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COMMITTEE V.6

CONDITION ASSESSMENT OF AGED SHIPS AND OFFSHORE STRUCTURES

COMMITTEE MANDATE

Concern for the assessment of the serviceability and safety of aging ships and offshore installations. This shall include reliability-based assessment of age-related structural degradation, inspection, maintenance and repair. Consideration shall be given to cost-benefit and risk-based decision procedures.

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KEYWORDS

Condition Assessment, Corrosion, Cracking, Fatigue, Deformation, Reliability, Nondestructive Examination, Condition Monitoring.

CONTENTS

1. INTRODUCTION

This is the third occasion that the ISSC has established a special committee to address the issue of structural integrity of aging structures. The current 2009 Committee V.6 on Condition Assessment of Aging Ship and Offshore Structures continues the work of the 2006 Committee V.6 on Condition Assessment of Aged Ships (ISSC 2006a), and 2003 Committee V.2 on Inspection and Monitoring (ISSC 2003).

This report intends to

- Define the issues related to structural degradation,
- Review the latest research on condition assessment, and
- Provide guidance about further research and development.

The report includes the following chapters:

- Chapter 1 Introduction
- Chapter 2 Age-related structural degradation
- Chapter 3 Condition assessment of ship structures
- Chapter 4 Condition assessment of offshore structures
- Chapter 5 Application of structural reliability approaches
- Chapter 6 Corrosion wastage and coating degradation
- Chapter 7 Consequence prediction of fatigue
- Chapter 8 Conclusions and recommendations

Chapter 2 describes the structural degradation mechanisms that may pose threats to the structural integrity of aging steel structures. This chapter also provides the background about the problems the Committee is assigned to cover. Chapters 3 and 4 summarize the current industry practice and emerging trends of condition assessment. Current practices of the Navy ships and offshore industry are discussed. Descriptions are given of the concept and methodology of structural integrity management (SIM) and risk-based inspection (RBI). Chapter 5 is devoted to structural reliability approach, which is a core technology that has been used and will continue to be used in assisting condition assessment. Chapters 6 and 7 discuss the research and development on corrosion, coating and fatigue. These are the major degradation mechanisms that have seen many research activities in recent years. Each of the Chapters 2 to 7 concludes with a list of recommendations for further studies related to the topics within each chapter. Chapter 8 summarizes the entire report, which lists key topics this Committee feels that will require greater focus of future research and development.

Condition assessment calls for knowledge of a wide range of issues and the processes used in which these issues are addressed. This report places focus on these items: how the industries assess structural conditions, how the industries develop best strategy for performing inspection, and mitigating the consequences of degradations. Over the years, ISSC Committees have covered extensively, and will continue to do so, the fundamental research and theory related to environment, loads, structural responses, design methodology, analysis and evaluation, and design principles. The reports of these ISSC Committees are also helpful in understanding the development and trends of condition assessment.

2. AGE-RELATED STRUCTURAL DEGRADATION

2.1 Statistical information on aging of hull structures

Structural damage is known to be a major contributing factor to marine incidents. As shown in a recent study (Fig. 1.1) on total vessel losses during 1997-2006, the hull damage ranks the top five causes leading to total vessel loss for vessels greater than 500 GT.

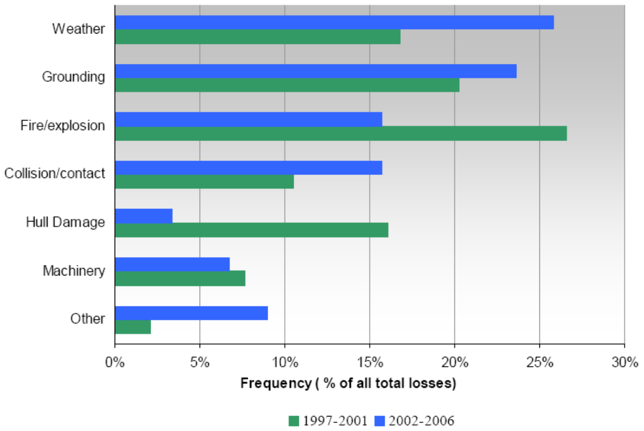
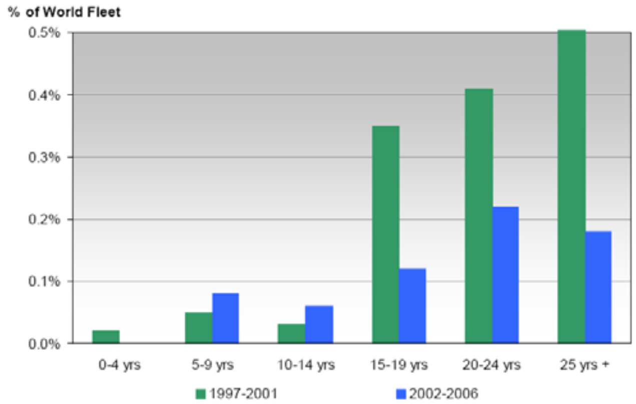


Figure 1.1: Total losses by causes for all vessel types greater than 500 GT (Sources: International Union of Marine Insurance IUMI).

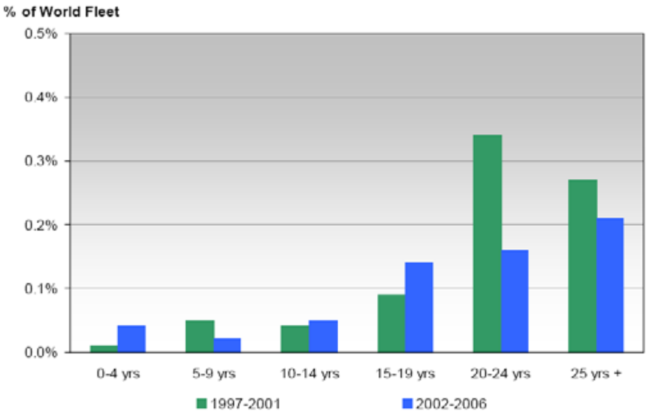
Aging has been perceived to be an important factor in hull damages. Statistical analyses of total losses of tankers and bulk carriers (Fig. 1.2) reveal the increasing trend of vessel losses tied to the age of the vessels.

Statistical analyses of past incidents have been utilized to uncover evidence regarding the effects of aging. However, interpreting the results of statistical analyses remains a challenge. Care needs to be taken when one attempts to predict the future based on past experiences. For example, Fig. 1.2 shows that the increasing trend of vessel loss with vessel age is reversed in the age group of 25+ years old. This reverse trend is difficult to explain if one does not take into account the fact that many vessels are removed from service before reaching the end of their design life, normally 20 to 25 years.

Statistical evidence from various sources does not always show the same trends. The previous ISSC Committee mentioned that the average age of vessels lost was only slightly more than the average age of the existing fleet. This implies a weak aging effect, which is contrary to the trend shown in Fig. 1.2. Another source of information about the aging effect is the detention of vessels by the port state control (PSC). A ship can be detained if found not complying with PSC requirements. While such noncompliance is usually not severe (i.e., would not potentially lead to loss of the vessel), it may indicate less favorable hull conditions. The detention rate is higher in older vessels, which also partially reveals the aging influences.



(a) bulk carriers
(b)



(b) tankers

Figure 1.2: Total losses of tankers and bulk carriers greater than 500 GT
(Sources: International Union of Marine Insurance IUMI).

2.2 Various forms of structural degradation and damage

Aging of ship structures may be defined as the progressive deterioration of structures as a result of normal operational use and environmental influences. The structural deterioration comes in the following forms:

- Coating damage
- Corrosion
- Cracking
- Deformations (dents), and
- Changes in material properties.

Coating damage

Coating degradation can take the form of coating cracking, blistering, rust and flaking. Coating cracking takes place when structural deformation exceeds the elongation of the paint film. Blisters appear where an adhesion of the paint is locally lost. Blisters contain liquid, but there is no corrosion under the blister. Flaking refers to the lifting of paint from the underlying surface. The loss of paint adhesion is often a result of unsatisfactory surface preparation, incompatibility with under-layer and contamination between layers.

Corrosion wastage

Corrosion is the result of a chemical reaction between metal and the environment (water, cargo or consumables). Corrosion takes the form of general corrosion, pitting corrosion, stress corrosion cracking, corrosion fatigue, microbiological corrosion, galvanic corrosion, erosion corrosion, etc. (Boon *et al* 1997). General corrosion, which is the most common form of corrosion, spreads evenly over the surface of the metal. Pitting corrosion, which is localized corrosion, is often seen on the bottom of cargo oil tanks or in the hold structures of bulk carriers carrying coal and iron ore. The shape of the pits depends on the surrounding environment (Yamamoto 2008a). Microbes (bacteria) can cause corrosion, even on stainless steel, due to their corrosive waste products. The most common bacteria are sulphate-reducing bacteria (SRB) and acid-producing bacteria (APB). SRB cause corrosion under anaerobic conditions. Specific combinations of alloy and environment can lead to stress corrosion cracking when the metal is mechanically stressed while being exposed to the corrosive environment. Galvanic corrosion occurs when two electrochemically dissimilar metals are physically connected and exposed to a corrosive environment. The less noble metal (anode) suffers accelerated corrosion attack. Erosion corrosion is usually caused by flowing fluid (water, cargo oil, etc) impinging at an existing corrosion cell. This kind of attack is dependent on the degree of liquid turbulence and velocity. In addition, corrosion may be aggravated in local areas of high stresses.

Rust is a corrosion product of an oxide and hydroxide generated to the surface of metal.

Since the initial rust is porous and hygroscopic, the range of rusting expands and the paint film is destroyed. Rust is generated from the part where an adhesion of paint film is insufficient and a paint film is broken.

Many factors contribute to the degradation of coatings and corrosion. These contributing factors are: type of cargoes (acidity of the cargo), frequency of ballasting, frequency and method of tank cleaning, trapped water or oil, oxygen concentration, sulphur concentration, salinity of ballast water, temperature, humidity, pollution, trade route, structural flexibility, corrosion protection effectiveness, marine fouling, corrosion films, speed of flow, stray-current, cargo residues and mechanical abrasion, maintenance and repair, material of construction, microbial attack, sludge/scale accumulation, etc. (Gardiner *et al* 2003, Hu *et al* 2004, Panayotova *et al* 2004, 2007, RINA 2004). Theses factors act individually or in combination, and their influences are difficult to quantify. As a result, corrosion wastage of structural members is dependent on the location of the member (IACS 2005, Wang *et al* 2003a, 2003b, Yamamoto 2005, Paik and Melchers 2008).

Cracking

Cracks often originate from defect of welds. Impact from a dropped object or accidental overload may also potentially lead to initiation of cracks. If such initial cracking is left undetected and / or not repaired immediately, it can grow into a crack that continues to propagate under repeated loads, hence enter the aging regime. In addition, brittle fractures have contributed to some marine incidents.

Mechanical damage, wear and tear

Ship structures may be damaged by external forces such as falling cargo, impact with the quay, repeated roll-over by wheels of vehicles (RoRo vessels), impact of ice and floating objects, etc. Generally, these actions will result in dents. With repeated loadings, dents may gradually continue to increase in size.

Some recent research was focused on ultimate strength of dented plates (e.g., Paik *et al* 2003, Nakai *et al* 2006, 2007). Simple design formulations were derived based on regression of calculated ultimate strength using nonlinear FEM. Often, a dent is idealized as a conical shape in the analysis. The reduced strength is expressed as a function of geometrical parameters representing the dent.

If deformations are found during inspection, the severity of the deformations is assessed against set criteria. Deformations measuring up to 50 mm may be considered as not detrimental to the structural safety, depending on the conditions of the structures surrounding the deformed structure. At present, there are no formalized acceptance criteria regarding allowable permanent deformation. In some limited cases, the shipbuilding industry has certain provisions for allowable permanent deformations; but for most cases the allowable permanent deformations are the result of balancing between safety needs and commercial demands (Wang *et al* 2006).

Wear and tear can be in the form of sliding wear and friction, low and high-stress abrasion, dry particle erosion, slurry erosion, etc. Wear and tear is usually described as thickness loss, and recorded accordingly in some survey reports. There are some studies related to the wear characters of low-carbon steel, stainless steel, metal alloys and weld joints. Modeling of wear mechanisms needs to consider the material's hardness, the shape and size of abrasive grit or roughness, attack angle, normal applied load, sliding speed and the fracture toughness of material.

Changes of material properties

In general, the material properties of metals do not change with time.

Interaction of different degradation mechanisms

Corrosion and crack propagation can take place simultaneously. Crack propagation in corroded structures can be accelerated because the stresses in the structure increase as a result of corrosion wastage. Hydrogen cracking in anaerobic conditions may be strongly influenced by SRB. This cracking proves onerous for high-strength steels such as those used in the legs and spudcans of jack-ups. Mud and sludge in cargo oil tanks may provide the right circumstances for microbially influenced corrosion and resulting crack initiation (Rauta 2004).

Local dents are often the area initiating cracks. Removal of corrosion may be accomplished by scraping it off with the use of track-mounted cranes on a work deck. This scraping off process may significantly increase the loss of thickness initially caused by corrosion. Increased strains due to higher stresses as a result of thickness diminution or crack forming in combination with unaltered loads may stimulate corrosion.

Mechanical damage to cargo hold structures of bulk carriers

Deformations are often observed in the lower portion of cargo holds of bulk carriers, including inner bottom, lower bracket of hold frames, sloping bulkheads, and lower portion of transverse bulkheads. Plating and stiffeners are set in between supporting members of floors and girders. Hold frames undergo sideways tripping. Mostly, these damages take place during the loading and unloading process as a result of cargo handling grab and dropped cargos. Since the mid-1990s, bulk carrier design rules specify that additional thickness allowance be provided to the inner bottom and structures in the lower portion of cargo holds.

Ice damage

Ice damage to ship structures can be identified as dents (local deformation), fractures, scratch, loss of painting, deformed bilge, and/or small gashes. A recent statistical study (Hänninen 2005) showed that among the hull damages to ships sailing in winter Baltic Sea, 30% of the damage was to hull structures, 35% was to propellers, and 25% was because of ship collisions when navigating in ice.

Often, such information of ice damage is used to determine the design ice loads. For example, the ice loads specified by the Finnish-Swedish Ice Class Rules (FSICR) were based on statistics of historical ice damages. The recent updates on FSICR (FMA 2003a, 2003b, 2004) were also partly triggered by the improved knowledge of ice damage.

Contact damage

During berthing operations as a ship comes alongside a pier, the ship may come into contact with the other structures exposing the side structure to very large local loads, thus resulting in local contact damage. Contact damage to side structures takes place in the form of local denting of plating between stiffeners, permanent deformation or local buckling in side longitudinals or frames, and local buckling in web frames and decks, or fractures.

The latest IACS Common Structural Rules (CSR) introduced a requirement of side shell thickness based on consideration of contact damage (IACS 2005, Wang *et al* 2006). In general, however, the mechanism of a contact event is less understood, and contact damage receives only limited attention in design rules and research studies.

Accidental damage due to collision and grounding

Accidental damage is typically caused by collision and grounding, which results in structural damage in a larger extent compared with contact damage. Collision and grounding and the residual strength of damaged structures can be found in ISSC 2006 V.1 (ISSC 2006c).

2.3 Measures for mitigating structural degradation

Design and operational measures have been in place to mitigate the impact of age-related degradations.

The focus of the design and shipbuilding stage is placed on reducing the likelihood of aging effects while considering production cost (Lee *et al* 2004). These measures include: explicitly implementing corrosion additions to structural design, improving fatigue detail designs, applying coatings and installing anodes to corrosion-prone areas (Hansen *et al* 2004), and using wear-resistant steel or anti-corrosion steel in some cases (Satoshi *et al* 2005).

Once the ship is delivered, the focus is switched towards the following: inspection and maintenance, timely and adequate repairs, crew training, imposing limits to cargo loading/unloading procedures with an aim to minimize unfavorable impacts on structures (e.g., Brooking *et al* 2004).

Options for mitigating the mechanical damages to bulk carriers include using less invasive cargo-handling grabs and proper operation of cargo handing equipment.

In the case of an offshore supply vessel (OSV), preventing or mitigating contact damage risks can be achieved through: 1) reducing the likelihood of an unwanted contact from occurring; 2) mitigating and minimizing damage to hulls if an unintended contact takes place, or both (Wang *et al* 2006). Reducing the likelihood of an unwanted severe contact can be achieved through these practices: better manning the OSV through training and education of crew, establishing operation procedures and guidance, installing advanced vessel maneuvering and control systems (e.g., dynamic positioning systems, controllable pitch propellers, azimuth thrusters, bow / side thrusters). In addition to the above remedies, structural reinforcement against the anticipated impact load is aimed at providing strength reserve against a certain level of impact energy that is usually expected during a routine operation. Normally, half-split steel pipes are installed as fixed structures at the deck levels of the OSV so that impact loads are distributed to a wider extent, and/or the main hull structures are not directly exposed to the impacts load. These half-split steel pipes, sometimes called “fenders”, can also absorb impact energy. As a rule, this reinforcement applies to some specified location, as OSVs generally come alongside and berth at designated locations.

2.4 Recommendations

Statistical investigations of marine incidents and structural damage should focus more attention on the consequences of ageing. In addition to collecting data, care should be taken in properly interpreting the trends revealed in such analyses.

Aging ship structures in particular are likely to suffer from wide-scale damage including corrosion wall thinning, pitting and multiple fatigue cracks. It is recommended that research and development efforts be employed to consider the interaction of such wide-scale damage and that maintenance schemes be developed for addressing the cumulative effects of wide-scale damage.

There is little understanding of the residual strength of damaged components, particularly in structures exhibiting appreciable amounts of redundancy. In order for risk-based methods to develop, criteria for assessing the residual strength and accidental limit states of aged structures need to be understood.

As the number of aging ships and offshore structures increase, it will become increasingly important to develop cost-effective repair and mitigation techniques. It is recommended that more effort be focused on developing and proving repair solutions, particularly for life extension.

This report has not considered ultra-high-cycle fatigue, a problem often associated with high speed aluminum vessels. It is recommended that the next committee deal with this topic in some detail.

The Committee recommended more attention be paid to the following issues, which remain less studied: cause and growth of groove corrosion, dent and the associated permanent deformation criteria, brittle fracture, and interaction between various aging mechanisms.

3. CONDITION ASSESSMENT OF SHIP STRUCTURES

This chapter is an update to the previous 2006 Committee report. Other comprehensive reviews of current practices can be found in Rizzo *et al* (2007), Paik and Melchers (2008), Rizzo and Lo Nigro (2008), latest updates of TSCF publications and IACS Unified Requirements Z Group.

3.1 The inspection regime

Table 3.1 attempts to summarize the current inspection regime, including mandatory surveys required by classification societies, flag states and port states, and voluntary/recommended inspections carried out for operational and commercial reasons. While there seems to be a considerable amount of overlapping between mandatory and industry-driven inspections, classification societies play a major role in the inspection regime, performing statutory surveys in addition to class required surveys, and offering consulting services (e.g., CAP) for some types of ships.

Recent analyses of the maritime inspection regime (Knapp and Franses 2006, Rizzo and Lo Nigro 2008) concluded that more frequent inspections do not necessarily decrease the possibility of marine incidents, but rather, the quality of inspections play a key role in maintaining adequate structural integrity. This is in contrast to the general tendency towards requiring more frequent inspections.

Table 3.1
Ship inspections

Organization	Regulation, rule, guidance	Survey	Inspection area & item	Applicable ship types
IMO	International conventions and class rules (mandatory)	Initial, Annual, Intermediate, Periodical/Renewal	Safety, pollution and load line ISM, ISPS	All type of ships
Classification societies			Hull and machinery	
Port state	Memorandum of Understanding	On purpose (targeting of ships)	Hull and machinery Safety, pollution, load line	

Flag state	National regulations	Initial, occasional, periodical		
Insurance company (including P&I Clubs)	Insurance / P&I requirements	Insurance inspections	CAS / ESP (mandatory)	Tanker, bulk carriers (mainly)
Terminal operators	Local regulations and procedures	Safety & pollution prevention survey	Cargo handling and equipment, procedures, loading master	Oil & chemical tanker, bulk carriers, gas carriers
Cargo owners	Commercial requirements	Charterer/vetting (oil majors, CDI, OCIMF/SIRE, etc.)	CAP, cargo operation and management, survey on purpose, risk-based analyses	
Ship owners / managers				

Notes: CAS - Condition Assessment Scheme, ESP - Enhanced Survey Program, CAP - Condition Assessment Program, ISM - International Safety Management, ISPS - International Ship and Port Security

3.2 Performance Standard for Protective Coatings, Goal-Based Standards and Common Structural Rules

The IMO Performance Standard for Protective Coatings (PSPC), IMO Res. MSC.215 (82), became effective on 8 December 2006 for CSR vessels. The impact of IMO PSPC and the accompanying IACS Procedural Requirement (PR) 34 has brought an immediate and profound impact to the shipbuilding industry. The long-term impact on the entire industry, from shipbuilding, ship operation to ship recycling, is yet to be seen.

The IACS Common Structural Rules (CSR) was developed as a design code. CSR explicitly states that inspection and maintenance are prerequisites to the applicability of these rules.

To what extent or whether or not the IMO Goal-Based Standards (GBS) will impact the survey practice remains to be seen. Expectedly, procedures of survey and inspection will become more quantitative and less experience based (Rizzo *et al* 2007, Rizzo and Lo Nigro 2008).

3.3 Inspections by owner, charterer, and insurance company

The IACS PR 33 states that Owner's Hull Inspections and Maintenance Schemes are encouraged as a means of maintaining compliance with classification and statutory requirements, but are not considered alternatives to mandatory requirements. Major classification societies have published guidance for the implementation of IACS PR 33. Some provide software tools (with Internet access capability) to assist owners in planning inspections and storing data of vessel conditions. See Table 3.2. INTERTANKO, INTERCARGO, OCIMF and ITOPF (International Tankers Owners Pollution Federation) have developed advice and notes relevant to the inspection by crew and superintendents. An overview of vetting inspections is described by Intertanko in their Guide to Vetting process. In addition, there is an emerging trend of using FEM models to re-assess structural integrity, which would potentially lead to improved CAP. Ideally, this re-assessment is based on the FEM models built during design verification stage (such as IACS CSR or Žanić 2007) with the structural scantling reflecting the latest thickness measurement results.

Table 3.2
Guidance and software provided by classification societies to assist inspection

Class	Guidance for qualified inspectors	Hull monitoring guidance	Online access of inspection record	Software for assisting inspection and data management	Features of software
ABS	Yes	Yes	Yes	Safenet, Hull Maintenance Model, Hull Inspection and Maintenance Program	3D virtual ship model, HIMP
BV	Yes	Yes	Yes	VeriSTAR Hull 5	3D FE model
CCS			Yes	Compass	
DNV	Yes	Yes	Yes	Nauticus, Exchange Hull Inspection Manual	3D FE model, CAD database inspection planning
GL	(PSC checklist)	Yes	Yes	Poseidon, Pegasus, ShipManager	3D FE model, gauging records automation
LR	(PSC checklist)	Yes	Yes	ClassDirect Live, ShipRight, Hull Integrity	3D FE model, ship-specific hull inspection checklists
KR	Yes	Yes	Yes	InfoShips, SeaTrust	3D FE model
NKK		Yes	Yes	PrimeShip-HULLCare	3D FE model, CAD database inspection planning
RINA	(PSC checklist)	Yes	Yes	Leonardo Hull	3D FE model
RS				Ruslan	3D FE model

3.4 Nondestructive examination and condition monitoring technology

Nondestructive examination/testing (NDT) and monitoring technologies, such as ultrasonic thickness measurement (UT), magnetic particle inspection (MPI), vibration measurement and strain measurement, are used to assist in condition assessment (see e.g., Hu and Prusty 2007). Review of corrosion measurement and monitoring can be found in Panayotova *et al* (2007), ABS (2009).

The cost-effectiveness of inspection leads more and more to automation of procedures. An example is the Automated Ultrasonic Testing technique (Dijkstra and De Raad 2006). Kalra and Gu (2007) proposed an autonomous self-contained, wall-climbing robot for nondestructive inspection of storage tanks; Negahdaripour and Firoozfam (2006) attempted to replace surveyors with a ROV stereovision system for ship hull inspection. The need is to assess and qualify automated inspection procedures.

Advanced visual inspection

Remote visual inspection through cameras has shown potential as an alternative to traditional visual inspection (De Petris and Macro 2000, Roy *et al* 2000, Armitt and Henning 2000). The advantages are twofold: minimal interruptions to operations and inspections at a safe distance in hazardous environments.

Corrosion and crack detection methods

Acoustic emission technology (AET) has been applied in many industries to detect cracks, corrosion and leaking (Athanasios *et al* 2008). AET has recently received a great deal of attention. An EU-funded project tested AET in the tanks of an oil carrier (Tscheliesnig 2006), while the AE sensors were submerged in the fluid. A testing program in the USA relied on attaching AE sensors directly on the steel structures (Wang *et al* 2008b). The USA tests were conducted while the tankers were operating at sea and in harbour. It was concluded that being a non-intrusive technology, AET is promising for monitoring the condition of hull structures in the marine environment.

A new fatigue damage sensor was applied in a fatigue management system of LNG carriers (Yamamoto *et al* 2007, Takaoka *et al* 2008). It minimizes the time for sensor installation, which under normal circumstances is time consuming when installing strain gauges.

Fiber optic sensors have attracted attention for their low spark hazard, a much-needed feature in tanker applications. Some fibre optic sensors allow multi-location sensing measuring temperature and strain (Méndez and Graver 2007). The current challenge is the cost and the need for signal conditioning devices.

The guided wave UT also shows some promise. A study reported detection of pitting corrosion and weld defects by ultrasonic Lamb waves (Sargent 2006) and detection of corrosion, using pulsed eddy currents (Scottini and Quakkelsteijn 2007). Shashikala *et al* (2008) propose electrochemical noise as an online corrosion-monitoring tool that seems to be an advancement of the UT guided waves.

De Oliveira Carneval and Damasceno Soares (2006) reviewed the efficiency of ACFM, UT TOFD and UT Phased Array, and compared them with conventional methods of MPI and UT. The latest ACFM allowed detection and sizing of defects beyond basic applications and even of stress patterns (Lugg and Topp 2006). An application of submersible sensor was reported by Mijarez *et al* (2006).

Coating condition monitoring and assessment

Visual inspection is widely applied for inspecting and assessing coating condition. Currently, the degree of paint coating degradation is judged by visual inspection (IACS 2006). A subjective judgment by the visual inspection sometimes involves uncertainty

(Yamamoto *et al* 2008b). Recently, new judgment procedures based on the measurement of current density, impedance, potential distribution, etc. were investigated (Sugimoto *et al* 2007, Nakayama *et al* 2008a, 2008b).

Camera vision systems and infrared thermograph seem to be possible alternatives (Omar *et al* 2005), allowing measurements of coating thickness prior to coating breakdown. A paint deterioration sensor was developed to measure the change in the potential distribution in a ballast tank (Nakayama *et al* 2008a, 2008b, Yamamoto *et al* 2009). This may lead to a quantitative coating evaluation system based on this sensor to assess the extent of coating degradation.

Structural condition monitoring system

Commercial systems for structural condition monitoring are now available (BMT SMARTSTRESS, CETENA Shaman, MARIN, R. Rouvary HULLMOS©, SST Naviscan, STREMOS). These systems offer long and short strain gauges, integrated with ship motion sensors, and pressure sensors, and fiber optic sensors sometimes. Real-time displays in the vessel's bridge provide information on ship motions, hull stresses, wave impact pressure, and accumulated fatigue damage. The challenges are data processing, integrated computer system (Kawano and Sueoka 2000), adoption of new technologies such as acoustic emission technology, fatigue damage sensors, or GPS-based hull girder deflection monitoring (Paik and Melchers 2008, Rizzo 2007, Carrera and Rizzo 2005), among others.

Quality of inspection and human factors

The quality of inspection depends more on the quality of device operation rather than on the equipment itself. A quality assurance scheme is in place for evaluating the surveyor's skill. See IACS Procedural Requirements 6, 7, 19 and 20.

Attempts were made to assess the human factor on the reliability of some NDT techniques (Stephens 2000, Alexiev and Mihovski 2000, Dymkin and Konshina 2000). The idea was to adjust model data considering the influences of humans and environments to make the predicted probability of detection (POD) comparable with those obtained in experimental trials. Studies with the same aim were reported for the marine industry (Zayed *et al* 2007, Jeppesen 2005). ISO 16587 (2004) describes the performance parameters for assessing the condition of structures but excludes non stationary structures as self-propelled ships from its application, thus highlighting intrinsic difficulties for ship structures.

3.5 Management of hull condition data

Reporting and documentation of inspection results are very important. Application of information technology to properly store the data and facilitate fast and accurate exchange of data has become a new trend. Classification societies are continuously developing web-based software to assist in managing data of inspection results about hull conditions. See the summary in Table 3.2.

The ISO 10303 - STEP standard (Standard for the Exchange of Product Model Data) has been proposed for representation and exchange of technical information about shipbuilding products. IACS Rec. No.75 Format for Electronic Exchange and Standard Reports addresses procedures for data exchange between IACS members. IACS Rec 77 and PR 19 state Guidelines for the surveyor on how to control the thickness measurement process.

One EU-funded project (CAS) included the participation of three classification societies and industrial partners. This study developed a method for automatically uploading measurement data (thickness measurements, crack positions and coating condition) into a virtual 3D ship model. The resulting software (Cabos *et al* 2008, Jaramillo 2006) has the capability of generating thickness measurement reports following the current IACS-required format (IACS PR 19 and UR Z10), mapping the gauging results with FE models, indicating coating condition, cracks, etc., and including photos if available. A similar EU project just started (RISPECT).

RBDM (Reliability-Based Decision Making) software, such as Rightship (www.rightship.com) or VDST (Lo Nigro *et al* 2005), provides a ranking system to assist with maintenance-related decision making. The condition of a vessel is ranked based on the collected information, class reports including CAP, vetting inspections, port state control, casualties, ship information and ship owner information. These tools cover tankers and bulk carriers.

3.6 Navy vessels

Condition Assessments of naval vessels are conducted for the purpose of identifying the level and nature of risk associated with the condition of a ship's system, to ascertain the known state and, ideally, to mitigate any risk to ”As Low As Reasonably Practicable” (ALARP). The CAP programs also include remedial action plans to address the noncompliance and to manage the residual risks at ALARP level. Condition assessment enables the associated Maritime Command to understand the level and nature of the residual risk associated with employing a capability (ship) in the defined manner in the assessed condition of the vessel.

The CAP process contributes to the assurance of the condition of the fleet through professional assessment of the functional performance (Fitness for Service) and physical condition of the ship's system and condition. The CAP process enables, through the CAP condition report, the identification and management of residual risks associated with noncompliance. The application of the CAP process is usually mandated under capability of naval vessel CAP management and instituted in the fleet as applicable.

The Maintenance Manager or equivalent position in the Navy is responsible for ensuring that a maintenance program is pursued in accordance with the hull maintenance plan. This is accomplished by maintaining close communication with the responsible naval person who manages the Navy Hull Survey program. Usually a Navy Hull Surveyor is employed and conducts the hull survey of all structures as appropriate to the Rolling Hull Survey Program for the particular ship. Structural deficiencies are addressed and the hull maintenance history recorded. The certificate verifying this process, together with both the classification society's certificate of class / compliance and the safety construction certificate, constitutes the objective quality evidence (OQE) that the hull structure is safe and fit for service as required by the naval authority.

The implications of deficiencies for any particular vessel will depend on the actual material condition under CAP and on operational programming imperatives. Naval classification extends to other useful functions. It can provide a framework for the control of a maintenance regime and a formal record of the ship's material condition. The former is of value in planning forthcoming maintenance requirements, while the latter can be of considerable value in assessing, often in a very short time scale (e.g. in the case of damage), the course of action to be taken for the ship's future.

Generally, the use of the classification societies and the issue of a Certificate of Class/Compliance address overall structural safety of the ship but do not necessarily cover Fitness for Service. This obligation is exercised by the naval authority, together with in-service support contractual arrangements. The requirements outline an agreement to ensure that naval vessels are fit for service and that their hulls and structural maintenance systems comply with the requirements of applicable rule requirements.

3.7 Recommendations

Inspections are time-consuming. It is desirable to conduct "informed" inspections by:

- Focusing inspection sources towards structural areas that are most prone to failure or degradation
- Properly consider previous inspection results and relevant information
- Clearly state acceptance criteria (preferably in quantitative terms)
- Applying structural condition monitoring techniques when possible
- Using data management tools to store and trace history data

Structural health (or condition) monitoring systems are developing rapidly and are likely to become commonplace in the future. There is a need to develop performance reliability measures for monitoring systems in the same way as these are available for NDT methods.

Future research should also address the following challenges:

- Application of NDT and monitoring technologies in the marine environments, and integration of these technologies into structural health monitoring systems
- Customized information management systems for shipping industry
- Uncertainties of inspections largely to 'human factors'

4. CONDITION ASSESSMENT OF OFFSHORE STRUCTURES

This is the first time that ISSC covers the condition assessment of offshore structures. The offshore industry is more inclined to adoption of advanced technologies. This chapter presents the advanced concepts of Structural Integrity Management and Risk-Base Inspection, followed by reviews of condition assessment of FPSO hull structures, topside structures and jacket structures.

4.1 Structural Integrity Management (SIM)

The Structural Integrity Management (SIM) is a process that aims at ensuring the fitness-for-purpose of the entire life cycle of an offshore structure from its installation until its decommissioning. The goal is to provide guidelines for the management of the consequences of degradation, damages, changes in the loading or use, accidental loads, etc. The concept of SIM is best illustrated by Fig. 4.1.

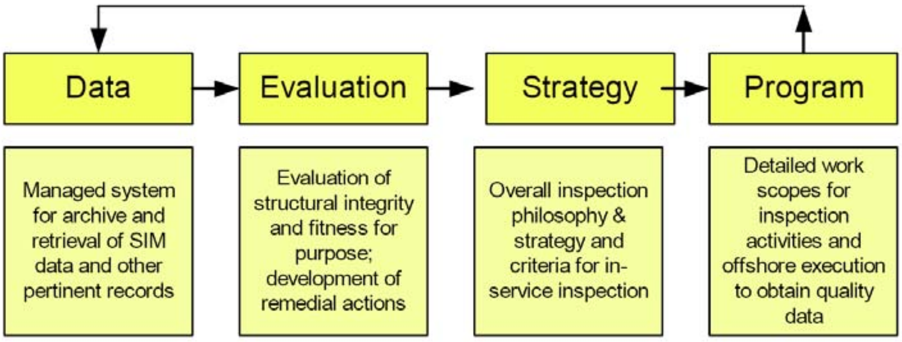


Figure 4.1: Concept of Structural Integrity Management (API 2009).

SIM starts with data collection, which in turn becomes the inputs to the evaluation structural integrity, leading to an overall inspection and maintenance strategy. A detailed inspection program is derived from this strategy and inspection outcomes are input into a data management system.

API RP 2 SIM (API 2009) defines the overall inspection philosophy for one or a fleet of fixed platforms. The in-service inspection defines the inspection frequencies and scope of work. This strategy includes the following basic elements of inspection and is periodically updated throughout the life of the platform:

- Periodical above-water inspections, normally conducted on an annual basis
- Baseline underwater inspection aimed at determining the installed platform condition
- Periodical underwater inspections

The SIM strategy is flexible. The inspection effort depends on the platform's susceptibility to defects and anomalies, its robustness and its present condition, the consequence level of its structural failures, and the manning level of the platform.

4.2 Risk-Based Inspection (RBI)

Risk-based inspections (RBI) aim toward defining the scope and frequency of inspection based on risk analysis (Serratella *et al* 2008, Dinovitzer *et al* 2009, Bhattacharjee *et al* 2009). Both quantitative and qualitative risk analyses can be applied. The outcome of both hazard identification and the risk analysis is a unit-specific inspection strategy taking into account the design, environment and operating conditions.

Some degradation mechanisms can be explicitly quantified, such as fatigue, crack propagation, generalized corrosion, etc. The uncertainties of these degradation phenomena and environment can be treated in a probabilistic manner. Using engineering tools of structural reliability approaches, it is possible to predict when the failure probability of selected failure modes would become lower than acceptable risks, quantified against personnel loss, environment impact or financial impact. Such analysis would make it possible to determine the best time to conduct inspection or maintenance.

For those items where degradation mechanisms cannot be explicitly quantified, risk analyses are either semi-quantitative (case where consequences are assessed from a quantitative point of view) or qualitative (case where both consequences and probabilities are assessed from a qualitative point of view). In these cases, time dependency cannot be quantified, disallowing inspection times to be defined according to the computation of degradation phenomena. Inspection frequencies are therefore predicted using a qualitative relationship between risk level and inspection frequency.
In all cases, risk analyses provide a refined, tailored inspection frequency and scope.

4.3 Hull structures of FPSO

In the early days of FPSOs, class requirements of tanker inspections were applied. Such a step was logical as the first floating units were conversion tankers. In the industry today, new-built units are still largely based on the current accepted standards of naval architecture engineering. As a consequence, transfer of knowledge from ship rules to FPSO has been carried out in a straightforward way.

There is a general trend in the offshore industry to move from prescriptive rules to risk-based rules for inspection and maintenance. This trend is mainly due to the unique needs of the offshore industry, namely, operational constraints and safety requirements. Structural reliability approaches and risk-based methodologies have been extensively applied, and both likelihood of structural failures and consequence can be taken into account in planning inspection and maintenance (Galbraith 2008, Hoogeland *et al* 2003, Ku *et al* 2005, Lee *et al* 2006, Biasotto and Rouhan 2004, Goyet *et al* 2004, Rouhan *et al* 2004).

Differences between FPSOs and trading tankers

Trading tankers are built to transport crude and/or refined oil from one port to another. The major challenge for a shipping company is shipping efficiency. This calls for reducing down time, including those associated with the required maintenance, inspection and repair.

Offshore production units (floating and fixed structures) are built to produce oil and gas. The challenge is to keep adverse impact of inspection, maintenance and repair on production as low as possible, while at the same time maintaining adequate structural reliability of the unit. FPSOs are not intended to be dry-docked on a regular basis.

A report on current practices of inspection, repair and maintenance (IMR) on FPSOs in the North Sea (UKOOA 2003) includes a comprehensive data collection on failures and defects, repairs carried out and recommendations for future IMR activities.

The Joint Industry Project FPSO structural performance (Serratella and Spong 2005) has collected data on the structural performance of hulls of FPSOs. Information includes thickness measurement (corrosion wastage), observed fatigue cracks, current practices on structural integrity management, and most influential factors on hull structural integrity.

Flexible inspection scope and frequency

The offshore operational constraints require that rules be applied differently from class requirements for tankers. In particular, operators ask for a more detailed inspection scope and frequency. Risk-based inspection has been accepted by the industry. In a RBI scheme, resources of inspection are directed towards structural areas of the highest risk. There is a common trend for class societies to move from prescriptive rules to risk-based rules for the maintenance of FPSOs and offshore platforms. This general trend includes risk-based verification and risk-based maintenance and inspection of hull structures (ABS 2003a, 2003b, 2003c, DNV 2001, 2004, 2006, Lee *et al* 2006, Ku *et al* 2005, Serratella *et al* 2008).

Operational experiences

A summary report on FPSO lessons learned from four Norwegian FPSOs (OGP 2003) revealed that three out of four FPSOs suffered green water and consequent damage, and three out of four FPSOs suffered fatigue cracking between tanks. Major events related to structural degradation include weld failures, leak and corrosion in ballast and cargo piping, and corrosion and coating failure.

With regard to structure and degradation of FPSOs hull, the report mentions the following challenges in the industry:

- Painting: There is a need for further research on painting technology and methods that fit project demand.
- Operation and support: In situ repairs and structural modifications are critical. There is a need for revising the standards with the aim to minimize maintenance and in-field repairs.
- Codes and classification: The operators ask for more stringent FPSO class specification.

Operational constraints

For FPSOs, some inspection or survey constraints are:

- Weather conditions: Inspection of the internal structure of tanks during high seas is very risky for the surveyor and NDT team. This restricts the time window for performing inspection.
- Availability of beds: Number of inspectors is often limited by the availability of beds.
- Constraints because of loading and unloading of tanks: FPSOs continuously load and unload. The sequences of unloading and loading are driven by the availability of pumps, oil flow rate, process equipment availability, schedule and size of shuttle tankers, weather conditions, stability and longitudinal strength requirements, etc. Inspections have to be scheduled well in advance to minimize the impact on FPSO operations.
- Availability of tanks: When to perform tank testing needs to consider adjacent tanks. They may be needed for maintaining vessel stability and/or global hull strength. They also may be required for loading and unloading.

In addition, constraints concerning the maintenance and repairs are:

- Availability of materials: There may be a delay before the needed steel plate or pipes arrive onboard.
- Fire hazard: Care is to be taken when performing hot-work repairs.
- Paint repair: Surface preparation for paint work, such as sand-blasting, is sometimes considered as hot work, and may not be allowed during certain time frames.

4.4 Data management

Ships are required to keep class and statutory documents onboard, some of which are updated to reflect the latest survey findings. When the ship enters harbor, its required certificates and documents can be checked by the Surveyor.

FPSOs are also required to keep documents. The difference is that verifying documents are to be offshore. An onshore support team is needed to keep updates of documents. This can be best achieved by using data management software. This in turn implies up-to-date documents and procedures stored on-board are the same documents available to onshore support teams. This task can be achieved by the use of an efficient document management system. Such a system allows fast, easy access to relevant documents onboard. It also provides for sharing these documents with onshore base teams.

The use of satellite communication systems allows internet access from almost any part of the world. The use of this system is especially effective for offshore production units. Major classifications societies now provide services on data management and structural integrity using web interfaces (Lanquetin *et al* 2007a, 2007b) for inspection, maintenance and repair for hull. The use of such techniques allows sharing of documents by various people. It also helps operational teams to keep access to and track design and maintenance documents.

4.5 Monitoring system

There are some monitoring systems in place for monitoring the hull conditions. Fundamentally, these systems are used to focus on: winds (storms, hurricanes), waves, current, motions, vortex induced vibrations (TLP tendons, risers), and anchor degradation.

To have a better understanding of these, several Joint Industry Projects (JIP) on monitoring of offshore structures have been performed (Djik and Boon 2007, Mitchell *et al* 2006, Boon *et al* 2005, Djik *et al* 2003). The Marco-Polo JIP aimed to better determine the dynamic behavior of TLPs in operational and survival condition. It provided data that may help verify design methods and numerical analysis. The following have been monitored: motions of the TLP, tensions of risers, tendon tensions, wave conditions, wind speed and directions, current speed and direction, and gusset plate stress measurements

Another JIP, MONITAS, aims to monitor fatigue damage. The idea is to monitor loads and structural stresses to provide data for predicting the remaining life of cracks. This project will develop an advisory intelligent monitoring system (Kaminski 2007).

4.6 Topside structure

Topside equipment plays a key role in oil production. Much work on their inspection, maintenance and repair has been done. In contrast, not much work on risk-based inspection and repair of structural elements of topsides has been done.

Topside structures are complex, and built with many modules. Consequently, there are a large number of welded connections that pose as potential sites for fatigue cracks. Both feasibility on-site and business efficiency demand prioritizing connections and identifying those that need to be periodically inspected. On the other hand, not all modules have the same role in the process of the facility. It is easy to understand that equipment failure in a water injection module does not have the same consequence on production or safety as in a hydrocarbon processing one. Probability on one side, consequence on the other, we can see from the above that we are naturally inclined to use risk as the driving parameter to design inspection programs for topside structures. Risk-based inspection is now a well-known method to design inspection programs, but it has only been standardized for pressure systems by API 581. Few approaches are available for these topside structures themselves.

One available approach for risk-based inspection of topside structures of offshore units is described in (MMS 2004). The objectives of the study were to develop a methodology for the integrity management of topside structures, process, and piping, and to integrate the process of survey and inspection with existing defect assessment procedures.

It was reported that many of the anomalies were attributable to external corrosion that can be detected using visual inspections. Few of theses anomalies resulted in failures. It was also found that a high percentage of internal corrosion anomalies led to failure. These findings lead to the conclusion that most anomalies leading to failure will not be detected visually. The report suggested the use of a risk-based approach to improve topside inspections. The method prioritizes the inspection depending on potential risks. This situation is likely to lead to more inspections of high-risk areas. At the same time it would reduce the inspection effort from current requirements if the risk level is shown to be low. One aspect of this methodology is that it uses previous inspection results in the risk assessment.

A risk-based inspection approach (Truchon *et al* 2007) consists of identifying structural failures, assessing the probability of fatigue failure of the structural elements, evaluating the consequences of these failures in terms of impact on personnel, environment, and impact on production, and finally, planning inspections depending on the risk level. The initiating event is the fatigue failure of one component. The consequences of the fatigue failure are addressed depending on its location and its structural importance, whether or not that component supports equipments with critical fluids.

4.7 Fixed platform

Jacket structures were the first offshore production units. Today, more than 7000 jacket structures exist worldwide. Guidelines for jacket structural design have existed for a long time. It is only recently that codes on the structural management of these structures have been developed. The two main efforts in that domain are the ISO 19902 guideline and the API RP2 SIM.

ISO 19902

In the mid-1990’s the International Standardization Organization (ISO) developed the draft guideline 19902 for Fixed Steel Platforms, which contains recommendations for (SIM). The ISO 19902 guideline is divided into clauses, including SIM for existing structures, (Galbraith 2008). Clause 23 concerns in-service inspection and structural integrity management of jackets. It aims at encouraging owners to understand the limitations and the strengths of each structure. This clause provides some default requirements regarding the inspection. Clause 24 concerns assessment of existing structures. This process includes data collection, structural assessment, acceptance criteria, assessment of structure condition and evaluation of loads and resistance. Clause 25 has requirements for the reuse of jackets, including strength, fatigue and inspection requirements.

API RP 2 SIM

The API RP 2 SIM aims at providing guidance for the integrity management of jacket structures in the Gulf of Mexico (API 2009). It introduces the concept of RBI strategy, allowing for better focus of inspection resources by the use of a risk matrix, which is often provided by the owner of the installation.

4.8 Recommendations

These are the main challenges for the coming years in the offshore area are:

- Data management: Large offshore projects (FPSOs, large field) involve a lifetime document and data management. This will be particularly challenging over the upcoming years.
- Training of onboard and onshore team
- Risk-based class rules for new designs, taking into account current practice and operational constraints
- Real-time monitoring of structure response: It is highly preferable to monitor fatigue and corrosion. This also demands management of these monitoring data.
- Condition assessment of reused jackets and hulls.

5. APPLICATION OF STRUCTURAL RELIABILITY APPROACHES

The reliability-based approach provides a viable tool for evaluating the structural integrity of aging structures. Assessment of existing structures requires a consistent treatment of all available information for determining safety and risks, thereby complying with appropriate acceptable safety levels.

Comprehensive review of structural reliability approaches can be found in ISSC (2006a, 2006b). This chapter is supplemental to those reviews and mainly covers the latest developments.

5.1 Time-variant reliability formulation

The structural reliability theory was introduced to ship structures in the 1970's. It was used as a tool to establish a rational safety margin between load and resistance by taking into account uncertainties in loading, response and structural strength. An important and frequently studied problem is the hull girder reliability.

The time-variant reliability formulation has been extensively applied to evaluate the effects of corrosion wastage and fatigue cracks. It is well suited to condition assessment and inspection planning.

5.2 Hull girder reliability, fatigue reliability and panel reliability

Time-variant probabilistic corrosion models have often been used in reliability-based inspection planning for ship hulls (Garbatov and Guedes Soares 2007b) and FPSOs (Sun and Guedes Soares 2005). Corrosion renewal criteria were considered to simultaneously account for thickness reduction and different failure modes. Moan *et al* (2004) established a reliability-based procedure for assessment of deteriorating ship structures by accounting for the interaction between fatigue and corrosion wastage under different environmental conditions. Ku *et al* 2005, Lee *et al* (2006) and Guo *et al* (2008) presented probabilistic models for predicting the failure of structural members due to local wastage for FPSOs and tankers.

A non-uniform thickness reduction leads to non-uniform stresses and hence leads to strains concentrating in the thinner parts. This may mean that the overall panel behavior is different. In a similar way, panel response may be different from that of a new panel under compressive loads (buckling) and lateral loads. Stiffeners as well may behave differently with non-uniform corrosion. This may lead to different failure modes than commonly taken into account for new construction. Groove corrosion near the stiffener-plate attachment, for instance, may make tripping a far more likely failure than in new construction. Cracks (whether plate or stiffener) may be treated as reductions in cross-sectional area, but in other situations this may not be the case. When the ultimate capacity of the structure is relatively unaffected, the overall stress-strain relationship for the panel may have changed. It may even be that the traditional quasi-static strength assessment is no longer adequate and that dynamic failure modes (energy absorption on impact) have to be taken into account. Mechanical damage may alter the effective plate width of stiffeners and web frames when loaded in compression or laterally. Overall, it may be stated that the structural behavior of small assemblies is less balanced when aged than a new build structure. This may mean that nonlinearity is relevant much sooner than is generally accepted in strength analyses.

5.3 Failure probability and reliability

A major challenge to the practical application of reliability methods is the selection of target reliabilities. The calculated failure probability is usually not a "true" or "realistic" value, but a nominal measure of failure. This nominal value is also dependent upon the analysis model and uncertainties models.

IMO report MSC 81/INF.6 describes a methodology for calculating annual hull girder failure probabilities for double-hull tankers. The target failure probabilities are listed as 10-4 ($\beta = 3.71$) and 10-3 (β=3.09) for gross and net scantling, respectively. Although the main purpose of the IMO document is the calibration of partial safety factors for ultimate bending failure mode in IACS CSR, it will probably have much broader implications. A study was done to extend IMO reliability to bulk carriers and containerships (Moan *et al* 2006) considering the effects of various model uncertainties including avoidance of heavy weather.

The failure probability of aging ships changes with time. Degradation phenomena and their interaction are associated with a high level of uncertainty. Assessment of structural reliability of aging structures is far more complicated than ordinary, time-invariant formulation.

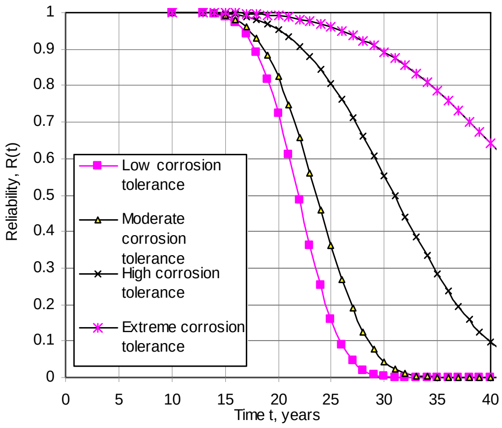
Statistical analyses of ship accidents may be referred to when one tries to specify target failure probabilities. A comprehensive analysis of recorded accidents of large oil tankers occurring between 1978 and 2003 (Eliopulu and Papanikolau 2007) revealed that the annual frequency of "no accidental structural failure" was 2.15E3, 2.90E3 and 2.58E3 for Aframax, Suezmax and VLCC tankers, respectively. It was noted that the frequency of accidents progressively and significantly decreased, particularly in the post-1990 period. A higher frequency of non-accidental structural failures was observed in middle-aged tankers. This is similar to Fig. 1.2. The author attributed these phenomena to reduced maintenance effort when the ships approached the design economic life (normally 20 years) and the tendency of ownership change.

The acceptable probability of failure can be established on the basis of failure consequences assessed in monetary terms (Rackwitz 2000). This approach is based on a fundamental work in the 1990s that addresses the value of the individual to society by means of the Life Quality Index. Implementation of such approaches may be difficult in practice, and is often influenced by the judgmental powers of individual decision-makers.

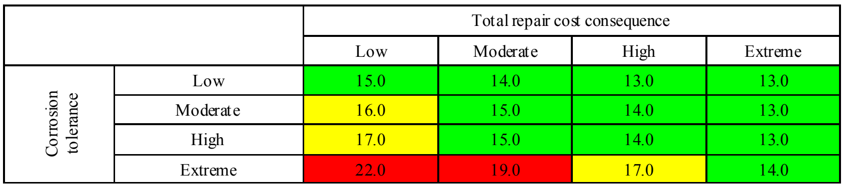
5.4 *Inspection and maintenance planning*

During the last 10 to 15 years, reliability-based and risk-based approaches were extensively applied in the planning of inspections (Ku *et al* 2005, Lee *et al* 2007). These approaches are based on the decision theory, often with an aim to minimize the overall lifetime costs.

The consequence of component failure, e.g. in terms of potential loss of lives or incurred repair and downtime costs, will depend on the component and its importance for the operation of the structure. The risk-based inspection approach takes component installation as a whole. Different inspection strategies with different inspection efforts, inspection quality and costs will have different effects on the risk. A risk-based inspection strategy would help allocate the resources towards higher risks first.



(a) Predicted structural reliability based on severity of corrosion wastage



		Total repair cost consequence			
		Low	Moderate	High	Extreme
Corrosion tolerance	Low	15.0	14.0	13.0	13.0
	Moderate	16.0	15.0	14.0	13.0
	High	17.0	15.0	14.0	13.0
	Extreme	22.0	19.0	17.0	14.0

(b) Predicted best time (vessel age) to conduction inspection

Figure 5.1: Example application of structural reliability in assisting inspection planning (Garbatov and Guedes Soares 2008a).

The inspection and repair work helps to minimize the consequences of cracks. Incorporating this effect in a time variant formulation requires information to assess the effect of inspections and repairs at different points in time. The effect of plate renewal as a result of corrosion wastage was modeled in a similar way as a fatigue repair problem.

Often, fatigue and corrosion take place simultaneously. Decreased net section due to corrosion will increase the stress levels, which in turn increases the rate of crack growth. It was shown that depending on the repair policy, one of the two phenomena would be the dominating one.

A Bayesian approach is often adopted to update some parameters, such as the time to crack initiation, crack growth law and probability of crack detection (Garbatov and Guedes Soares 2002).

Garbatov *et al* (2007) analyzed corrosion wastage data of structural components in tankers of ABS (Wang *et al* 2003a, 2003b), and derived nonlinear time-variant corrosion function for predicting future wastage (an example of wastage data can be seen in Fig. 6.1). These data were then used by Garbatov and Guedes Soares (2008a) for predicting the reliability adopting the Weibull model, which is a function of vessel age (see Fig. 5.1a). The optimum time to conduct inspection (Fig. 5.1b) was determined to ensure that the reliability will not fall below a certain level, or target reliability, which was selected based on the acceptable consequences of the considered structural failure. A similar study on tankers' deck plate failure using a semi-probabilistic approach (Guo *et al* 2008) showed how this kind of technology can be used in determining best time to perform hull inspection, and the consequential economical life of different tankers built in the 1970s, 1980s and 1990s.

The approach for analyzing the failure data based on historical thickness measurements in bulk carriers and the progress of corrosion failure have been used by (Garbatov and Guedes Soares 2009) to demonstrate how data could be used to address important issues such as the inspection intervals, condition-based maintenance action and structural component replacement.

5.5 Lifecycle cost assessment and Reliability Centered Maintenance (RCM)

Repair costs can be used as a criterion (Garbatov and Guedes Soares 2001) in reliability-based maintenance planning to achieve an optimal inspection interval. In order to keep the reliability level above a certain acceptable value, in some cases, the costs will not dominate and the reliability criterion will be the governing one.

The goal of an inspection strategy is to achieve a balance between reliability and economy (Garbatov and Guedes Soares 2001). Simulated strategies for inspection planning showed that the application of repair cost optimization for floating structures involves many uncertainties, including the repair costs and the inspection procedures.

The importance of RCM has also been recognized in the marine industry. RCM has been tested by shore-based consultants and academics, mostly for the maintenance of machinery systems. This method directs maintenance efforts towards critical components from the point of view of reliability, safety and efficiency of the system. Decision logic and specific forms are used to identify the worthwhile maintenance activities.

Most of the structural reliability applications were focused on modeling corrosion and crack growth. A new approach (Garbatov and Guedes Soares 2008b) is based on analyzing statistics of failure, developing probabilistic model of time to failure, and using these data and models for making maintenance decisions. Results using this approach were in good agreement with standard practice.

5.6 Recommendations

Structural reliability should be used in the safety assessment of aged structures for determining survivability, recoverability, operability and maintainability. Reliability-based analysis procedures and uncertainty models should be further developed and refined, adopting a systematic approach. The reliability has to be estimated in a reliability-based decision format. Uncertainty models should be further developed and refined. Cooperation of many organizations is highly recommended for obtaining reliable failure data. The proper format of data recording is also needed. Interactions of different aging effects, such as non-uniform corrosion and fatigue cracks, should be considered.

The greater emphasis should be given to the structural monitoring systems. Such systems will help in obtaining actual data of corrosion wastage and crack propagations, in addition to the general guidance to seafarers and operators about the behavior of the ship structure at sea.

Training of SRA would become necessary. The Committee supports the training initiatives such as the European TEMPUS project “ASDEPP - Advanced Ship Design for Pollution Prevention”.

6. CORROSION WASTAGE AND COATING DEGRADATION

A major focus of recent research and development is the collection of degradation data and prediction of corrosion and coating failure. Analytical models have been proposed for predicting coating degradation, corrosion wastage and pit depth. A probabilistic presentation is often preferred because of the involved high levels of uncertainty as a result of many contributing factors to corrosion wastage.

6.1 Measurement data

A lot of data on corrosion wastage has become available (TSCF, SSC, Paik *et al* 2003, Harada *et al* 2001, Wang *et al* 2003a, 2003b, 2008a). See also the summary of ISSC (2006a). Figure 6.1 presents examples of corrosion wastage of individual structural members and loss of global hull girder strength.

The thickness measurement data is useful in identifying the trends in corrosion. They were extensively used in developing analytical models for predicting corrosion wastage and time-variant reliability analysis. Interpretation of the trends revealed in various database remains, however, limited. Continuously collecting and updating these databases is also necessary.

Most of the data is about general corrosion. Data of other types of corrosion (pitting, grooving, etc) remain scarce.

Figure 6.1b is typical of collected wastage data – the mean and standard deviation generally increases when vessels become older, and they fluctuate with vessel ages. See the lines of "mean" and "mean + stdv". Analytical models are often used to show the trends of the wastage over the years. They are smooth curves, as shown in Fig. 6.1a, and are conveniently used in the reliability analysis and the rule development such as CSR.

Note that Fig. 6.1b shows less loss of hull-girder strength when the vessel age is around 24 to 26 years old. This trend is likely because of the population of vessels in this age group is often in better condition while less robust vessels have already come out of service. This situation is quite similar to Fig. 1.2.

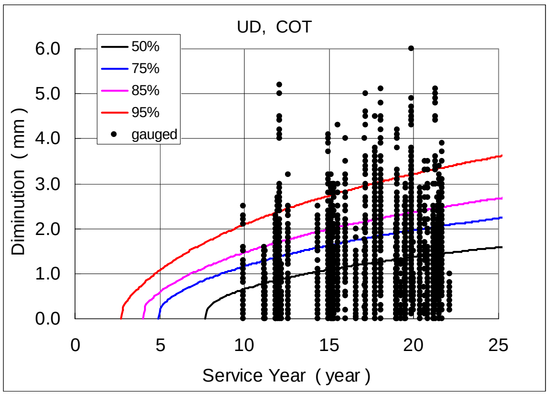
6.2 Degradation models

There was a concentrated interest in development of degradation models. This was a major research topic in the recent years.

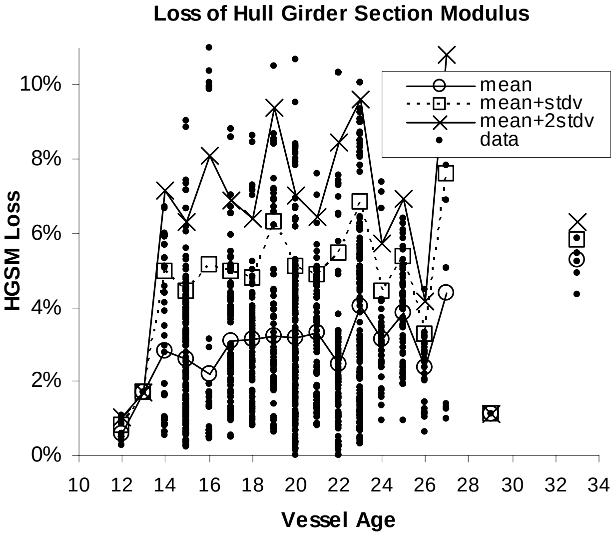
Corrosion wastage model

Conventionally, corrosion rates were assumed to be constant. Lately, it has been concluded that this practical assumption is simplistic and may not be valid (Melchers 2007a). Experiment and measurement data show that the corrosion rate varies in different stages of the corrosion development.

Recent corrosion models are more refined. A comprehensive review of these time-dependant models can be found in ISSC 2006. Melchers (2003a, 2003b, 2003c, 2005a, 2005b, 2007a, 2007b) developed the probabilistic corrosion model that divided the corrosion process into four stages: initial corrosion, oxygen diffusion controlled by corrosion products and micro-organic growth, limitation on food supply for aerobic activity and anaerobic activity. Probabilistic corrosion models have been used which include probabilistic representation of these different stages.



(a) Loss of deck plate thickness in cargo oil tanks of tankers (IACS 2005)



(b) Loss of tankers' hull-girder sectional properties (Wang *et al* 2008a)

Figure 6.1: Measurement data of corrosion wastage of local structural members and global hull property.

Garbatov *et al* (2004a, 2004b, 2005, 2007a) and Guedes Soares *et al* (2005) presented an investigation on the effect of parameters that may influence corrosion wastage. The large number of parameters poses a challenge to the development of corrosion wastage models. Validity of corrosion models should be examined by comparing the estimated results with the actual data. Updating the corrosion model when measurement data of the object structure becomes available is also a useful and practical procedure (Yamamoto *et al* 2005).

Coating degradation models

There is limited literature that treats models of coating deterioration (Murakami *et al* 2007). The need exists to further develop models concerning the coating performance. When assessing corrosion conditions of structures, probabilistic evaluation of coating life is important. This stems from the fact that the corrosion rate calculation depends on the assumed coating life, which is the time when coating does not protect steel anymore and corrosion starts. Apparently, prediction of corrosion wastage depends more on coating life rather than on the probabilistic nature of progress processes. See examples of Fig. 6.1.

Pitting corrosion models

A commonly employed model is the extreme value model for the maximum pit depth (Katoh *et al* 2003). Melchers (2005b) pointed out that the probability distribution of maximum corrosion pit could be represented by a bi-modal distribution of an exponential distribution and a normal distribution for shallower and deeper pits. Yamamoto (2008a) proposed the probabilistic model of pitting corrosion to represent the uneven corroded surface by introducing the shape function of corrosion pit.

Pitting corrosion condition is difficult to capture by plate thickness measurements because of the heavy unevenness of the metal surface. IACS (2003) recommended using the degree of pitting intensity (DOP) as the index for presenting the pitting corrosion condition.

Grooving models

There are a limited number of publications on modeling grooving. In the 1990s, Class NK did some work on simulating grooving along welds.

6.3 Consequences of corrosion wastage

Excessive loss of material may lead to fracture, buckling or yield failure. Corrosion causes loss of cross-sectional area. Deterioration of ship structures reduces local and global strength and can finally lead to disastrous casualties in rough seas under certain circumstances.

Influences on hull girder strength

Table 6.1 lists major studies on the loss of hull girder section modulus (Ayyub *et al* 2000, Guedes Soares *et al* 1996, Horte *et al* 2007, Ivanov *et al* 2003, Paik *et al* 2003, Wirshing *et al* 1997, Wang *et al* 2008a, Yamamoto *et al* 2001). Representative results from these publications were hull girder strength loss for ships 20 years old. A large scatter in the results is observed. Most of the publications were based on calculations using wastage of individual structural members. The calculated loss of hull girder section modulus varies from 4 to 20%, which appears to depend mainly on the assumed corrosion condition in the analysis, the input data and selected sample vessels. Note that almost all the analysis papers show loss of section modulus much higher than what is revealed in the only statistical analysis of the measurement of 200 vessels 12 to 32 years old (Wang *et al* 2008a).

Yamamoto *et al* (2001) concluded the effect of the stochastic nature of corrosion of each member could be neglected in the assessment of hull girder strength, even though the scatter of the amount of thickness diminution in each structural element was very large. A corroded hull girder section can be reasonably modeled by assuming that all structural members are corroded by an average amount in percentage of their original thickness.

Influences on local strength

Localized corrosion pits cause a decrease in local strength. Nakai *et al* (2004a, 2004b, 2005, 2006, 2007) made the serial studies on the effect of corrosion pits on local strength and showed that total elongation decreased in the case where corrosion pits exist. It is considered that the reduction of total elongation is closely related with localization of plastic deformation at the corrosion pits (Sumi *et al* 2006).

Table 6.1
Studies on reduction of global hull girder strength in 20 years

Paper	Ship(s)	Loss of hull girder section modulus at 20 years old	Basis
A	A single hull tanker	about 7%.	Analysis
B	A single hull VLCC	about 20% in mean value, 6% in standard deviation.	Analysis
C	Double hull tankers	about 10%.	Analysis
d	A handy-size bulk carrier	4.2%.	Analysis
E	A double hull tanker	12% (average corrosion).	Analysis
f	A conversion single hull FPSO	7.5%	Analysis
g	Single hull tankers	About 8% in mean, 2% in standard deviation	Analysis
h	A single hull tanker	About 10%	Analysis
i	A fleet of 210 single hull tankers	3.2% in mean value and 1.9% in standard deviation	Measurement

Influences on fatigue strength

The crack propagation can be accelerated when the metal is in a corrosive medium (Ebara 2001). This can take place in ballast and oil tanks when the tar epoxy resin coating loses its effectiveness as the coating breaks down. Magnin *et al* (2001) investigated the effect of anodic dissolution and hydrogen on the corrosion fatigue mechanism. Stress corrosion cracking (SCC), which is the cleavage-like fracture, is the phenomenon in the corrosive environment (Yokobori *et al* 2001, Miatiev *et al* 2001). Huang *et al* (2006) clarified that fine-grain steel had a good resistance as compared to conventional steel.

Leaking potential

Localized corrosion pits on the inner bottom of cargo oil tanks of tankers have the risk of oil leakage which may lead to pollution. A recent study reveals that pitting corrosion on the tank top plate of oil tankers is initialized at the docking survey with a 2.5-year cycle (SRAJ 2002).

Prediction of corrosion consequences

Evaluation of corrosion consequences calls for using probabilistic models. See the example of Gao *et al* (2005), Moatsos *et al* (2005), Garbatov *et al* (2007b), Guo *et al* (2008). The reasoning behind this is the high uncertainty associated with the degradation process. The aging mechanisms may be different from the one considered at the design stage. There are many different forms of aging which interact in many potential ways. Vessel operations of cargo loading and unloading, maintenance and repairs all can contribute to the uncertainties of the aging process. Apparently, it is very difficult to address all these uncertainties using a deterministic approach.

6.4 Corrosion protection

Corrosion addition, which is an additional thickness to compensate an anticipated thickness loss due to corrosion during the design life, is a kind of corrosion protection method for maintaining structural integrity (IACS 2005). Anti-corrosion steel is another type of corrosion protection method (Sakashita *et al* 2007, Kashima *et al* 2007, Inohara *et al* 2007, Imai *et al* 2007a) It has almost twice the resistance as compared with conventional steel in corrosion environments. Imai *et al* (2007b) confirmed its effectiveness by an onboard evaluation.

Painting is perhaps the most effective means of corrosion protection (IACS 2006). The efficiency of the anti-corrosion painting is influenced by surface preparation, kind of paint, specification of applied coating and the environmental conditions at coating. Therefore, the quality control of coating during vessel construction is important (IMO 2006, Seo *et al* 2007, Osawa *et al* 2007, Seki *et al* 2007, Hindmarsh 2007).

Cathodic protection is usually employed together with the coating. Akid (2001) verified that the cathodic protection had the same effect of reducing the damage effects of localized corrosion and crack growth as that in the air. However, high temperature reduces the effectiveness of cathodic protection (Lervik *et al* 2004).

6.5 Recommendations

Data of corrosion wastage of local members has become available in large quantities. Their systematic interpretation remains, however, limited. There does not seem to be a consensus among researchers with respect to the progress of corrosion, prediction of wastage and corrosion rate over time.

A corrosion model should be based on the field data rather than the laboratory data. The validity of a corrosion model is dependant on the data used and proper interpretation of these data.

Coating degradation, corrosion and wear of structures are the consequences of extremely complex phenomena governed by many factors. The structural degradation processes are usually subjected to substantial uncertainties that originate in the environment, loading, material, etc.

It is preferable to use a probabilistic model for presenting the degradation processes. Such a model should reflect the various uncertainties, and can be updated based on the latest information of structural conditions, which becomes available at inspections.

7. CONSEQUENCE PREDICTION OF FATIGUE

There is a dedicated Technical Committee within ISSC that considers fatigue and fracture issues associated with ships and offshore structures. This section intends to focus on the application of relevant methodologies for the fatigue modeling of aging ships and offshore structures and the consequences of significant fatigue cracking. The previous committee ISSC 2006 gave limited coverage of fatigue prediction models, whereas the Official Discusser echoed the amendments to statutory and class regulations following the Erika (1999) and Prestige (2002) casualties.

It is important to recognize that different fitness-for-service approaches are required for different types of structures and structural components. This report focuses on both primary structures and structural components. Ship and offshore structures are generally defect-tolerant and can withstand relatively large amounts of corrosion and fatigue damage without affecting overall structural capacity. However, such progressive damage needs to be measured, monitored and understood so that timely remedial action can be implemented in order to avoid catastrophic failure.

7.1 State-of-the-art technology for predicting fatigue failure and consequences

Offshore units

The most generally accepted standard for offshore structures (Ersdal 2005) is the ISO 19900 “Petroleum and natural gas industries – Offshore Structures – Part 1: General Requirements” ISO (2002). This standard gives general design rules and general rules for assessment of existing structures. The Norwegian regulations (PSA 2004) refer to NORSOK N-001 (NORSOK 2004) for structural design, which again refer to ISO 19900 (ISO 2002) for assessment of existing structures. However, ISO 19900 is a rather general standard, not very specific on how to perform assessment. The standard gives some indications that a Design Code format, a Reserve Strength Ratio format and a probabilistic format are acceptable. The ISO 19900 refers to ISO 19902 for design and assessment of offshore steel structures. A detailed assessment procedure for existing structures is found in ISO 19902, API RP2A-WSD (API 2000) and ISO/DIS 13822 (ISO 2000).

However, it should be noted that regulatory requirements normally represent the minimum acceptable standards. Responsible operators are likely to conduct preventative maintenance procedures so that cost effective repairs can be carried out.

IACS common structural rules

With respect to ship structures, the Common Structural Rules (CSR) for oil tankers and bulk carriers (IACS 2006) require a fatigue analysis for all structural details. In the North Atlantic scatter diagram and for 25-years design life, both by means of analytic formulae (for a library of structural details) and FEM fine-mesh calculations. The IACS CSR has also defined the corrosion additions to be added to the net scantlings as a function of the use and protection of the structures in each compartment.

Differences in tankers versus bulk carriers

The Joint Bulker Project and the Joint Tanker Project used two very different procedures for fatigue assessment of ship structures Lotsberg (2006). The procedures are however largely based on well known S-N approaches using BS 7608 as a basis. Lotsberg and Landet (2005) compared five full-scale fatigue tests of side longitudinals of FPSOs with the recommended FAT 90 hotspot stress design S-N curve. They reported that in spite of the different types of connections, different crack initiation points and different crack growth areas, the scatter in the resulting hot-spot test data was not larger than that normally observed for one specific detail, and therefore a single hot-spot S–N curve was supported by the full-scale tests. Fricke and Kahl (2005) continued the study of different structural stress approaches for fatigue assessment of welded ship structures and Caccese *et al* (2006) considered the effect of weld geometric profile on the fatigue life of cruciform welds made by laser/GMAW processes. These studies are useful for the fatigue design of new vessels and are considered fully by the ISSC Fatigue and Fracture Technical Committee. S-N damage models however are of little help in the assessment of aging or damaged structures where there is no load history available.

To design the marine structure with respect to fatigue damage, the “hot spot stress” approach is one of the most practical methods. Usually, it is combined with detailed finite element analysis. It should be pointed out that the calculated local stress around the structural singularities depends significantly on the structural idealization of the element types used and the mesh subdivision. Some applications of this approach can be found in Janssen (2000), Garbatov *et al* (2004).

7.2 *Fracture mechanics – based approach*

In order to properly assess the remaining life of a cracked member, a fracture mechanics approach is necessary (Rizzo 2007). For example, Mahmouda and Dexterb (2005) reported cyclic tension fatigue tests conducted on approximately half-scale welded stiffened panels to study propagation of large cracks as they interact with the stiffeners. A linear elastic fracture mechanics analysis was used to simulate the crack propagation, which gave reasonable agreement with the experiments. The range in stress intensity factor (ΔK) was determined with either a finite-element (FE) analysis or an analytical model at increments of crack length. Analytical and FE models included an idealized residual stress distribution similar to what was measured in the panels. Crack propagation rate as a function of ΔK was estimated using the Paris law with upper-bound coefficients. The experiments and analyses show little sensitivity to stiffener type. They claim the models developed can be used to assess the remaining life of ships with large cracks, leading to more accurate assessment of safety and more efficient scheduling of repairs.

7.3 *Ultimate capacity of cracked members*

It is important to understand the ultimate capacity of cracked members so that limit states can be defined. Talei-Faz *et al* (2004) reported a number of large-scale static strength tests on cracked tubular T and Y Joints similar to those used in fixed and jack-up platforms. These residual static strength tests of cracked tubular joints showed very little difference in static strength capacity between equivalent partial and through-wall cracks which superficially might support the use of flooded member detection (FMD) rather than other more advanced NDT techniques. However, it should be remembered that once a crack is through-wall, it normally propagates at a far higher rate than a partial through wall crack making remedial action increasingly difficult. This is vitally important where life-extension might be required.

7.4 *Inspection, maintenance and repair of fatigue cracking*

Design standards and guidance invariably deal only with the fatigue and damage assessment of new or as-built structures and structural components. The safe and economic operation of ships and offshore structures depends to a large extent upon the ability to determine the condition of the structure so that decisions on maintenance and repair can be made. Condition assessment can be achieved in a number of ways ranging from engineering assessment of manufacturing and operational reports to give a qualitative view of fitness-for-service to detailed quantitative risk assessment using inspection and monitoring information with appropriate damage modeling to predict remaining life (Sharp *et al* 2003). The above study represents a sound fracture mechanics approach to crack propagation under cyclic loading. Ngiam *et al* (2005) demonstrated the development of a stationary standardized load sequence for variable amplitude corrosion fatigue testing of jack-up structural components within a fracture mechanics framework. This means that a representative simulated variable amplitude load sequence can be used to test jack-up platform structural components under corrosion fatigue behavior and the results readily compared with others from laboratories around the world.

Other recent developments that make linear elastic fracture mechanics more accessible are Brennan and Teh (2004), Brennan and Love (2006) and Chahardehi and Brennan (2008). These studies illustrated the rapid calculation of stress intensity factors (SIFs) for complex structural details from relatively simple constituent reference solutions. These solutions are in the form of SIF weight functions allowing the incorporation of residual and other complex stress fields. Okawa *et al* (2006) illustrated a simulation-based fatigue crack management of ship structural details applied to longitudinal and transverse connections. They commented that crack propagation may considerably change depending on the loading conditions, structural details and residual stress distributions, and concluded that it is possible to avoid fatal damage of the skin-plate by properly designing structural details and by implementing a rational fatigue crack management regime.

Repair and improvement techniques are an important element of any crack management and mitigation strategy. Okawa *et al* (2006) showed that by carefully designing stiffeners, cracks in plates can be controlled so that they are forced to follow a tortuous path, taking a considerably longer time to become critical. Ngiam and Brennan (2007) demonstrated that controlled peening (a method of cold working) can considerably delay and possibly arrest crack propagation, showing a five fold increase in propagation life in components under bending. Rodríguez-Sánchez *et al.* (2005) illustrated carefully weld toe grinding (removing cracks by profiling the new surface) can reinstate and possibly even improve original fatigue resistance without re-welding. These methods used in conjunction with an effective fatigue management program can avoid costly replacement and refitting measures while maintaining structural integrity.

The use of composite patches to control crack propagation has found little application in ships and offshore structures. Overall, the effect of corrosive environments on fatigue propagation receives too little attention, as does fatigue propagation in corroded structural components. In some cases, the effect of dents and similar damage on fatigue behavior is also likely to be significant.

7.5 Probability of detection (POD)

Dover *et al* (2003) explained how the reliability of inspection techniques and procedures can be measured and represented in terms of Probability of Detection (POD) and Probability of Sizing (POS), by conducting inspection reliability trials on representative defects under realistic conditions. Most defect assessment codes, for example, BS 7910:2005 and API 579-1 / ASME FFS-1 (2007), now prescribe the use of inspection procedures with minimal POD of 90/95% (95% confidence in the measured 90% POD value). POD appears to be widely used for comparing inspection systems and to prescribe minimum performance levels, but none of the available defect assessment codes describe the implementation of inspection reliability information into fatigue damage predictions. Brennan and deLeeuw (2008) describe a simple treatment of POD and POS (Probability of Sizing) in defect and criticality assessments (see Fig. 7.1).

Fatigue life predictions should be based on a statistical distribution of as-manufactured defects. This means that following a number of years in service, all critical locations are likely to experience crack growth if the fatigue damage models are properly applied. Following inspection, in the case of defect detection, the analysis is updated by applying a new initial defect size based on the results. The accuracy of sizing and probability of false detection should be considered at this stage. In the event of non-detection, it is assumed that the largest defect corresponding to a 90/95% could have escaped inspection. In this way, inspection will always result in a new distribution function to replace the as-manufactured defect distribution. The advantage of applying inspection results is reducing the scatter of fatigue life predictions associated with an as-manufactured defect distribution.

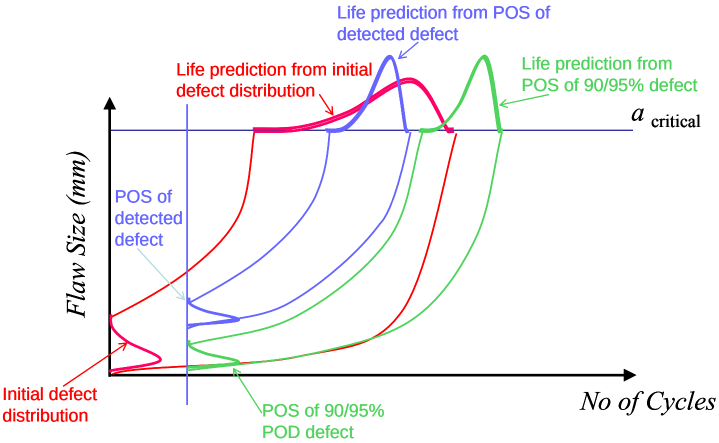


Figure 7.1: The scatter in life prediction can be reduced using latest inspection results (deLeeuw and Brennan 2008).

POS should be considered to determine the extent to which the applied inspection method would over-or underestimate the inspected defect size. They also illustrated how this treatment of POD and POS can be implemented into a limit state for reliability based assessment strategy.

There is, however, no equivalent basis for comparison of many structural integrity monitoring techniques. For example, these measures are completely inappropriate to describe the performance of stress monitoring equipment. In addition, traditional binomial statistics on which POD and POS are generally based can not address the improved confidence that a monitored result will have compared to a blind inspection. Uncertainty associated with relatively few inspection positions becomes much less of a problem because increasing amounts of pertinent information means increased confidence in defect detection and characterization, which will ultimately benefit the decision making/planning process. There is a need to address this situation as the number of monitoring systems used in ship and offshore applications is rapidly increasing.

7.6 Recommendations

The Committee believes that the methods and knowledge of fatigue life prediction developed for damage-tolerant offshore structures can be suitably applied for the damage assessment of aging ship structures.

It is relatively easy to make general statements that good practice should be used to carefully design details and minimize stress concentrations, to allow access for inspection and to carefully control materials and fabrication processes. These, however, are of little benefit in the structural integrity assessment of aging structures.

Numerous references are made to the importance of periodic inspection and increasingly of monitoring techniques. Much fewer references are about the reliability of the information from inspections and with respect to ship structures. There appears to be little understanding of the mechanics of progressive fatigue damage and fracture mechanics, which are the mainstay of any fatigue-dominated damage and criticality assessment.

One aspect that needs further attention is that of widespread fatigue cracking including multiple crack models taking into account the effect of crack interaction. This has become an important area in the aerospace industry which also shares the problem of aging structures. So far, only very simplistic rules exist for the assessment of structures containing multiple cracks and the fundamental understanding of the mechanisms involved need to be developed.

8. CONCLUSIONS AND RECOMMENDATIONS

Continuation of ISSC coverage of integrity of aging structures: The Committee strongly recommends continuation of ISSC committee to cover integrity of aging structures. This is because the regulatory bodies demand for improving safety levels, and the industries need for better management of the structural integrity. In addition, the research communities are continuously advancing the technologies on corrosion, fatigue life prediction, risk and reliability analysis, and structural health monitoring systems.

Corrosion data collection: There has been a concentrated interest in corrosion wastage. Large volumes of data have been collected, which leads to improved knowledge about corrosion wastage in tankers and bulk carriers. The Committee advocates collecting data on other vessel types and offshore units. We also recommend expanding data collection efforts to include information beyond class records or results of tests under controlled conditions.

Interpretation of data: Apparently, a major challenge is presented on the problem of how to properly interpret collected data. This can be seen in both Chapters 2 and 6, where the trends and predictions of the future vary in a wide range. Consensus among research groups is lacking on what method or approach should be used to best interpret data. The Committee advocates comparative studies on existing prediction models with due consideration of the high uncertainty associated with these data.

Reliability and risk-based approaches: Risk and reliability-based approaches have been maturing. They have been applied more and more in condition assessment and inspection planning. The Committee advocates that future research and development be focused on symmetrically applying these approaches, formalizing the analysis procedures, and integrating them as practical tools.

Offshore unit: Coverage of offshore units has been a challenge to this Committee and also ISSC. We recommend increasing the coverage of activities of offshore units.

Structural health monitoring system The Committee predicts that there will be continuous activities in research and development related to structural health monitoring.

Prediction of various degradation mechanisms: The Committee recommends more application of fracture mechanics approaches, continued research on corrosion and prediction of corrosion wastage, and studying of interaction of different aging mechanics.

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USEFUL LINKS

Classification societies
American Bureau of Shipping (ABS), www.eagle.org
Bureau Veritas (BV), www.bureauveritas.com
China Classification Society (CCS), www.ccs.org.cn
Croatian Register of Shipping, www.crs.hr
Det Norske Veritas (DNV), www.dnv.com
Germanischer Lloyd (GL), www.gl-group.com
International Association of Classification Societies Ltd. (IACS), www.iacs.org.uk
Korean Register of Shipping (KR), www.krs.co.kr

Lloyd's Register (LR), www.lr.org
Nippon Kaiji Kyokai (ClassNK or NK), www.classnk.or.jp
Registro Italiano Navale (RINA), www.rina.org
Russian Maritime Register of Shipping (RS), www.rs-head.spb.ru

Regulatory bodies
American Petroleum Institute (API), www.api.org
European Maritime Safety Agency (EMSA), www.emsa.europa.eu
Health and Safety Executive, www.hse.gov.uk
International Maritime Organization (IMO), www.imo.org
International Organization for Standardization, www.iso.org
Minerals Management Service, U.S. Department of Interior, www.mms.gov
Norwegian Petroleum Directorate (NPD), www.npd.no
United States Coast Guard (USCG), U.S. Department of Homeland Security, www.uscg.mil

Incidents investigation
Australian Transport Safety Bureau, www.atsb.gov.au
Bureau d'enquêtes sur les événements de mer, www.beamer-france.org
Marine Accident Investigation Branch, www.maib.gov.uk
Transportation Safety Board of Canada, bst-tsb.gc.ca
Centre of Documentation, Research and Experimentation on Accidental Water Pollution, www.cedre.fr
United States Coast Guard, www.uscg.mil/hq/g-m/moa/casua.htm
U.S. National Transportation Safety Board, www.ntsb.gov
Marine Accident Investigation and Shipping Security Policy Branch, www.mardep.gov.hk
Danish Maritime Authority, www.sofartsstyrelsen.dk
IMO Sub-Committee on Flag State Implementation (only after the FSI 10th session), www.imo.org
Accident Investigation Board Norway, www.aibn.no/default.asp?V_ITEM_ID=29, www.sjofartsdir.no/en/Safety/Accident_Investigations

Shipowners and charterers associations
International Association of Dry Cargo Shipowners (INTERCARGO), www.intercargo.org
International Association of Independent Tanker Owners (INTERTANKO), www.intertanko.com
International Chamber of Shipping (ICS), www.marisec.org
International Tankers Owners Pollution Federation, www.itopf.com
Oil Companies International Marine Forum (OCIMF), www.ocimf.com
Chemical Distribution Institute (CDI), www.cdi.org.uk

Port State Control, Memorandum of Understanding
Paris MoU, Europe and Canada, www.parismou.org

Tokyo MoU Asia Pacific Region, www.tokyo-mou.org
Carribean MoU, www.caribbeanmou.org
Viña del Mar Agreement, Latin American Region, 200.45.69.62/index_i.htm
Indian Ocean Memorandum of Understanding, www.iomou.org
Mediterranean Memorandum of Understanding, www.medmou.org
Black Sea MoU, www.bsmou.net
West and Central Africa (Abuja MoU), www.abuja-mou.org
United States Coast Guard (USCG), homeport.uscg.mil

Protection and Indemnity Clubs
The London Steam-Ship Owners' Mutual Insurance Association Ltd., www.lsso.com
American Steamship Owners Mutual Protection and Indemnity Association, Inc., www.american-club.com
International Group of P&I, www.igpandi.org
The American club, www.american-club.com
UK P&I, www.ukpandi.com

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