects on the lifetime extension need for offshore units. Stacey describes the issues that are important, such as improved monitoring and maintenance and better (internal) guidelines on how to treat ageing units. Ersdal points out that maintenance may be lacking, but especially the recording of it. When a mismatch exists between the expected conditions and the actual condition, risk for accident escalation is increased. Operators are to be prepared better for the potential risks, but in the meantime maintenance needs to be brought to a higher level, especially to cover increased needs of older installations.

For offshore installations, Risk Based Inspections are used successfully by different companies, e.g. Petronas (Nichols et al., 2008). The RBI methods are often used for jacket structures. Deep water access for inspection is costly and has safety risks. Available measurements and inspection data are combined with analyses to predict the condition for similar structural details. These methods are gaining attention from the floating platforms as well (Landet et al., 2011). In this paper 4 FPSOs are analysed according the RBI methods outlined in NORSOK N-006. As the idea behind may be rather straight forward, the actual implementation on ship shaped structures is very complex.

For vessels, lifetime extension is more an evaluation of whether the vessel might be operated after the next survey or not. Caridis (2014) compiled a comprehensive book on the various options, issues and solutions available today.

The appropriate acceptability criteria of the structure and maintenance strategy need to be made clear in order to facilitate life extension analysis. Various papers have been published to show the effect of defects (either corrosion or cracks) on the structural integrity (Gao et al., 2012, Tran Nguyen et al., 2012, Tran Nguyen et al., 2013). It is noted that the rules and criteria may have changed over the years of service, giving additional challenges. For jackets, it has been shown that an update of the rules may increase the projected lifetime (Jia, 2008).

The objective of a re-assessment and life extension of an existing structure is to establish that the structure is fit for its intended purpose over the residual service life, and that the consequences in terms of risk to human life, to the environment and to the assets, in the event of structural failure, are acceptable from both a reliability and an economical point of view.

The most common reason for re-assessment is uncertainty about the safety of the structure and the assessment process is focused towards reassuring that the structure has adequate safety. The interpretation of "adequate" may be discussed, since it can be understood as simply fulfilling given code requirement or as determining the consequences and associated probabilities for different failure events and evaluate these against acceptance criteria. Other reasons for re-assessment may be doubts about the durability, the serviceability or the functionality of the structure.

The assessment process will typically include or be based on:

- documentation of as-is condition,
- planned changes and modifications of the facility,
- calibration of analysis models to measurements of behavior if such measurements have been performed,
- history of degradation and incidents,
- prediction of future degradation and potential incidents based on history,
- the effect of degradation on future performance of the structure,
- documentation of technical and operational integrity,
- planned mitigations,
- plan or strategy for maintenance.

The assessment for life extension should conclude with a safe life extension period with respect to technical and operational integrity of the facility. The assessment should also identify the circumstances that will limit the life of the facility without major repairs or modifications, and specify criteria defining safe operation (e.g. permissible cracks lengths, permissible corrosion or remaining thickness, remaining anodes, degrading of paint protection, subsidence), including appropriate safety factors.

An example of the assessment process is illustrated in the flow sheet shown in Figure 4. (NORSOK, 2009). The flow sheet may be followed for assessment of all groups of limit states (ULS, SLS, ALS and FLS). Structural analyses for assessment may be performed provided that a sufficient data basis for performing reliable analysis is available. Then the safety level of the structure can be assessed and it can be decided if mitigation is required. An analysis, in this case, is an engineering process that can imply assessment based on simple hand calculation or more refined structural analysis.

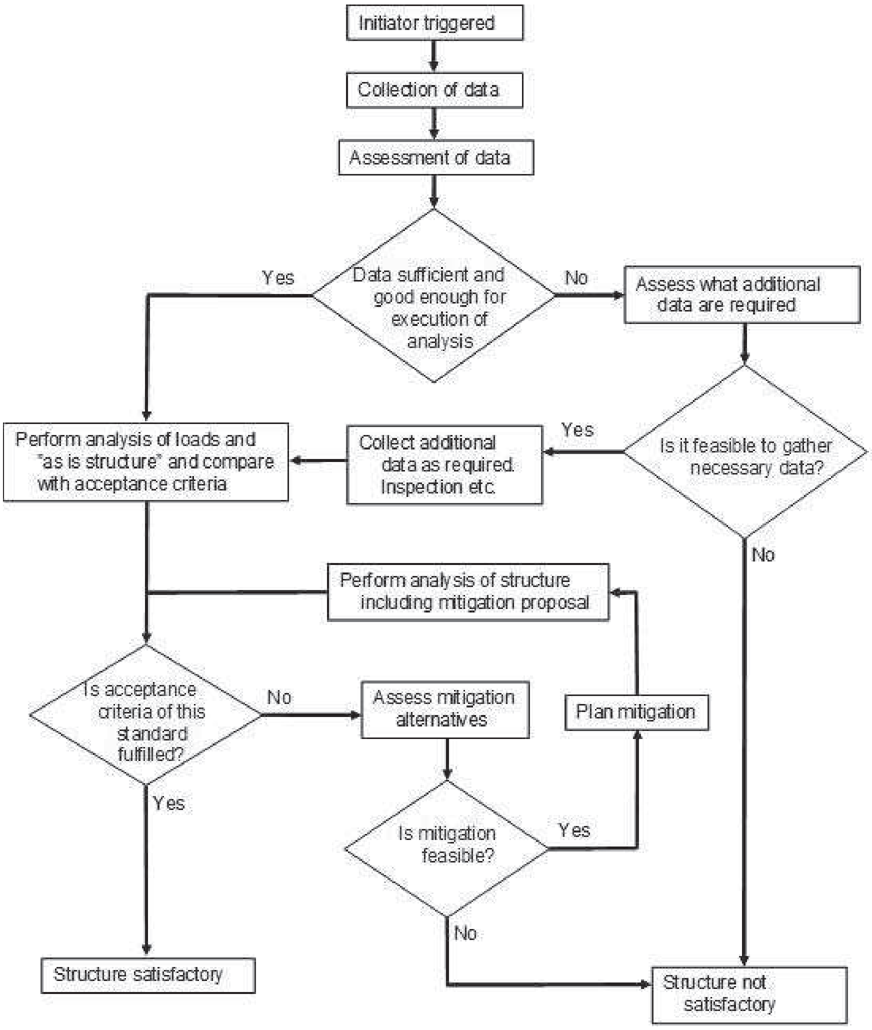

Figure 4. Flow sheet of the assessment process (NORSOK, 2009)

A plan for mitigation as indicated in the flow sheet in Figure 4involves:

- A plan for the mitigation itself
- Documentation
- Plan for maintenance after mitigation

Examples of circumstances or initiators that may trigger a need reassessment are as follows:

- Changes from the original design or previous assessment basis, including
  - o modification to the facilities such that the magnitude or disposition of the permanent, variable or environmental actions on a structure are more onerous,
  - o more onerous environmental conditions and/or criteria,
  - o more onerous component or foundation resistance data and/or criteria,

  - physical changes to the structure's design basis, e.g. excessive scour or subsidence, or relocation of mobile offshore units to a new location and,
  - Inadequate deck height, such that waves associated with previous or new criteria will impact the deck, and provided such action was not previously considered.
- Damage or deterioration of a primary structural component: minor structural damage can be assessed by appropriate local analysis without performing a full assessment. However, cumulative effects of multiple damages should be documented and included in a full assessment, where appropriate.
- Exceedance of design service life, if either:
  - the remaining fatigue life (including design fatigue factors) is less than the required extended service life, or
  - Degradation of the structure due to corrosion beyond any design allowances has occurred, or is likely to occur within the required extended service life.

Existing design documentation can be applied as basis for the assessment if inspection of the structure shows that time-dependent degradation (i.e. fatigue and corrosion) has not become significant and that there have been no changes to the design criteria (any changes to the original design basis are assessment initiators, see a) above). This requires that in-service inspection has been performed to document a proper safety level.

A structure which has been totally decommissioned (e.g. an unmanned facility with inactive flow lines and all wells plugged and abandoned), or a structure in the process of being decommissioned (e.g. wells being plugged and abandoned) generally does not need to be subjected to the assessment process unless its failure has consequences for nearby facilities.

9.3 Other industries

Leadership in the technology of structural longevity has come from the aerospace community for decades. For example, the US Air Force has developed, beginning in 1958, a methodology for using structural health monitoring of aircraft through the Aircraft Structural Integrity Program, which is intended "…to achieve structural integrity in USAF aircraft while managing cost and schedule risks through a series of disciplined, time-phased tasks," (US DOD, 2005). The program uses a damage-tolerant, fail-safe philosophy that incorporates a surveillance program that is based on allowable damage limits and damage growth rates for all observed defects in aircraft structure. This philosophy requires detailed finite element analysis to reveal probable locations of fatigue crack initiation, analysis of detected cracks to assess anticipated growth rates, and updating the analyses based on observed crack growth rates and changes in aircraft operations. The program incorporates risk analysis to assist in developing inspection times, evaluate options such as repair versus modification, and to operate aircraft beyond the design service life. Extensive research has been conducted into using instrumentation to monitor cracks. Also Paul Hoffman (2009) describes naval aircraft where fatigue loading is closely monitored in conjunction with probabilistic assessments of strength and failure detection. As a naval aircraft is relatively small and relatively well monitored such an approach is feasible.

The structural longevity of civil engineering structures, particularly bridges has become increasingly important. For example, over 20 percent of railway bridges across Europe are metallic, 70 percent of them are over 50 years old, and 30 percent of them are over 100 years old. As a result of this, multiple communities have developed with regular meetings to share information. For example, the International Association for Life Cycle Civil Engineering (IALCCE) started in 2006 and meets bi-annually and is supported by the journal Structure and Infrastructure Engineering: Maintenance, Management, Life-cycle Design and Performance (Editor-in-Chief: Dr Dan Frangopol, published by Taylor and Francis) in which appropriate civil structural research is reported, but with some coverage of other platforms such as ships and offshore structures.

Reinforcement of degraded civil structures with composites is being done to compensate for loss due to corrosion, provide strengthening to reduce fatigue crack initiation, or to increase the load-bearing capacity of the structure. A consortium of fifteen organizations from eight European countries was formed in January 2007 to explore composite patch repair for marine and civil engineering infrastructure applications (CO-PATCH, 2013).

Monitoring of bridge structures is being done to assess the load profile, determine stresses in the structures. Technology development is being pursued to detect cracks in bridge structures, particularly in areas that are difficult to inspect. An example of this is provided by Inaudi (2009) who reported on the use of fiber-optic sensors to monitor bridges.

9.4 Differences in approaches for ships, offshore structures, and other marine structures (ranging from navy to renewable energies)

Ships may be active in international trade, but also operate in offshore support activities. These units typically have regular inspections, have recorded routes and face limited exposure as they can be in harbor, sailing in benign waters and use weather routing. They also may be exposed to extreme conditions, with loading closer to their design values, including polar conditions. The condition of the structure is heavily dependent upon the care the owner gives to the unit. Defects are typically repaired in controlled conditions.

Offshore structures, considered to be stationary off the coast, may experience fiercer loads, especially in the more harsh areas. Rough conditions may refer to extreme wind, high waves and low temperatures. Maintenance and repair are harder to execute, due to the operational limitations. Challenges include the ability to execute hot work as well as limitations on the amount of people you can take on board to do the work. The activities associated with inspections start with preparation such as staging and cleaning. The inspection itself may require different techniques to be applied (MPI, CVI, X-ray, eddy current), while working at heights or deep under water. This means the variety of workers and effective working time is limited by the safety precautions and inaccessibility. Together, this means that the drive to limit inspections and maximize the use of it is mainly driven from offshore.

Other marine structures are those that are none of the above categories such as naval vessels and the renewable energy installations. The maintenance and loads are different from any commercial standard, although there is a trend to class naval vessel under commercial class societies. Further, due to budgetary constraints, there is an increasing need to extend the life of navy vessels, far beyond the lifetime as originally planned. Load measurements and defect analyses are popular ways to justify lifetime extension.

Renewable energy installations are very new and range from wind turbine generators installed offshore to tidal energy converters and current driven turbines. For tidal energy converters, the current must be high to be effective. In such case the maintenance and inspections are very difficult to carry out. This topic should surely come back in the next ISSC.

These approaches result in areas where differences are found:

- Inspection scheme: The rules prescribe inspection schemes and intervals. For ships (DNV, 2014), there are, for instance, intervals of 2.5, 5 and 15 years. Each interval comes with a prescribed scope of survey. For offshore units, continuous survey can be opted for (ABS, 2003b). In such case the inspections can be staggered and done at convenient times. For offshore units, the underwater inspections are required to avoid dry docking. For ships this is getting more popular as well and it is included in the vessel rules (ABS, 2014d), however it is not an operational requirement.
- Repair requirements: Ships are required to have anomalies repaired and can face lay-up to enforce repairs. For offshore units, anomalies can also result in conditions of class. Unsatisfactory resolution ultimate may lead to cease of operation and abandonment. Class and owner will work together to avoid this (Newport et al., 2004).
- Reported anomalies: Ships may face different kind of defects, ranging from corrosion, to fatigue, buckling to impact damage. As a sailing unit, the variation in loads is large. For offshore units, loads are more concentrated. It means that waves may hit the unit form a predominant direction or at a predominant waterline level. The extremes may be larger, resulting in green water as a destructive load. Ships however, are more prone to slamming or impacts with other vessels. Several monitoring projects have been launched to get a better view on the loads experienced by offshore units, vessel and naval platforms.

9.5 Conclusions

When it comes to extending the lifetime of an existing ship or offshore structure, improved monitoring and maintenance methods receive greater attention. Risk-based inspections and other assessments of structural integrity are carried out, including fatigue analysis and assessment of corrosion and other structural damage. A plan is formed to mitigate the effects of the damage, including structural modifications and repairs.

Other industries and organizations, such as the US Air Force, have more organized and documents programs to ensure structural longevity. The structural longevity of civil engineering structures, particularly bridges has been subjected to more analysis, and measures such as reinforcement with composites has been done to some of those structures. New offshore structures for energy collection, such as wind turbines and tidal energy converters should receive more attention in assessment of structural longevity.

10. CONCLUSIONS & RECOMMENDATIONS

10.1 Conclusions

The purpose of this newly formed 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, 3, and 9 describe the importance of structural longevity from different perspectives. Chapters 4, 6, and 7 describe the information gathered and knowledge needed in order to support an understanding of structural longevity. The use of this information for operational and maintenance activities is covered in Chapters 5 and 8.

From this work, 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 lifecycle fatigue analysis, but there is little indication that the results of such studies have been integrated into lifecycle 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:

- In comparison to the aerospace, chemical processing, and nuclear power industries, the maritime industry is not as prolific in its uptake of lifecycle assessment and management, and may require organizational culture change for their general adoption.
- The goal-based standards of the International Maritime Organization, which apply to all international-trading vessels, are enforced though the rules of classification societies, resulting in a class survey system that is nearly identical for all vessels, and is the main basis for how structural longevity is handled by vessel owners today.
- The design phase is the optimal time to incorporate measures that ensure the desired longevity of a structure, with the additional cost spent at the design/construction stage much less than the cost of repair.
- Bonded repairs are becoming an attractive alternative to welding based repairs. Although currently considered to be temporary repairs, ongoing research is aimed at improving the methods of fabrication and materials so that these can become permanent repairs.
- Strategies for inspection of structure must consider factors such as probability of detection, cost of inspection, risks of structural failure if damage is not found, and avoiding costly inspection and maintenance that could result in unintended and expensive downtime.
- A variety of sensing technologies, both active and passive, for the detection of structural damage are becoming available, including sensor networks that can integrate various measurands of interest and collect them effectively, with data-feature extraction and statistical pattern recognition.
- Structural health monitoring systems on ships and offshore structures have the potential to provide real-time guidance of structural loading trends and advise on the possibility of an extreme loading condition, including slam avoidance. These systems can also obtain real-time operational data on long-term fatigue loads experienced by the ship structure, so that this information can be used to estimate future fatigue life.
- Many operators have now implemented a structural integrity management system in order to ensure safe operation of the asset throughout the service life of the structure, beginning at the design phase with a risk-based inspection plan that will be updated as the conditions of the asset changes due to modifications, unplanned events, or extension of the service life...
- It is very desirable to develop coatings that can provide corrosion protection but also include possible early detection of corrosion through the use of smart coatings that can sense corrosion and respond.

10.2 Recommendations

This committee report describes elements important to structural longevity, building upon past ISSC committee efforts. The future for this committee and topic area rests on the ability to capture and integrate the aspects that will grow in importance for the prediction and assurance of structural longevity such as uncertainty quantification and management, on-board monitoring and inspection, effective use of collected data, and integration of knowledge gained by collected data in asset management and operation.

- On-board hull instrumentation systems as required by regulatory bodies and classification societies should be developed and deployed as lifecycle structural management tools that consider the holistic aspects of application of a life extension assessment on an asset.
- Structural health monitoring systems have been actively studied, but laboratory proven SHM techniques need to be expanded to address real structures, with more full-field testing of the system to develop their full maturity. Further development of on-board instrumentation to detect structural damage should be encouraged, including trial installations of operating ships and offshore structures to prove out the technology.
- Past and future operational environment and operating conditions needs to be known as well as the fatigue parameters of the materials and an appropriate fatigue model for use in calculating the useful fatigue life of the asset.
- Further research is needed to develop optimum inspection strategies that will safeguard structural longevity but minimize cost and disruption of service.
- Smart coatings that can sense corrosion and respond could be further developed to provide prolonged corrosion protection and at the same time monitor damage and detect and/or repair damaged coatings.
- Repair of structure with composite patch repairs need further exploration and evaluation aimed at developing systems for permanent repairs.
- Surface layer with Ultra-Fine grained microstructure (SUF) materials could provide for crack arrest and should be explored.
- New offshore installations are being rapidly developed in the renewable energy sector and their long-term lifecycle needs should be considered as an extension of ship and traditional offshore structures, specifically wind turbines, tidal energy converters, and current-driven turbines.
- Ship breaking and platform removal are costly enterprises that influence decisions on structural longevity and should be explored further

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