Proceedings of OMAE2008
27th International Conference on Offshore Mechanics and Arctic Engineering
15-20 June 2008, Estoril, Portugal

OMAE2008-57411

LIFE EXTENSION ISSUES FOR AGEING OFFSHORE INSTALLATIONS

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ABSTRACT

With many offshore installations in the UK sector of the North Sea now reaching or being in excess of their original anticipated design life, there is a particular need to evaluate approaches to structural integrity management by offshore operators. Ageing processes can affect the structural integrity of the installation and demonstration of adequate performance beyond its original design life is thus a necessary requirement. This paper addresses the issues relevant to the life extension of ageing installations.

INTRODUCTION

With over thirty years of oil and gas production in the UK sector of the North Sea, a significant number of platforms are approaching or have exceeded their original design life, which was specified as typically 25 years. There is a continued requirement that they are operated to produce oil or gas, either from the original fields or to serve as a base for neighbouring subsea completions, and hence they are likely to remain operational for a significant period of time in the foreseeable future. Indeed, in some cases, there are plans to extend the operational life to up to several times the design life.

The age profile for fixed platforms on the UKCS is shown in Figure 1. This indicates that over 127 platforms, i.e. approximately 50% of the total population, are beyond their original design life. It is evident that this proportion is steadily increasing with time, particularly as the rates of platform decommissioning and new installations are relatively low.

Additionally, in recent years a number of mobile installations have been brought onto the UKCS for use as production platforms entailing long-term use on-station. This is not the manner of use for which they were originally designed, as the option of regular dry docking for inspection, maintenance and repair is not allowed for in such cases. This mode of operation introduces issues associated with ageing and reduced inspection and maintenance activity. These operational trends highlight the increasing importance and consideration which need to be given to the subject of ageing and life extension.

Semi-submersible installations are used widely in UK waters in drilling, accommodation, production or construction support roles. A number of the installations are around 20 years old and some date from 1973. It is likely that many of these installations will continue to be operated for several years to come. Previous accidents such as those that occurred to the Alexander Kielland, Ocean Ranger, West Vanguard and Ocean Odyssey show the range of hazards faced by these installations and the consequent risk to life.

Ageing is characterised by deterioration which is caused mainly by fatigue and corrosion. Loss of structural integrity can have serious consequences, depending on the redundancy, component strength, system strength and fatigue life. It is clear that ageing processes affect the structural integrity of the installation and the risk of failure increases with time unless properly managed.

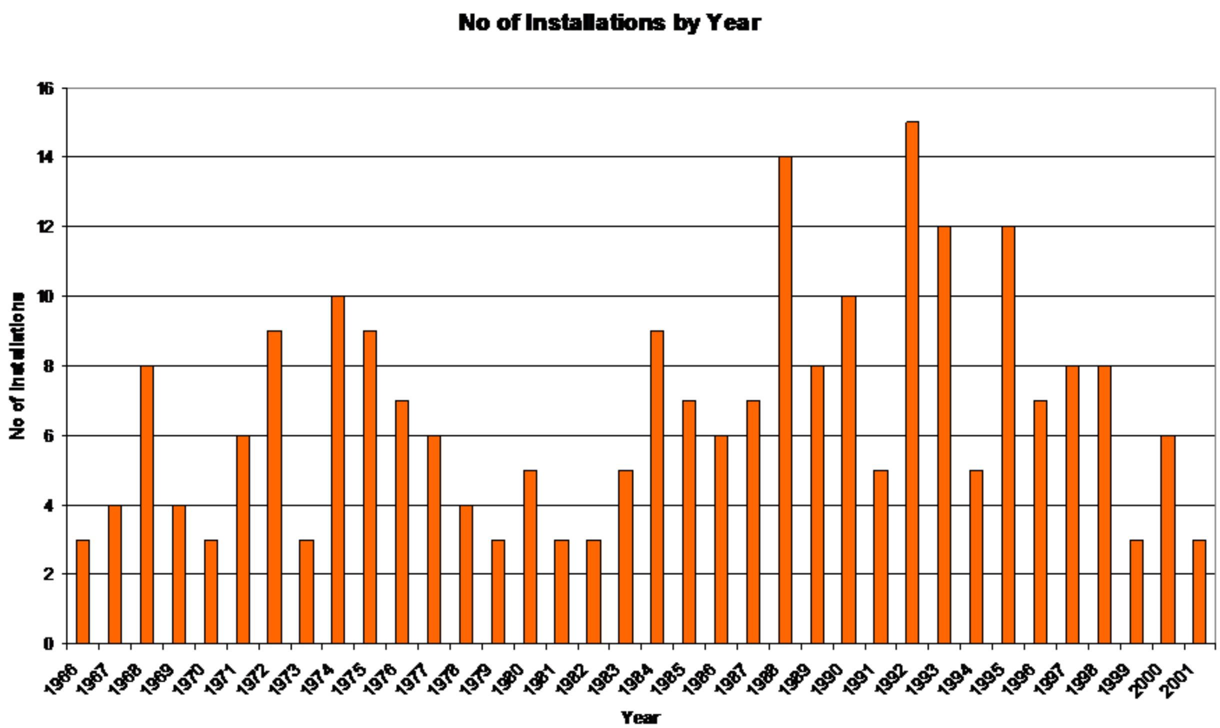

Figure 1: Age histogram for UKCS platforms

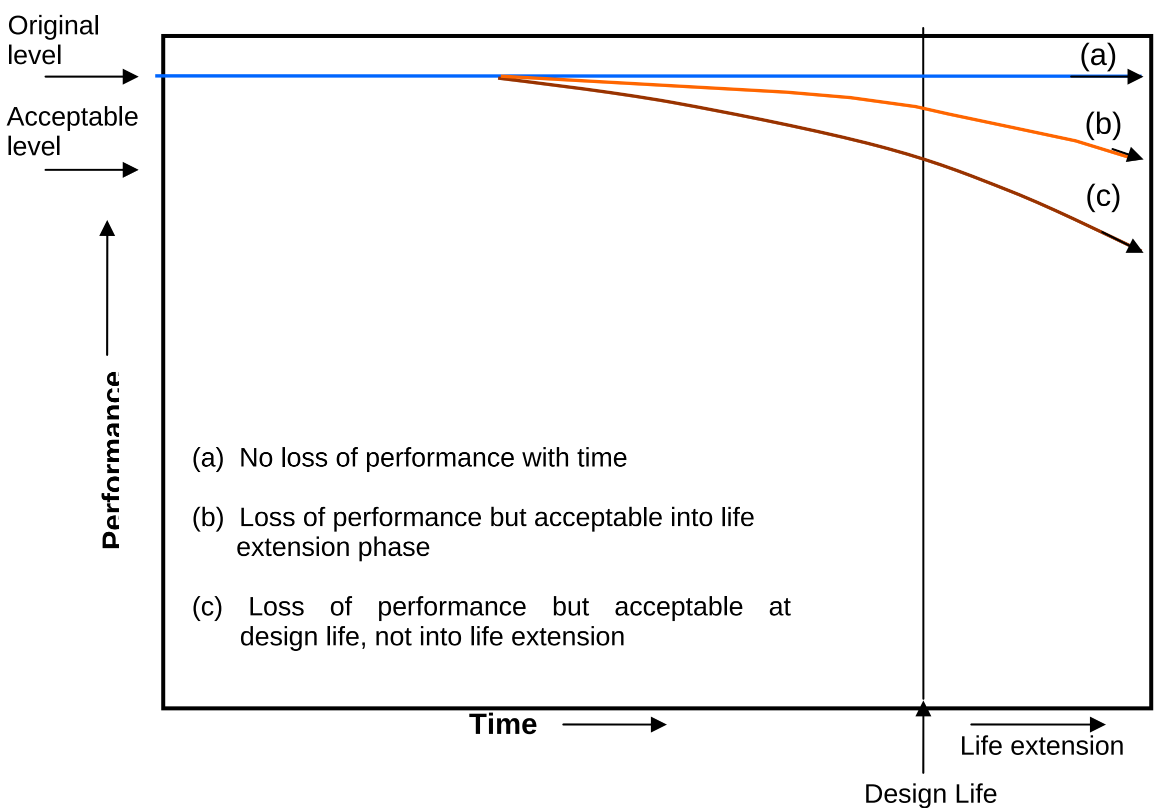

Figure 2: Structural performance during life extension phase

Thus, there is a need to give appropriate consideration to the implications of life extension on the management of structural integrity and to demonstrate continued safe performance beyond the original design life.

Figure 2 illustrates possible variations of deterioration of structural integrity with time. The key issue for ageing installations is the increased uncertainty associated with their performance in the later stages, characterised by the life extension phase, and the assessment of the associated structural integrity. Changes in ownership and cycles of contracting out structural integrity management activities, as well as the change from certification to verification in the period 1996 to 1998 (see below), have contributed to a loss of corporate knowledge, e.g. on the design criteria, the history of inspection and repair (including accidental damage) which impact on understanding of the current condition of the structure. It is important, therefore, that operators ensure that continuity of knowledge and experience is maintained.

Additionally, the uncertainty about the presence of fabrication defects which exist from the outset in all installations is of increasing relevance in ageing installations as small defects may become more significant under the sustained impact of the harsh environmental loading to which installations in the North Sea are subjected. The changes in (a) inspection approaches from detailed to global methods and (b) offshore engineering, codes of practice and environmental criteria are additional factors that need to be considered and are addressed below.

The structural integrity management of ageing installations requires accurate knowledge of both the condition of a structure with respect to fatigue and corrosion and the response of the structure in the aged condition. These, in turn, require appropriate inspection techniques and structural analysis methods. It is important to achieve the correct balance between structural analysis and inspection for the effective structural integrity management of offshore structures in general and this is even more so for ageing installations where there is a greater likelihood of deterioration that needs to be both detected and assessed.

Requirements for the structural integrity management of ageing structures operated in the North Sea are specified in UK and Norwegian national regulations and in national and international standards which have been developing over recent years [1, 2]. This development and the recent emergence of codes dealing with assessment of existing structures – see section 17 of [3], [4], section 25 of [5] and [6] - has provided support for duty holders now having to address explicitly the subject of life extension which is also covered in [7-9] as well as in previous published papers [10-13].

The successful implementation of a structural integrity management plan for life extension depends on understanding the degradation processes, the availability of an appropriate level of data on the actual condition of the structure, reliable assessment methods and an implementation strategy to deal with the increasing risk of failure with time. Thus, the need for a good understanding of the structural integrity performance of ageing installations containing potentially significant deterioration is paramount. The key considerations for life extension of ageing offshore installations are discussed in detail below.

REGULATORY ASPECTS OF AGEING AND LIFE EXTENSION

Regulatory Practice in the UK

The regulatory requirements for the structural integrity management of structures operated on the UKCS are specified in

(a) the Safety Case Regulations [1], which make preparation of a safety case a formal requirement;

(b) the Design and Construction Regulations (DCR) [14], which require the duty holder to ensure that suitable arrangements are in place for maintaining the integrity of the installation, through periodic assessments and carrying out any remedial work in the event of damage or deterioration.

The duty holder needs to provide evidence that foreseeable structural damage to the installation, escalation potentials and all likely scenarios have been considered. Thus, it is of utmost importance that deterioration and degradation are incorporated into a well-formed structural integrity management (SIM) system and associated plan.

The revision of the Safety Case Regulations in 2006 explicitly addresses for the first time the extension of operation beyond the original design life. As part of the update of the UK Safety Case legislation in 2006 [1], a revised safety case is required to be submitted to the HSE where material changes to the previous safety case have occurred. These include:

- extension of use of the installation beyond its original design life;
- modifications or repair to the structure where the changes have or may have a negative impact on safety;
- introduction of new activities on the installation or in connection with it;
- decommissioning a production installation.

The original design life was usually based on fatigue criteria and in the absence of a defined life the recommendation was to assume a design life of 20 years [15]. A revised safety case would need to identify all of the hazards with the potential to cause a major accident, and how the major risks arising from these are or will be adequately controlled. These hazards include those arising from ageing processes associated with life extension, such as corrosion and fatigue. The UK safety case legislation requires reassessment of safety cases every five years by the duty-holder, so in terms of life extension a case for an extended life of five years is the maximum requirement.

The UK offshore Safety Case Regulations [1] require the verification of Safety Critical Elements (SCEs), defined as those parts of an installation the failure of which could cause or contribute substantially to, or the purpose of which is to prevent or limit the effect of a major accident. Typical structural SCEs are the platform sub-structure and the topsides.

For installations on the UKCS there is a formal requirement as part of the safety case legislation for a verification scheme to be provided by which an independent and competent person (ICP) reviews the record of safety critical elements (which would include the platform's structure) and to provide any reservations on this. The verification scheme needs to be reviewed on a regular basis and where necessary revised or replaced in consultation with the ICP. This verification process should include the review of performance standards which are normally associated with safety critical elements. The performance standards are normally based on four main elements which are (i) functionality, (ii) availability and reliability, (iii) survivability and (iv) dependency. In terms of life extension the important elements are availability and reliability and survivability; all of which could be affected by ageing processes.

Performance standards should be developed for SCEs; these standards are usually defined in terms of their functionality, availability, reliability and survivability. It is expected that these performance standards should take account of ageing effects, in that for example corrosion and fatigue could reduce the availability and reliability aspects. To date, structural performance standards are less well developed than those for accidental hazards such as fire and explosion. The application of performance standards to offshore structural components has been addressed in a previous paper [16]. It was noted that design criteria in codes and standards provide a strong basis for setting structural performance standards. In addition, inspection and maintenance are recognised as important for maintaining performance standards, particularly when ageing effects are becoming important. Key performance indicators for offshore structural integrity have been developed and are reported in [17].

Audit is also a formal regularity requirement, as part of the safety case regulations. Such audits are important in demonstrating the organisation's ability to follow the processes which have been set in place. In terms of structural integrity management the development of an overall inspection philosophy and strategy and criteria for in-service inspection are important and would be expected to be demonstrated as part of an audit. The demonstration of structural fitness-for-purpose at the evaluation stage is also very important for the overall safe performance of an installation and should be checked as part of the audit function.

Use of modern codes and standards are recommended by HSE in achieving good practice, which is a requirement in the ALARP approach – see below.

Recommendations for ageing semi-submersibles are given in HSE's Offshore Information Sheet 5/2007 [18]. It is stated that duty holders should periodically reassess their arrangements that are used to maintain integrity, to take account of the effects of ageing processes and to ensure that any deterioration is detected in good time, particularly for installations beyond their notional design life. A number of measures that should be considered (if not already in place) when reassessing the arrangements. These include fatigue life assessment both in the in-tact and damaged condition, inspection requirements, use of information on past performance, replacement / repair of ageing components, review of the effectiveness and reliability of barriers and review of the effect of changes in knowledge concerning technology and environmental conditions that could influence existing barriers or make further measures reasonably practicable.

Regulatory Practice in Norway

In Norway there is a formal regularity requirement for an operator to get permission from the Petroleum Safety Authority to operate beyond the original design life. Formal approval to extend life it is already a requirement under the Norwegian Petroleum Safety Authority (PSA) Regulations [2]. In the guidelines to the PSA regulations information is provided of a list of items that a requirement for consent should contain. These include:

- fatigue life calculated according to current rules and regulations and corrected for changes in assumed weights and weight distribution caused by modifications or changes in assumed usage;
- verification of physical match between the facility and as-built documentation so that- later modifications or changed usage are taken into account in analyses and calculations;
- operators' additional considerations and requirements with respect to inspection and maintenance as a result of extended life for load-carrying structures with respect to fatigue, corrosion, erosion and thickness measurements.

The Norwegian regulations are underpinned by relevant NORSOK and international standards. These are discussed below.

PSA has taken a proactive attitude to managing the life extension process and organized two seminars, one on ageing installations and life extension in September 2006 and the second one in 2007 on the use of components from decommissioned structures to aid an understanding of ageing processes. Relevant papers can be found on the PSA website [19].

Regulatory Practice in the USA

In the USA the leading practice for managing structural integrity is API RP 2A. A new Section 17 was added to [3] as a result of Hurricane Andrew that led to the collapse or severe damage of a number of platforms in the Gulf of Mexico. The damaged caused by Hurricane Andrew showed the need for the offshore industry to obtain a standardized way of documenting the structural integrity of existing structures. Since the offshore activity in the Gulf of Mexico started much earlier than in the North Sea, the number of old platforms is much larger in the Gulf of Mexico. More strict design requirements have been introduced over the years and hence older platforms have a much lower capacity against environmental loads than new installations even without considering the effects of ageing processes such as corrosion and fatigue.

A joint industry project is established to develop a new API recommended practice (API-RP-SIM) that is dealing with Structural Integrity Management (SIM) of fixed platform structures [6]. The document is presently under development. Although life extension is not listed as a trigger for structural assessment there are a number of factors listed which could apply to ageing installations.

Relevant Codes, Standards and Guidance

Relevant codes, standards, recommended practices and guidance that deal with the key elements of the life extension management process, including fatigue and corrosion aspects, are shown in Table 1.

The key documents for life extension are ISO 19900 [4] and ISO 19902 (fixed structures) [5]. In the ISO codes, assessment for life extension is treated as a part of reassessment.

The NORSOK standard on Design of Steel Structures (N-004) [22] also contains a section on reassessment, which includes recommendations to demonstrate 'fitness for purpose' when one or more of the following conditions exist:

- extension of service life beyond the original calculated design life;
- damage or deterioration of a primary structural component;
- change of use that violates the original design or previous integrity assessment;
- departures from the original basis of design (e.g. increased loading or inadequate deck height).

Life Extension Features	Relevant Codes, Standards, & Recommended Practices
Assessment issues	ISO 2394, General principles on reliability for structures, Chapter 8, Assessment of existing structures [20]
	ISO 13822, 'Basis for design of structures, Assessment of existing structures' [21]
	ISO 19900, Offshore Structures, General Requirements, Section 9 - Assessment of existing structures [4]
	ISO 19902, Fixed structures, Section 25, Assessment of existing structures [5]
	API RP 2A 1997, Section 17, Assessment of existing platforms (but excludes life extension as a trigger) [3]
	NORSOK N-004, Design of Steel structures, Chapter 10, Reassessment of structures [22]
	DnV OSS 101, Special provisions for ageing mobile offshore and self-elevating units ([23]
Fatigue life extension	ISO 19902, Fixed structures, Section A15 (Fatigue), Cumulative damage and extended life [5]
	NORSOK N-004, Design of Steel structures, section 10.2, Extended fatigue life [22]
	DnV RP C203, Fatigue Strength Analysis of Offshore Steel Structures, Chapter 5, Extended fatigue life [23]
	DnV OSS 101, Special provisions for ageing mobile offshore and self elevating units [24]
	ABS, Guide for the Fatigue Assessment of offshore structures [25]
	HSE, Offshore Information Sheet 5/2007 'Ageing Semi-submersible Installations' [18]
Corrosion protection	NORSOK, Cathodic Protection, M-503 [26]
	DnV, Recommended Practice, Cathodic Protection Design [27]
Inspection, maintenance & survey	D.En/HSE Guidance Notes – section on Surveys [15]
	API RP2A section 14, Surveys [28]
	ISO 19902 section 24, In-service inspection & structural integrity management [5]
	NORSOK N-005, Condition monitoring of Load bearing structures [29]
	DnV OSS 101, Special provisions for ageing mobile offshore and self elevating units [24]

Table 1: Relevant codes and standards for life extension

The NORSOK section covers several topics in more detail, such as extension of fatigue life, material properties, corrosion allowance, foundations, damaged and corroded members, cracked members and joints, repaired and strengthened members and joints and plates and shells with dents and permanent deflections. However, limited data are available on the residual strength of damaged structural components.

In addition, there is the development of a NORSOK standard (N-006) [30] on assessment of structural integrity for existing offshore load-bearing structures.

One proposed initiator for assessment is the exceedance of design service life. This standard is at an early stage of development.

Design Life & Life Extension

The structural integrity management of ageing installations requires that the definitions of design life and life extension are understood.

The 'design life' of an installation is not well defined in codes and standards. Table 2 shows that there are many different interpretations of ‘design life’ in codes and standards for offshore structures. For the purposes life extension, the definitions given in ISO 2394 [20] and ISO 19902 [5] considered to be the most appropriate and can be adapted thus:

'*The design life is the assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair from ageing processes being necessary*'.

Fatigue life is usually related to a 'design life' and the Department of Energy / HSE Guidance Notes [15] identify a 20-year minimum period.

The original design life is the design working life of the installation assumed at the time of design. Change in use and / or structural modification, if it occurs within the original design life, is considered as ‘reassessment and re-qualification’. A reassessment may lead to a revision of the (remaining) ‘design working life’ but is generally based on the initial design assumptions and criteria.

‘Life extension’ refers to continued operation of an installation beyond the design life assumed at the time of design or revised following a reassessment. Life extension may be accompanied by a change in use of the installation and/or modification of the structure. As it must be assumed that ageing during service will have changed the physical condition of the structure, the baseline for assessment for life extension is not the same as at start of life, and therefore a new assessment is required. This process is therefore different to that of reassessment mentioned above, although they have many aspects in common.

Code, Standard or Guidance	Definition of Design Life
ISO 19900, Petroleum and natural gas industries - General requirements for offshore structures [4]	Section 3.5 - Service requirements - the expected service life shall be specified in design.
ISO 19902 - Fixed steel installations [5]	Section 4 - The assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair being necessary
NORSOK - N001 [31]	Structures shall be designed to withstand the presupposed repetitive (fatigue) actions during the life span of the structure.
HSE Design & Construction Regulations 1996 [14]	Reg. 4 - need to ensure integrity of a structure during its life cycle. Processes of degradation and corrosion to be accounted for at the design stage. Reg. 8 - need to maintain integrity of structure during its life cycle.
ISO 2394 - General principles on reliability for structures [20]	Definition of design working life: "The assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without substantial repair being necessary".
DnV - Classification Note 30.6, Structural reliability methods [32]	Definition of design life: ‘The time period from commencement of construction to until condemnation of the structure’.
D.En / HSE Guidance Notes [15]	Calculated fatigue life should not be less than 20 years, or the required service life if this exceeds 20 years. The (cathodic protection) current to all parts of the structure should be adequate for protection for the duration of the design life.

Table 2: Definitions of design life in codes and standards

STRUCTURAL INTEGRITY MANAGEMENT REQUIREMENTS FOR LIFE EXTENSION

Overview

It is evident from the above that, whilst life extension and the associated structural integrity management is not necessarily a totally new concept, it has been handled historically as part of the ongoing maintenance routine for operational installations without formal recognition as an explicit activity. The introduction of the new requirement in the revised Safety Case Regulations and direct reference to the subject in ISO 19900 and ISO 19902 highlights the need for guidance on the integrity management of structures with life extension.

In general, the duty holder needs to provide evidence that foreseeable structural damage to the installation, escalation potentials and all likely scenarios have been considered. Thus, it is of utmost importance that deterioration and degradation are incorporated into a well-formed structural integrity management (SIM) system and associated plan. The purpose of a SIM plan is to provide a link between the assessment process and the inspection strategy for the installation. SIM plans are

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

Table 3: SIM processes and associated issues affecting life extension

designed to maintain structural integrity on an ongoing basis but did not until recently (see below) address explicitly the extension of operation beyond the original design life.

The principles of a structural integrity management plan are presented below.

Structural Integrity Management Plan

ISO 19900 [4] and ISO 19902 [5], in particular, provide the basic framework for structural integrity management. As noted earlier, ISO 19902 specifically lists one of the initiators for a platform reassessment as exceedance of the original design life.

The developing codes and standards for SI management generally include four main steps in the process which are based on those included in ISO 19902. These are listed in Table 3. As shown in Figure 3, the SIM management process is continuous and sequential, providing a logical framework. It is based on an evaluation of the original design of the structure, inspection findings throughout the life of a structure, any damage found through inspections and its treatment, evidence of overloading and any changes in loading and / or use of the installation. Treatment of life extension based on the above model requires knowledge of additional information.

One of the significant limitations is the lack of knowledge of the installation's history, either through lack of previous inspections or loss of data from the original design, construction and installation and subsequent operation. This lack of data requires careful treatment at the evaluation stage and possibly the use of higher than normal safety factors in the analysis. Current inspection approaches often rely on detection of large cracks or member severance through gross visual inspection or flooded member detection. This provides limited data on the presence of smaller defects which could be important for the assessment of life extension. A more detailed inspection may therefore be required prior to approval for life extension.

One of the four main processes required for structural integrity management is structural evaluation which includes the demonstration of fitness-for-purpose and provides input to the development of relevant strategies for inspection and any remediation required. Evaluation requires consideration of many factors which may affect the structural performance. These include:

- platform age;
- condition (including damage or deterioration of a primary structural component);
- the original design criteria and any information that demonstrates that the original design criteria are no longer valid;
- reserve strength and the degree of structural redundancy;
- platform modifications, additions, any repairs / strengthening;
- change of use that violates the original design or previous integrity assessment;
- departures from the original basis of design (e.g. increased loading or inadequate deck height);
- the versions of the design codes used.

In terms of assessment for life extension, all of the above are important, together with consideration of the expected period of life extension. This depends on the location of the installation. In the UK, a safety case is required to be re-assessed every five years which provides the baseline for the period of life extension.

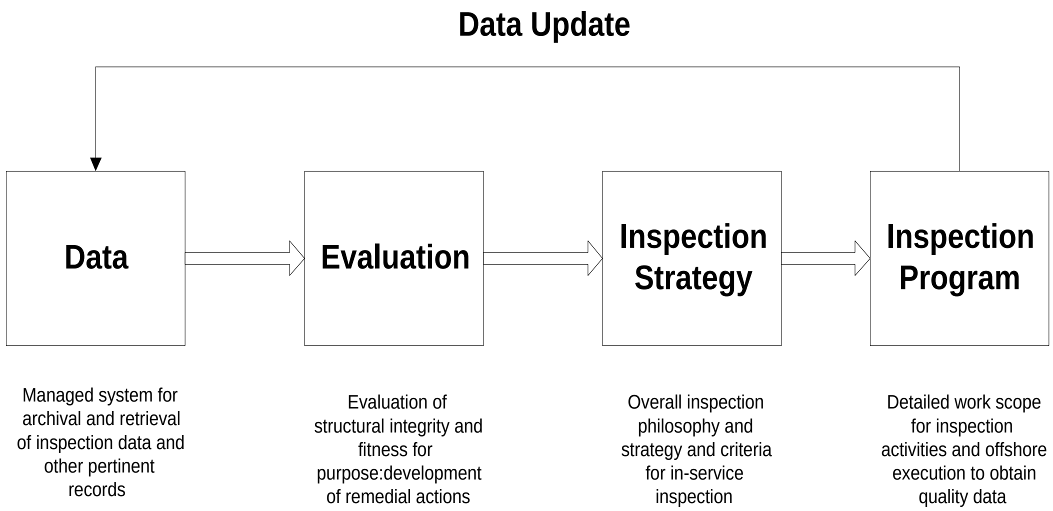

Figure 3: Structural management cycle from ISO 19902 [5]

Competency

ISO 19902 [5] and the draft API RP SIM [6] list a number of competencies required for the effective management of structural integrity. These include the following:

- SIM process (engineer or group of engineers):
  - familiar with relevant information involved in the SIM process
  - familiar with relevant information about the specific platforms under consideration
  - knowledgeable in offshore structural engineering
  - knowledgeable about underwater corrosion processes and prevention
  - cognisant of the difference between design and assessment engineering
  - experienced in offshore inspection planning
  - knowledgeable in inspection tools/techniques
  - cognisant of general inspection findings in the offshore industry

- Data collection & update – familiarity with:
  - structural arrangement, inspection techniques, analysis techniques, interpretation, database administration, material specifications;

- Inspection Programme – engineer, familiar with the
  - content of the overall inspection strategy, and
  - with appropriate experience and technical expertise, related to tasks to be performed

- Offshore execution of inspection programme – supervisors, divers, ROV operators etc qualified to international or equivalent regional standards, with:
  - knowledge of how and where to look for damage;
  - experience in NDE methods;
  - familiar with structure owner's data validation & recording requirements;
  - divers (performing NDE) with accredited training/ qualifications).

In addition, for competency in life extension the following knowledge could be considered on:

- the effects of degradation mechanisms and damage evaluation;
- current structural integrity status (in-service inspection);
- structural assessment processes;
- mitigation measures and risk reduction (repair, load reduction etc.).

Demonstrating competency is an increasing requirement, both for safety and overall performance of an installation. Accreditation is one of the formal ways in which competency can be demonstrated. At present this is only available for offshore execution of an inspection programme, where for example CSWIP accreditation [33] covers supervisors, ROV operators and divers. Some suggestions have been made that accreditation of competency for ageing and life extension issues would be useful, particularly given the increasing number of installations that will require life extension.

STRUCTURAL INTEGRITY CONSIDERATIONS FOR AGEING INSTALLATIONS

Overview of Ageing Processes

Many offshore installations are designed to codes and standards based on limit states, typically ultimate, serviceability, fatigue and accidental. Ageing is most likely to affect the fatigue limit state but the presence of cracking can also affect the reserve strength of an installation, thus affecting the ultimate limit state for the system. Such cracking can also affect the 'after-damage' state of an installation following an accidental event, e.g. boat collision. Subsidence or foundation problems can reduce the air gap, with major implications for survivability in extreme weather conditions. Foundation failure can also have serious consequences leading to platform tilt or even collapse.

Fatigue, System Strength and Inspection

As indicated above, fatigue is a major hazard to offshore structures operating in the harsh environment of the North Sea and indeed usually defines the design life. Cracks initiate and propagate during the operating life in welded joints with high stress concentrations subjected to severe cyclic loading and fatigue failure is considered to occur when a through-thickness crack forms. However, there is considerable uncertainty in the assessment process and it is recognised that cracking can occur within the design life, particularly if defects from the fabrication process remain. In recent years, a number of cases of incidents of severed members and fatigue failures in installations operated in the North Sea have occurred and are a matter of some concern.

An important requirement in the structural integrity assessment of ageing installations and life extension is detailed information from inspections both at the fabrication stage and during the operational phase. However, information on the full inspection history isn't always available. The current trend of relying on global inspection techniques, namely flooded member detection (FMD) and general visual inspection (GVI), as the principal inspection methods applied to primary and secondary members in steel jacket structures has been an important development with respect to structural integrity management. This approach does not allow for the detection and management of the occurrence of small cracks with the potential to cause accumulating and accelerating structural damage which is likely to be associated with ageing structures. Instead, it has brought about an acceptance that significant damage, e.g. through-thickness cracks, must occur for the damage to be detected.

The consequences of local fatigue failure need to be properly understood in the management of ageing installations. The remaining static strength and residual fatigue life in heavily cracked tubular joints, which are addressed in [34, 35], are shown to be reduced substantially. Thus, the adoption of global inspection practices has moved integrity away from the detailed weld inspection approach to one in which more needs to be known about redundancy and the overall integrity of the structure. It follows that the selection of members or joints for inspection should depend significantly on their redundancy level in the structure.

In low redundancy structures the damage necessary for FMD to be effective may result in a reduction in ultimate strength and an associated, unacceptably high risk of structural collapse. For low redundancy structures, it is theoretically possible for such structures to exist in a seriously damaged condition in the interval between inspections. This possibility represents a very high exposure to the risk of catastrophic structural failure. For high redundancy structures, damage may have less serious consequences on structural integrity.

Whilst structures are normally designed on a component basis, fixed offshore platforms generally have a multiplicity of load paths so that failure of one component does not necessarily lead to catastrophic structural collapse. The topic of system strength is discussed in more detail below.

Through-thickness cracking of welded joints can be followed by member severance and loss of stiffness in the local structure. This will lead to load redistribution which will cause other components to be more heavily loaded, possibly resulting in more rapid fatigue cracking, multiple cracking and, depending on the level of redundancy, structural collapse. Thus, as both fatigue life predictions and component strength are affected by load redistribution [36], it is important that due consideration is given in the development of the structural integrity management plan to the possibility of total member failure occurring after penetration of the wall and to its consequences.

It is apparent that the influence of load redistribution on fatigue life can lead to unexpected failures based on the fatigue analysis of the intact structure. It is also possible fatigue cracks may initiate and propagate at fabrication defects which are not necessarily located in those joints identified from the structural analysis as being critical. A lack of information on such defects will give an incorrect view of the structural integrity of the installation. This places additional emphasis on the need for an understanding of the system performance.

Extreme wave loading or accidental ship collision could also lead to local collapse in areas with significant amounts of fatigue cracking. However, it should be noted that the occurrence of multiple cracking, as might occur towards the end of life of a jacket structure, and its impact on structural integrity are not normally considered in the integrity management of ageing installations.

Some structural components are difficult or impossible to inspect but may be vulnerable to ageing processes.

Hence, their current condition is difficult to determine in terms of life extension. Current design practice is to provide such components with large design fatigue factors (as high as 10) which provides a level of safety against ageing. However, earlier designs did not provide this level of safety factor. Examples are piled foundations where the circumferential butt welds are very difficult to inspect and ring-stiffened joints where the internal stiffeners are also difficult to inspect using conventional equipment. In the latter case, there is some indication that fatigue crack in stiffeners can be detected by ultrasonic inspection [37], although this is not current inspection practice offshore. A case for life extension would be expected to address structural components which are difficult to inspect.

Corrosion

Corrosion is an ever-present hazard in a marine environment, especially in the splash zone and topside environments, though it has not led to any major failures in the North Sea to date. However, as a time-dependent process, it is highly relevant to ageing installations. The consequence of corrosion is loss of member thickness, leading to reduced static strength, buckling capacity and possible local structural collapse. Corrosion of riser supports can lead to more rapid fatigue damage to the riser and cracking which, in the extreme, could lead to a hydrocarbon leak. It follows that corrosion performance and the consequences of inadequate control are important considerations in the reassessment process.

Most platforms use sacrificial anode systems, with a distribution of anodes provided to give sufficient protection over the structure. In addition, it is also common practice to provide a 'corrosion allowance' for members located near mean sea level (often between 6-12 mm) where corrosion rates are higher. Steel exposed to sea spray is also vulnerable and in the splash zone epoxy or similar paints are often used to provide corrosion protection, since the CP system is ineffective in this zone. Normal underwater inspection programmes include a condition survey of the anodes, as well as corrosion potential monitoring of areas of the jacket structure. Through this, anodes can be identified and subsequently replaced to ensure an adequate level of cathodic protection is provided for the life of the structure.

Overprotection, defined as where potentials are more negative than -1100mV Ag/AgCl, can be damaging to fatigue (i.e. it can increase fatigue crack growth rates significantly) and to epoxy or similar coatings, with the possibility of bonding to the steel being lost. Hence, design of the anode system is important to minimise this effect and regular monitoring of potentials is also essential to reduce this problem in practice.

ASSESSMENT OF STRUCTURAL INTEGRITY FOR LIFE EXTENSION

Structural Integrity Assessment Overview

The assessment process is established in ISO 19902 [5] and the draft API RP SIM [6] and consists of several stages which include:

- **Assessment** information: the acquisition of the data needed for the assessment, mainly existing platform characteristic data and recent inception data, which demonstrates the current condition of the platform
- **Review of Actions** (loadings): acquisition of relevant metocean data required for the assessment.
- **Resistance assessment:** evaluation of the structure at different levels of assessment. Level 1 is a basic check of the structure following the same requirements as for a new deign. Other levels of assessment include more refined approaches to the assessment of both actions and resistance. Level 3 is based on a linear elastic redundancy analysis. Higher levels of analysis are proposed depending on the data available and the approach needed.
- **Acceptance criteria**: there are needed for each of the assessment levels.
- **Prevention and Mitigation**: appropriate measures need to be considered at all levels of assessment, for structures that do not meet requirements. Measures could include structural strengthening and reduction of lauds on the structure.

Many installations have been designed to earlier versions of structural codes and standards which have subsequently been updated to reflect improved knowledge and experience. Hence, design criteria based on the original version of the code may now be unconservative and no longer valid and reassessment is necessary. In-service inspection practices will determine the nature and extent of the reassessment process to demonstrate structural integrity. Hence, the reassessment process needs to take into consideration the changes in inspection practices that have taken place in recent years as these have implications on the approach to structural integrity assessment.

When it is shown that the structure is not acceptable by analysis then strengthening or repairs may be required to complete the ALARP demonstration. When this is not possible, operational limits may be needed on the platform (e.g. demanning when extreme weather is imminent). The adequacy of fatigue life for the intended remaining life should also be reviewed and this should be taken into account when planning repairs and future inspection schedules.

Knowledge of the design specification and the damage state may not always be available for ageing structures. Safety margins during reassessment need to be increased in such circumstances. It is therefore important that good records of both design details and changes in the structural condition (due to in-service damage and deterioration) are maintained.

Assessment of Fatigue for Life Extension

The codes, standards and recommended practices listed in Table 2 address fatigue life in relation to life extension, both for fixed platforms and also for mobile installations. The basic approach is through the application of design factors to fatigue life, the value of the design factor depending on the criticality and the accessibility of the structural component being assessed. Design factors range form 2 to 10 in ISO 19902 [5], NORSOK N-004 [22] and the ABS document Fatigue Assessment of Offshore Structures [25]. For mobile installations, recommended factors in [25] range between 3 and 5, with critical mooring components allocated a factor of 3. The factors range from 1 to 3 in DnV RP C203 [23] with special considerations being required where fatigue failure will entail subsequent consequences, such as loss of life. However, no specific recommendations are given for this case.

The two DnV classification rules [24, 38] require that when the life exceeds the design fatigue life, mobile installations should be subjected to special evaluation prior to the renewal survey when the nominal age exceeds the documented fatigue life. If no cracks are found prior to the fatigue utilisation index (FUI) reaching one then no special provisions are required until such cracks are found. If fatigue cracks are found prior to the FUI reaching one the owner is required to assess the structural details in the relevant areas at the latest prior to the renewal survey for the 5-year period in which the FUI will reach one. The purpose of the assessment is to improve the fatigue properties of the structure (e.g. by replacement or grinding).

In cases where units have suffered fatigue cracking prior to the FUI reaching one and where satisfactory compensating measures in the form of structural improvements have not been implemented, these units should be subject to additional NDE at intermediate surveys corresponding to the extent required for the renewal survey. An additional requirement is for an approved leak detection system to be fitted when the FUI exceeds one and areas identified for leak detection should be examined for leaks at least twice monthly when the FUI exceeds one. When joints have a FUI greater than unity, additional measures should include a fracture mechanics crack growth assessment of the time to failure of the largest through wall crack that could escape detection from leakage.

ISO 19902 states that for structures that have their life extended or are re-used or converted to a new application, prior fatigue damage may have to be estimated via inspection findings. An absence of crack discoveries should *not* be assumed to mean no prior damage has occurred and the prior damage in terms of the Miner's sum is limited to 0.3 for a welded tubular joint and to 0.5 for a welded plate detail. It is not clear what data these figures are based on. The standard also considers that, assuming a defect-free inspection, lower values of assumed damage may be justified by the designer. This justification may be based on analysis if the prior history of the structure can be established with confidence. However, a value of zero is usually only used for those details that will be modified so as to eliminate prior damage. The ABS procedure [25] has a similar rule to covers situations where an existing structure is being reused or converted.

Fracture mechanics analysis provides a complementary approach to the fatigue life assessment of offshore structures and has a particularly useful role for ageing installations and life extension. Unlike the conventional S-N approach, it enables the assessment of defects detected during inspection and, in principle, provides a more reliable method of predicting remaining life. Furthermore, using deterministic and probabilistic approaches, it provides a means of scheduling the extent and frequency of inspections and determining appropriate inspection techniques based on the accepted level of risk. Fracture mechanics procedures are provided in [39, 40, 41]. The BS 7910 procedure [39] is currently under review and a revised procedure is expected in due course.

Assessment of System Strength

The design of offshore structures is based on satisfying component adequacy. However, structures contain additional strength beyond the failure of individual components and much emphasis has been placed in recent years on understanding the behaviour of the whole structure, i.e. system strength, and developing methods based on pushover analysis to predict the performance of the entire structural system following failure of individual components. System strength analysis provides an indication of the reserve capacity in the structure which, as well as enabling designs to be optimized, enables any available reserve strength to be used following component failure.

The concept of residual strength is very important in assessing the capacity of a structure containing damage, e.g. a large fatigue crack, and is therefore particularly relevant to the assessment of ageing installations, especially in view of the current trend towards reliance on flooded member detection (FMD) as the primary inspection technique for fixed steel installations in the North Sea. There are several definitions of reserve strength [42] and the measure is usually load dependent, giving different values for different wave loading directions. The ability of alternative load paths to carry applied loads when damage is present determines the residual strength of the installation. In general, fixed offshore platforms have a multiplicity of load paths, so that failure of one component does not lead to catastrophic structural collapse. However, two or more cracks in joints within the same failure path could have more serious effects on platform integrity.

Platform configuration is a key factor to be considered in the reassessment of ageing installations. It is widely recognised that X braced panels are more 'ductile' in that they offer alternative load paths compared to, for example, K bracing where once a member fails there is no alternative load path through the frame. The ability to redistribute loads depends on the stiffness of alternative load paths. Thus, the potential reduction in static strength of a joint in K-based framing is likely to be more damaging than a cracked joint in X-braced framing and this needs to be reflected in the level of reassessment of system strength.

It should be noted that the reserve strength alone may not be sufficient to demonstrate the true reserve capacity of a structure - the capacity after the first component failure can also be important, particularly if first component failure leads to system failure. It is important that accidental or other damage to part of an installation should not lead to progressive collapse of the whole structure and this is reflected in recent codes and guidance. However, this may not have been accounted for in ageing installations designed to much older codes and standards. Furthermore, very few tests have been carried out on cracked joints within frames, so knowledge of their performance in this situation is very limited, and most analyses of the damaged state do not allow for more than one component suffering damage at any one time.

In many cases overall capacity is determined by initial member failure, since current design codes (e.g. API) specify that joints should be designed to have greater capacity than members. However, it is recognised that many older platforms contain critical joints, where damage could have significant effects. In addition, the presence of large through-thickness cracks in nodes can reduce the joint capacity to a level where the strength is less than that of surrounding members. Several platforms that failed in Hurricane Andrew showed joint failure, with recovered K joints indicating there was complete severance across the gap region due to extreme loading. In this situation, the presence of a fatigue crack could clearly lead to significant reductions in overall frame strength.

INSPECTION, MAINTENANCE AND REPAIR (IMR)

Current IMR Practice

The treatment of IMR in codes and standards is variable. Under the new goal-setting DCR Regulations [14] the survey requirements are not specified, allowing the duty-holder to detail these to manage structural integrity overall. As a result, different approaches are possible, although most of these rely on FMD, as noted above.

In ISO 19902 [5], IMR is seen in the wider context of managing the overall structural integrity, as indicated in Figure 3. The process includes a managed system of inspection and other structural data, evaluation of this information to develop an inspection strategy and hence a programme of planned inspection for each installation. ISO 19902 provides two different routes for planning inspections, dependent on whether there is a SIM plan (e.g. North Sea structures) or a default periodic inspection programme (for Gulf of Mexico structures), which is very similar to that specified in API RP2A. For the former general guidelines are provided assuming that there is a well developed inspection strategy.

In the assessment of existing structures, surveys to establish the current state of the structure are a necessary step. The level of survey needs to be agreed and in ISO 19902 the recommended minimum level is only level II. This includes an underwater visual survey and, depending on the state of the structure, additional more detailed inspections are recommended to be performed, using appropriate techniques to verify suspected damage, deterioration due to age, major modifications etc.. However a level II survey is somewhat limited and consists only of a general underwater visual inspection, together with measurement of cathodic protection potentials. This level may be adequate for structures which are not subjected to fatigue damage (e.g. US waters) but may not be sufficient for North Sea structures, where the detection of fatigue cracking requires magnetic particle inspection as a minimum.

NORSOK N-005 [29] addresses the implementation of a programme for condition monitoring. There are also specific annexes dealing with methods, jacket structures, column stabilised units, ship shaped units and concrete structures. The standard provides overall guidance only on the principles of condition monitoring, with few specific details of technical requirements and frequency. The importance of maintaining inspection records is also emphasised.

Survey requirements in classification society rules are based on regular five-yearly inspections. Special surveys are generally required at five-year intervals, with the aim of providing an in-depth look at the structural condition of the vessel and all compartments are subjected to survey. Dry-docking is also a part of the requirement that ensures that sufficient access and repair facilities are available. The extent of the requirements of a special survey usually increases with the age of the ship.

On-Line Monitoring

On-line monitoring (OLM), which is discussed in detail in [43, 44], has the advantage of providing a continuous check on integrity and may remove the need for underwater inspection. The technique is based on the principle that in low redundancy structures, the annual probability of failure is dominated by a few critical members. The significant effect of critical members on structural strength implies that their failure would also have a significant effect on structural stiffness and hence a structure's response to periodic loading (i.e. wave loading). If this is the case then the failure of critical members could be detected immediately by a sufficiently sensitive on-line monitoring scheme. This would (a) enable assessment to be targeted at damage as soon as it occurs (directly relevant to one of the five reassessment triggers), and (b) reduce the time to repair and therefore minimise the damage caused to adjacent members due to load redistribution.

On-line monitoring methods have been investigated in the past [43] and have had some success in a few cases where the operator has incorporated the concept into the overall integrity management system. This has been done, for example, where a platform has had a record of member severance. There is a need to consider the further development and adoption of structural integrity monitoring methods which could play a key role in managing life extension by the continual monitoring of structural integrity of offshore installations and the provision of information on ageing processes. This has been recognized in other industry sectors, e.g. bridges, where sensors are installed for continuous monitoring of loads and performance.

Post-Decommissioning Examination

When platforms are decommissioned there is an opportunity to assess the effects of ageing on structural components. This is particularly important for those components which are difficult to inspect in service. To date little opportunity has been taken to test decommissioned components. However when the West Sole platform was removed from the North Sea in 1978 a very detailed analysis was made of the structure as it was the first platform removed from the North Sea [46]. It had a limited life (13 years) but nevertheless provided an opportunity to see what the effects of for example corrosion and fatigue were on components. In general the effects of ageing were limited although some fatigue cracking was found. Structural damage of a minor nature was noted on the jacket as a result of boat collisions and wall thickness and dimensional surveys revealed significant differences in member sizes from as-built drawings (members were stronger and thicker than expected which may have contributed to the good condition of the jacket).

The Forbes offshore platform was removed in 1993 after 8 years of service and subjected to a detailed analysis [47]. The grouted pile-sleeve connections were tested and voids in the grouted annulus found, as well as lower then expected grout strength. However, it was concluded that the measured grout strength was still sufficient to meet design requirements. Inspection by NDE methods of two welded connections showed good agreement with results from an offshore survey preceding the decommissioning. Inspection of the anodes showed a 20% loss of material, consistent with their planned design life.

HSE INITIATIVES ON AGEING INSTALLATIONS

The formal recognition of the significance of ageing highlights the requirement for guidance on the integrity management of structures with life extension. For this reason, HSE, in parallel with initiatives by Norway's Petroleum Safety Authority (PSA), has commissioned studies reviewing structural integrity issues for offshore installations requiring life extension [19] and the development of a structural integrity management framework for offshore installations. The latter is nearing completion and is producing a framework document which is aimed at identifying the key components of a structural integrity management system for offshore fixed steel installations to facilitate a common industry approach. It is planned to extend the study to mobile installations in the next phase. The details of the framework study are presented in [48].

The significance of ageing on structural integrity has been recognised from the outset by the Offshore Safety Division (OSD) of the Health and Safety Executive (HSE). The initial concern originated from the difficulty of agreeing adequate procedures for certifying older platforms, in particular concerning application of new codes, proposals to limit inspection of structures (related to fracture mechanics assessments) and the matter of modifications to facilities.

HSE's Offshore Division is currently involved in a number of interactive activities associated with the question of ageing installations and life extension:

- the development of a technical policy and strategy;
- technology projects;
- standards and guidance development;
- the Structural Integrity Management Inspection Programme (SIMIP) [49];
- collaboration / exchange of information and experience with its Norwegian counterpart, the Petroleum Safety Authority (PSA).

The Structural Integrity Management Inspection Programme (SIMIP) supports OSD's Structural Integrity Strategy on the major accident hazard area of 'loss of integrity'.

The recent structural integrity inspection programme is based on four discrete theme inspections, namely:

- ageing installations and integrity management (for all types of structure – floaters, fixed and jack-ups; topsides and underwater);

- understanding uncertainties in extreme weather hazards;
- fire & explosion response;

Additional theme inspection programmes being developed for implementation in 2008 are:

- impact loading & response;
- foundation failure
- reliability techniques (quantification and performance standards).

The above items are described in more detail in [49].

DISCUSSION

The subject of ageing installations is of considerable significance for the offshore industry and one that will remain so with an ever-increasing population of ageing structures. This significance is increasingly reflected in the content of current regulations, codes, standards and recommended practices which give recognition to the requirement that specific consideration of the ageing process is required.

The fundamental aspects of the structural integrity management process are provided in ISO 19902 and work currently being undertaken by HSE and PSA is providing fuller definition to the elements of a structural integrity management framework for fixed installations. This will be extended duly to mobile installations. In parallel with this, HSE is undertaking a number of inter-related activities to advance its programme on ageing installations, including a review of new technology research relevant to the assessment of ageing installations, investigation of on-line monitoring techniques and SIMIP, which is obtaining information on the structural condition of installations on the UKCS. Furthermore, there is direct collaboration with PSA to enable exchange of information and experience with a view to establishing best practice in the North Sea.

It is apparent that the structural integrity management of ageing offshore installations can be a complex process. The performance of ageing installations can be highly variable as deterioration can occur at any stage in the life cycle, depending on the design of the structure, the fabrication quality, the in-service inspection and repair activities and the quality and extent of structural assessment. There is also the issue of deterioration which is not known about, either because of inadequate inspection or because the component is uninspectable.

The above considerations indicate that ageing offshore installations are subject to considerable uncertainties which demand that there is a need for detailed information on their performance. This requires further understanding of structural behaviour (characterised principally by the fatigue strength and system strength) and the importance of inspection strategies that provide accurate information on the condition of the structure. The effective management of ageing installations entails the effective application of inspection and maintenance strategies and structural analysis techniques. This also requires competency in the wide range of activities essential to the structural integrity management process and the importance of this cannot be overstated.

A considerable amount of research on the structural performance of offshore structures has been performed over the years. Much of this has been used in the development of current standards and guidance. The information is generally openly available and will be used in the next phase of standards development. Areas of particular progress include the understanding of system performance following single and multiple member failure, the effects on fatigue life due to load redistribution and structural reliability analysis for the determination of inspection plans and evaluation of system reliability. Other areas include the latest metocean data, materials performance (e.g. grade A ship steels and high strength steels used in jack-up construction) and foundation failure criteria.

The understanding of structural and materials performance is an ongoing activity. As platforms age, the industry needs to make use of the information that becomes available to improve knowledge and current practices and assessment procedures. The inspection of decommissioned structures would provide particularly valuable information on structural and materials performance for all types of component but particularly for normally uninspectable components.

Operators have tended to treat installations in the life extension phase in the same way as installations operating within their design life. This is particularly associated with the move to the goal-setting verification regime from certification (which required a five-yearly review prior to qualification for a certificate of fitness), despite the fact that the goal-setting approach of the current verification regime has not eliminated the requirement for evaluation. Nevertheless, the explicit reference to life extension in recent regulations, codes and standards has helped to clarify the situation. Additionally, the development of a framework document for structural integrity management [48], incorporating best industry practice, should provide further assistance with the management of life extension.

CONCLUSIONS

A review of the subject of life extension for offshore installations leads to the following conclusions:

(1) life extension assessment is a distinct activity which has only recently been formally recognised by the offshore industry, largely due to the recent introduction of regulatory requirements and the new

ISO standards for offshore structures, ISO 19900 and ISO 19902.

(2) guidance on life extension is limited but is developing.

(3) life extension of offshore installations raises safety issues relating to structural integrity that go beyond traditional practice in the offshore sector.

(4) there is a need for better awareness of the hazards arising from ageing processes and preparedness for the possibility of accumulating and accelerating structural damage that might occur in the life extension phase.

(5) the main technical issues to be addressed are accelerating local fatigue beyond design limits, widespread fatigue damage and subsequent loss of redundancy, maintenance of corrosion protection and allowances, pile integrity, accumulated accidental damage.

(6) current structural integrity management plans are variable in the type and amount of information they contain about the methods and means by which structural integrity of safety critical elements is assured, particularly in the life extension phase. It is considered that many plans do not provide sufficient information from which the adequacy of these methods and means could be judged to demonstrate safe life extension. It would be appropriate to review current inspection and maintenance regimes to ensure that they are designed to detect and manage the onset of accumulating and accelerating structural damage.

(7) the effective structural integrity assessment of installations for life extension requires detailed knowledge of the current state of the structure.

(8) information on the structural condition may not necessarily be available from current inspection practice, e.g. GVI and FMD - there is a requirement for more extensive data for life extension assessment.

(9) current inspection and maintenance regimes are not generally designed to detect and manage the onset of accumulating and accelerating structural damage.

(10) structural components which are susceptible to ageing processes and are difficult or impossible to inspect, e.g. piles, are a matter of particular concern for life extension and require special consideration.

(11) there is a need for the development and application of new inspection techniques, e.g. on-line structural monitoring methods, to enable continuous monitoring of the structural integrity of offshore installations during the life extension phase.

(12) data on the original design criteria, material properties, fabrication quality and installation performance are also required but may not necessarily be available.

(13) it is important that assessment for life extension takes account of new technology developments in structural assessment, particularly in system strength, to enable a better understanding of the structural capacity of ageing installations which are likely to have a higher incidence of deterioration.

(14) it is important to take advantage of inspecting and testing components from decommissioned structures to establish the effects of ageing – this is particularly beneficial for components that are difficult to inspect.

(15) the ISO 19900 series of standards provides a good basis for the assessment of life extension but the standards are still evolving. Neither ISO 19904 for semi-submersibles, which was published in 2006, nor ISO 19905 for jack-ups, which is not expected to be published prior to 2010, contains specific recommendations on life extension. Other codes, standards and guidance (e.g. API, HSE Guidance Notes) do not adequately cover life extension, although some industry codes and regulatory guidance (e.g. DNV, HSE Safety Notice 1/2003) are becoming available in selected areas.

(16) the benefits of sharing duty holder experience on managing life extension need to be exploited.

ACKNOWLEDGEMENTS

The views expressed in the paper are those of the authors and do not necessarily represent those of the Health and Safety Executive.

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