Petroleum Safety Authority Norway

Report no
REN2021N00099-RAM-RP-00004

Date
February 14, 2022

THE USE OF DIGITAL SOLUTIONS AND STRUCTURAL HEALTH MONITORING FOR INTEGRITY MANAGEMENT OF OFFSHORE STRUCTURES

INDUSTRY STUDY AND GUIDANCE REPORT

RAMBOLL Bright ideas. Sustainable change.

Report title:	The use of digital solutions and structural health monitoring for integrity management of offshore structures	
Report name:	PSA – Monitoring of Structural Integrity	
Customer name	Petroleum Safety Authority Norway	
Date of issue:	2022.02.14	
Project no.:	1100046947	
Organisation unit:	Energy / Marine structures	
Report No.:	REN2021N00099-RAM-RP-0004	
Report type:	Study report	

Ramboll
Hannemanns Allé 53
DK-2300-Copenhagen S
Denmark
T: +45 5161 1000
https://ramboll.com

PSA has commissioned Ramboll to carry out an industry knowledge gathering study with the purpose of providing guidance to the industry regarding the use of digital solutions and structural health monitoring for integrity management of offshore structures. The expectation in doing so is that it is possible to elevate the integrity of structures through guidance and adoption of these fundamental solutions. Furthermore, there is a potential positive impact of improved safety of offshore structures on the Norwegian Continental Shelf.

Made by:

Bjørn T. Svendsen

Ulf Tyge Tygesen

Jens Kelly-Rosenville

Nadir Azam

Checked by:

Niels Dollerup

Nadir Azam

Approved by:

Bjørn V. Jønsson

Made by	Checked by	Approved by	Date	Rev.	Comment
BJTS, UTT, JXR, NAAZ	NSD, NAAZ	BVJ	2022.02.03	0	Issued for comments
BJTS, UTT, JXR, NAAZ	NSD, NAAZ	BVJ	2022.02.14	1	Final issue

CONTENTS

APPENDICES

Appendix 1
Considerations for implementation of the framework (simplified guidance)

Appendix 2
Questionnaire

Appendix 3
Acknowledgements

Appendix 4
The SIM process

ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AE	Acoustic Emission
AI	Artificial Intelligence
BP	British Petroleum
CAPEX	Capital Expenditure
CoV	Coefficient of Variation
DC	Direct Current
EFDD	Enhanced Frequency Domain Decomposition
EI	Energy Institute
EMA	Experimental Modal Analysis
ER	Electrical Resistance
FAT	Factory Assurance Test
FDD	Frequency Domain Decomposition
FE	Finite Element
FEM	Finite Element Model
FMD	Flooded Member Detection
FPSO	Floating Production, Storage and Offloading
FSO	Floating Storage and Offtake
GBS	Gravity Based Structure
GPS	Global Positioning System
HSE	Health Safety and Environment
IMR	Inspection, Maintenance and Repair
LiDAR	Light Detection and Ranging
LVDT	Linear Variable Differential Transducer
MAC	Modal Assurance Criterion
MEMS	Micro-electromechanical System
ML	Machine Learning
MSL	Mean Sea Level
NCS	Norwegian Continental Shelf
NDT	Non-Destructive Testing
OMA	Operational Modal Analysis
OPEX	Operating Expenses
PBSHM	Population-Based Structural Health Monitoring
PoF	Probability of Failure

PSA	Petroleum Safety Authority
RBI	Risk Based Inspection
RP	Recommended Practise
SAT	Site Assurance Test
SIM	Structural Integrity Management
SHM	Structural Health Monitoring
SHMS	Structural Health Monitoring System
SSI	Stochastic Subspace Identification
TLP	Tension-leg Platform
UMS	Unit for Maintenance and Safety

1. EXECUTIVE SUMMARY

This project is based on funding from the Petroleum Safety Authority (PSA) in Norway. The objective of the project is to develop a guidance report regarding the use of digital solutions and structural health monitoring (SHM) for integrity management of offshore structures. To accomplish the objective, an overview of existing codes and standards that include digital solutions for structural integrity management is established, and information obtained from the industry regarding sensor technology for data collection is presented. The information from the industry has been obtained through comprehensive work and dialogue with several industry partners and companies. Most importantly, a framework to structure the use of digital solutions and SHM for integrity management of offshore structures is proposed. Additionally, the value creation of this framework is presented.

SHM can provide information regarding the current state of the structural condition. There is a potential in using SHM systems on offshore structures to move towards condition-based inspection while maintaining or increasing the structural safety. The motivation for performing SHM is to detect structural damage and obtain information to provide risk reduction and optimization of maintenance, lifetime extension, reduction of inspection costs and increased structural safety.

The existing codes and standards such as ISO, API and NORSOK cover topics related to inspection and structural monitoring of offshore structures. Although the application of structural monitoring systems and SHM are considered mature from a scientific perspective, there is limited information in the existing codes and standards regarding these topics. Furthermore, an overview of data collection using sensor technology relevant for structural monitoring applications is presented. Although extensive measurement equipment and sensor technology applicable for offshore structures exist, there are increasing challenges related to data management. Furthermore, the most important phase for successfully implementing SHM is the planning phase. In particular, mapping of critical elements related to the structural safety and identification of failure modes are important to consider when designing a structural monitoring system.

A novel framework for how digital solutions and SHM for integrity management can be structured is established. The presented framework, which consists of a pre-study and five levels, provides a coupling between a digital twin and measurements obtained from structural monitoring. This coupling facilitates a direct performance evaluation of the digital twin against measurements and creates the basis for improving the performance of the digital twin to capture the actual condition of the structure more accurately. Furthermore, the state-of-the-art recognised digital and automated solutions that can enhance structural integrity of offshore structures include experimental and operational modal analysis, virtual sensing, FE model updating, wave load calibration, quantification of uncertainties from measured data and risk based inspection (RBI) planning analysis.

The use of SHM on offshore structures provides value in terms of change management, decision-making, predictive maintenance and risk control. These factors result in a safer and cost-optimized operation of the offshore structures. In the future, the presented framework will set the *standard* with respect to the use of digital solutions and SHM for integrity management of offshore structures.

Keywords: Structural health monitoring (SHM), instrumentation, damage detection, framework, structural integrity assessment, lifetime extension, offshore structures.

2. INTRODUCTION

2.1 Background

Being in the early 2020s, it is recognised that the North Sea has been developed for oil and gas production for close to 50 years. As many of the installations (fixed platforms as well as floating units including semi-submersibles) are reaching or have exceeded their original design lives, there is a particular need to evaluate both past and present approaches for structural integrity management (SIM) and accompanying structural monitoring and inspection techniques. Such an evaluation is needed throughout the entire chain of the industry, i.e., from suppliers and consultants to operators and regulatory entities. These aspects are equally important when considering optimization of the operation and maintenance of offshore wind substructures.

A large part of the ageing structures on the Norwegian continental shelf (NCS) is now being operated by different operators than the original operators. Some of these operators are new in the industry. Furthermore, new and existing operators experience several challenges with respect to ensuring that the structures at all times meet regulatory requirements according to national and international standards. Typically, operators and asset owners are the main responsible and accountable entities to ensure that adequate integrity management of assets are put in place and effectuated accordingly. The operators and asset owners are equally dependant on viable solutions in the market to do so - balancing end-value, cost, and practical and technological barriers. The importance of controlling the structural integrity offshore is increasingly recognised through SIM [1], which covers the need to monitor, inspect, maintain, repair, evaluate and document an asset to ensure that its condition remains fit-for-purpose during its entire lifetime. The alternative is a potential loss on the investment by initiating decommissioning of the outdated production facility.

The amount and quality of the information gathered from offshore structures are essential, particularly considering how this information can provide greater confidence in the structural integrity, complement existing inspection methods, or reduce inspection and maintenance costs. Furthermore, it is important to ensure that existing numerical models adequately represent the true condition. An offshore structure may change during the operational lifetime due to natural degradation mechanisms and structural changes such as new platform extensions, increase in the topside mass, subsidence issues, structural damage, or changes in the operational and environmental loading. Consequently, numerical models should be updated using state-of-the-art algorithms and methods to reflect the actual and current conditions of the structure during its lifetime to ensure correct numerical predictions, keeping in mind that the overall goal is to document compliance to the regulatory requirements and standards.

Structural monitoring systems can continuously gather information of the structure through instrumentation and the corresponding data acquisition. Furthermore, SHM, referred to as the process of implementing an automated and online strategy for damage detection in a structure [2], [3], can provide information about the current state of the structural condition [4]. Today, traditional inspection methods[1] are often used to gather information regarding the state of the structural condition. The frequency of inspection intervals of these methods is to a certain degree predefined or determined using risk-informed methods. There is, however, a potential in using SHM systems to move towards condition-based inspection while maintaining or increasing the structural safety. The motivation for performing SHM is to detect structural damage and obtain information to provide risk reduction and optimization of maintenance, lifetime extension, reduction of inspection costs and increased structural safety.

[1] Traditional inspection methods are considered as visual inspection, non-destructive testing (NDT) or flooded member detection (FMD)

2.2 Regulatory requirements on the NCS

The Petroleum Safety Authority (PSA) Norway is a government supervisory and administrative agency under the Norwegian Ministry of Labour and Social Inclusion. PSA has regulatory responsibility for the safety, work environment, emergency preparedness and security in the petroleum sector. Further, PSA is responsible for determining parameters for the oil and gas industry and ensuring that activities in the sector are pursued prudently. Authority has been delegated to PSA to establish detailed regulations for the safety and working environment in the Norwegian industry and to take administrative decisions in the form of consents, orders, coercive fines, shutting down operations, prohibitions and exemptions, etc.

Each company involved in the Norwegian petroleum industry is responsible for the safety of its own operations. This responsibility represents a fundamental principle in the petroleum regulations. Furthermore, the operators are responsible for ensuring that everyone doing work on their behalf complies with the requirements specified in the Health, Safety and Environment (HSE) regulations and prudently conducts the relevant activities [5]–[9].

In the context of management and control of the integrity and associated risks for structural assets, there are key requirements for integrity and monitoring provided in the PSA regulations, particularly in the Framework Regulations [5], the Activities Regulations [6], the Facilities Regulations [7] and the Management Regulations [8]. The clear rationale is that all involved parties shall work to continuously reduce risk and identify the processes and activities where improvements are needed. Additionally, improvement measures should be implemented where and when necessary. Furthermore, according to the Management regulations §19 (collection, processing and use of data) [8]:

"*The responsible party shall ensure that data of significance to health, safety and the environment are collected, processed and used for:*

a) monitoring and checking technical, operational and organisational factors,

b) preparing measurement parameters, indicators and statistics,

c) carrying out and following up analyses during various phases of the activities,

d) building generic databases,

e) implementing remedial and preventive measures, including improvement of systems and equipment.

Requirements shall be set as regards the quality and validity of the data, based on the relevant need".

The requirements by PSA are supplemented by the NORSOK standards, such as NORSOK N-005 [10], which covers in-service integrity management of structures and marine systems. Hence, it is evident that there is a framework for structural integrity management and structural monitoring by considering the defined regulatory requirements. In general, such a framework is valid not only for structures and assets on the NCS but also for other parts of the North Sea and world. Consequently, considering the growing number of aged offshore structures on the NCS, PSA has initiated a project with the purpose to identify, describe and front-load how technology and knowledge can be used to improve the safety of the Norwegian offshore industry. PSA has commissioned Rambøll to carry out this work.

3. THE PSA PROJECT

3.1 Objective
The objective of the project is to gather and evaluate current knowledge and information and further to develop a guidance report regarding the use of digital solutions and SHM for integrity management of offshore structures.

3.2 Scope of work
To accomplish the objective, the following scope of work is defined:

- Obtain an overview of existing codes and standards that include digital solutions for structural integrity management.
- Establish current information, methodologies and knowledge in the industry regarding the use of digital solutions for structural monitoring with focus on sensor technology for data collection.
- Propose a framework for how digital solutions and SHM for integrity management can be structured, particularly related to offshore structures.
- Develop a simplified guidance for implementation of the proposed framework and highlight the value creation.

Through the scope of work, technology within SHM and digital solutions related to integrity control, digital twinning and damage detection algorithms will be identified and addressed to enhance the general understanding in the industry. Consequently, the experience obtained from an industry knowledge gathering process and the associated evaluation process is shared through this project report.

3.3 Limitations and assumptions
The following assumptions and limitations are included to further clarify the framework of the scope of work defined in this project:

- Detailed technical aspects of sensor technology, algorithms or methods will not be considered, but merely clarifications of the possibilities, limitations, overall purpose and value creation. Already established and published material will be included as a basis and referenced.
- The main focus will be to cover existing offshore structures. These structures include, but are not limited to, fixed structures, gravity-based structures (GBS), topside structures and semi-submersibles (floaters). However, the technology and methods described may also apply to new build structures and structures within the wind industry (wind turbines and population of structures in wind farms).
- The aspects of inspection and monitoring are introduced through the definitions provided according to the existing codes and standards. However, it is the aspect of monitoring that is the focus of this report in the context of SHM.

3.4 Project execution description

Figure 3-1 shows an overview of the project execution strategy which is divided into separate phases. An important part of the project has been to establish current information, methodologies and knowledge in the industry. Consequently, acknowledgements are made to relevant regulators, operators, engineering companies, service companies and institutes. These include HSE, PSA, BP, Chevron, Altera Infrastructure, DHI, DNV, FORCE Technology, Fugro, Kent PLC, Light Structures, NetDesign, ROSEN Group, EI, MARIN and SINTEF.

For further details of the process to establish current information, methodologies and knowledge in the industry, see Appendix 2. For further details of each company, including relevant contact information and a short description of the specific contribution to this work, reference is made to Appendix 3.

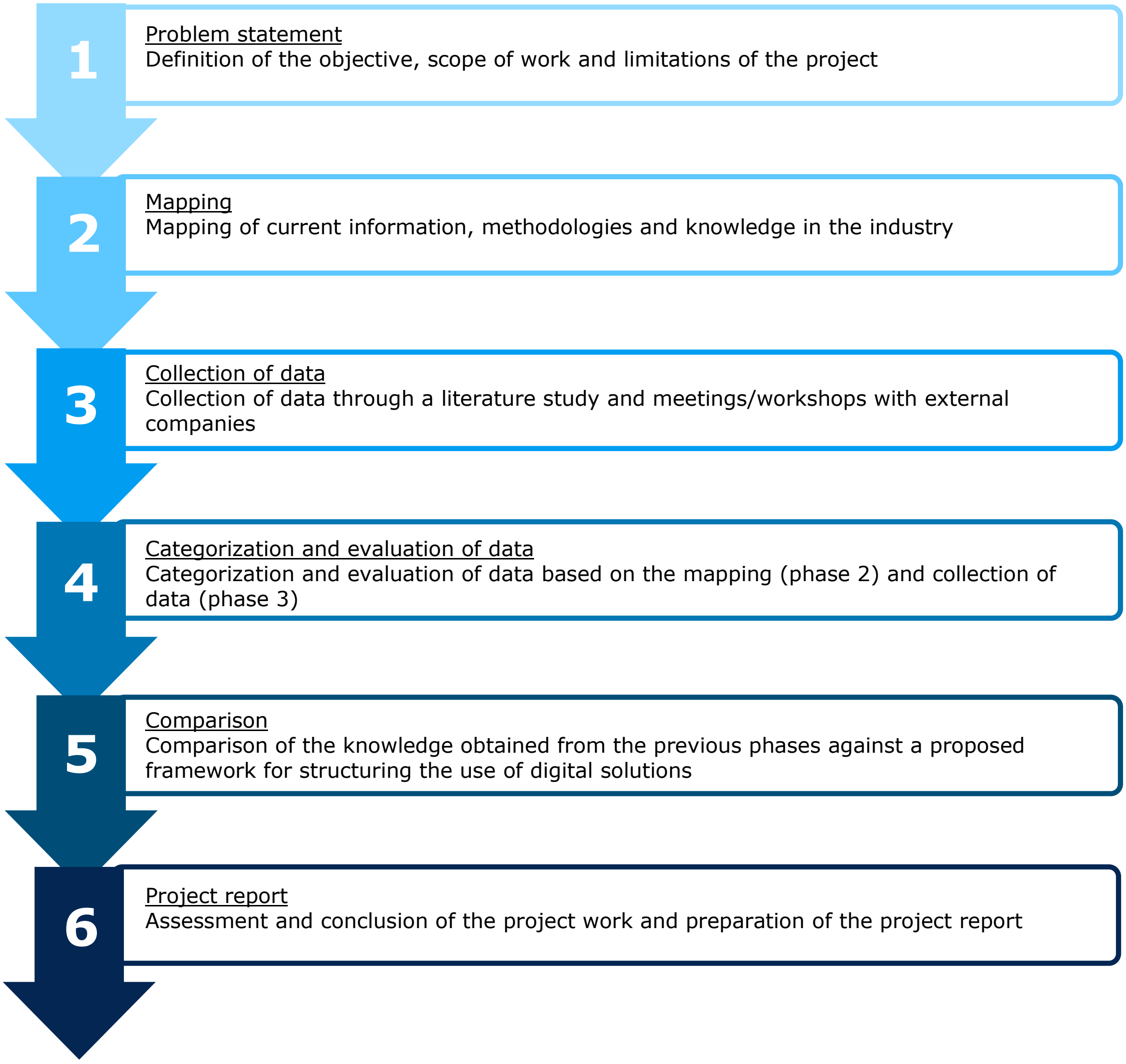

Figure 3-1: Overview of the project execution strategy.

4. EXISTING CODES AND STANDARDS FOR DIGITAL SOLUTIONS AND STRUCTURAL INTEGRITY MANAGEMENT

4.1 General

This section presents an overview of existing codes and standards for digital solutions and structural integrity management (SIM). More specifically, the existing codes and standards presented primarily cover topics related to inspection and structural monitoring of offshore structures.

The philosophy behind the concept of SIM is to create a structured process that provides evidence for relevant stakeholders and to the operator that the structure is fit for purpose at all times. Fundamental parts of this process include inspections and periodic and systematic evaluations of data from structural monitoring systems. A simplified overview of the SIM process is shown in Figure 4-1. The intent of the process is to enhance the quality of the data used to confirm fitness-for-service [1]. A detailed overview of the SIM process is included in Appendix 4. It should be noted that structural monitoring can be classified as a subset of inspection.

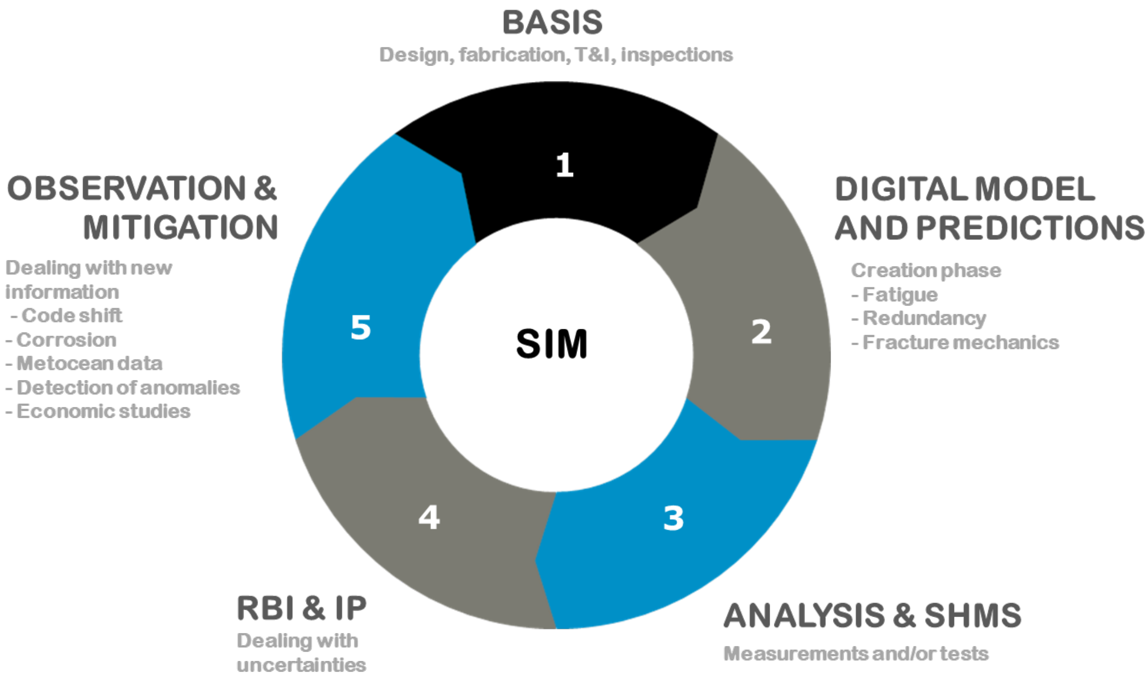

Figure 4-1: A simplified overview of the SIM process that includes the integration of SHM.

4.2 Existing codes and standards

In general, recognised international standards such as ISO, API and NORSOK define requirements and recommendations relative to in-service inspection, condition monitoring and maintenance. The requirements and recommendations cover phases such as design, fabrication, transportation, installation and in-service conditions, the latter as a part of the associated integrity management standards.

Table 4-1 and Table 4-2 present an overview of relevant parts of ISO and NORSOK standards, respectively, that cover specific requirements for offshore structures. Relevant parts of the API standard are not included since these correspond well with the ISO and NORSOK standards [11].

Table 4-1: Overview of relevant ISO standards and associated parts that cover specific requirements for offshore structures.

Standard	Notes
ISO 19900 [12]	General requirements for offshore structures The standard specifies general requirements and recommendations for the design and assessment of bottom-founded (fixed) and buoyant (floating) offshore structures. It is defined that the durability of a structure shall be achieved by adequate design and assessment, inspection, monitoring, maintenance and repair. Only in-service inspections are mentioned relative to a required strategy (Clause 5.5). The concept monitoring is covered relative to the required SIM scheme (Clause 12.3).
ISO 19901-1 [13]	Part 1: Metocean design and operating conditions The standard gives general requirements for the determination and use of meteorological and oceanographic (metocean) conditions for the design, construction, and operation of offshore structures of all types. With respect to monitoring, the standard is intended as an initial reference for operators and asset owners when planning metocean monitoring equipment for offshore installations. Applications such as weather forecasting and climate statistics are included by adopting measurements as a source for, e.g., metocean databases.
ISO 19901-3 [14]	Part 3: Topsides structures The standard provides requirements for the design, fabrication, installation, modification and structural integrity management for the topside structure. For in-service inspections and SIM, reference is made to ISO 19902 (and thereby ISO 19901-9), i.e., baseline, periodic and special inspections are mentioned, and requirements are made relative to the level classification. Several considerations are made for corrosion aspects regarding monitoring. However, monitoring is only mentioned two times, i.e., for root-cause analysis of vibration problems and for accidental actions.
ISO 19901-4 [15]	Part 4: Geotechnical and foundation design considerations The standard contains provisions for those aspects of geoscience and foundation engineering that are applicable to a broad range of offshore structures. While inspection and monitoring are covered in general terms, specific recommendations are provided for certain cases, such as in Clause 5.4. In this clause, it is recommended that the structure or its foundation should be fitted with permanent instrumentation if excessive foundation settlement, tilt, or other problems are present. Similar other examples and recommendations are provided.
ISO 19901-9 [1]	Part 9: Structural integrity management The standard primarily covers fixed steel structures. It is defined that a required SIM strategy shall identify the mitigation, monitoring and inspections to be included in the continuous risk reduction requirements for the structure and safety critical components. Different inspection methodologies are provided. However, while basic and periodic (consequence-based) inspection intervals are defined, definitions of RBI and the associated value to be obtained by monitoring are sparse (see Clause 10). Furthermore, monitoring (as a separate field) is only defined in terms of degradation mechanisms and/or integrity enablers (e.g., monitoring of natural frequencies).

ISO 19902 [16]	Fixed steel offshore structures The standard covers design of fixed steel offshore structures. For the development and execution of inspection and monitoring strategies, reference is made to ISO 19901-9.
ISO 19903 [17]	Concrete offshore structures The standard specifies requirements and provides recommendations applicable to fixed, floating and grounded concrete offshore structures. Inspection and condition monitoring are covered through Clause 14, where requirements and recommendations are provided. Similar to fixed steel structures, inspection and monitoring programs shall be developed. Monitoring shall be carried out to detect and give warnings regarding damage and serious defects, which significantly reduce the stability and load-carrying capacity. While different inspection and monitoring strategies are defined, including requirements for documentation and guidance on mechanisms to be captured, no default or detailed methodology is provided.
ISO 19904-1 [18]	Part 1: Ship-shaped, semi-submersible, spar and shallow-draught cylindrical structures The standard specifies requirements and guidance for structural design and/or assessment of floating offshore platforms. For all entities covered by the standard, the structural integrity management system is the anchorage point with respect to inspection and monitoring (Clause 19), which also includes monitoring of environmental data. Requirements and recommendations regarding inspection and monitoring programmes are provided. These requirements and recommendations include information about techniques, extent and minimum requirements (Clause 19.5). Regarding monitoring, examples of use are provided (Annex A.19.4.5) without further detailing.
ISO 19905-1 [19]	Part 1: Jack-ups The standard specifies requirements and guidance for the site-specific assessment of independent jack-up units. In relation to inspection, only project specific in-service inspection programmes are mentioned when the existing in-service inspection programme is outdated (as a result a long-term application). In-service conditions are managed according to a classification by a recognized classification society. Monitoring is specifically recommended with respect to weight control and marine growth.

Table 4-2: Overview of relevant NORSOK standards and associated parts that cover specific requirements for offshore structures.

Standard	Notes
NORSOK N-001 [20]	Integrity of offshore structures The standard specifies general principles and guidelines for the design, verification, quality control and assessment of structures and marine systems in offshore facilities subjected to foreseeable actions and operations. Like ISO 19900, the structural elements and marine systems shall be designed to facilitate for inspections (general terms). However, N-001 primarily mentions inspection with respect to assessment of existing structures, with reference to in-service integrity management (N-006).
NORSOK N-003 [21]	Actions and action effects The standard specifies general principles and guidelines for determination of characteristic actions and action effects. The concept of monitoring is considered through action effect analysis (Clause 11) for full-scale measurements (e.g., updating of action effect predictions). The use of measurements is included throughout all sections regarding design conditions (current, actual, or near-site conditions).

NORSOK N-004 [22]	Design of steel structures The standard specifies guidelines and requirements for design and documentation of offshore steel structures. Since the standard specifies design conditions, minimum requirements for inspection and monitoring are provided with respect to structural types, design class (including consequence of failure) and other. Specific considerations are mentioned for certain cases such as grouted connections for fixed steel platforms, inspection of fatigue critical details, condition monitoring on ship-shaped units, etc. The main reference for inspection and monitoring is generally N-005.
NORSOK N-005 [10]	In-service integrity management of structures and marine systems The standard contains principles, practices, functional requirements and guidelines for the integrity management of offshore structures and marine systems throughout their lives. N-005 is applicable to all types of offshore load-bearing structures. The standard covers all aspects of integrity management, which includes the management of data, inspection and monitoring strategies, inspection and monitoring execution, integrity evaluation and integrity assessment. It should be read in conjunction with N-005. An essential part of N-005 (as an extension to N-004) is the required preparation of a strategy plan for inspection and/or monitoring of the condition of the facility, including evaluation and follow-up. Inspection and monitoring programmes are generally covered through Clause 8. Furthermore, requirements are described in a general manner (examples are inspection types, required intervals, execution strategy, etc.). A specific guidance is provided in the informative annexes, which differentiates between the various types of structures. It should be noted that different inspection methods and their use are also described.
NORSOK N-006 [23]	Assessment of structural integrity for existing offshore load-bearing structures The standard specifies general principles and guidelines for assessment of the structural integrity of existing offshore structures as a supplement to N-001. N-006 serves as an alternative to N-001 for cases where 1) structures are to be operated beyond original design requirements, 2) structural resistance is not easily verified through ordinary design calculations and 3) the use of additional information gained through the life of the structure can be used to demonstrate structural adequacy. As a supplement to N-005, it is defined in Clause 5 of N-006 that in-service inspection history shall be available for assessment, which include information on marine growth, corrosion, cracks, dents, deflections, etc. Additionally, references are made to the other NORSOK standards in the N series and standards within the ISO 19900 suite. Monitoring is mentioned with respect to in-service history of fatigue performance and degradation effects. In Clause 9 of N-006, requirements for in-service inspections and post-assessments are defined with a special focus on fatigue performance.

4.3 Observations and discussions

From Table 4-1 and Table 4-2, it is observed that the standards emphasize the importance of preparation, execution, recording and evaluation in the required inspection and monitoring programs. Furthermore, the standards include lists of preselected areas, including minimum inspection requirements, for periodical inspections. The inspections are often predefined in relation to the consequence class of the structure or the in-service inspection and monitoring strategy. It should also be highlighted that analysing inspection findings and implementing a SIM program is required. Such analyses and implementation can ensure safe operations and reduce costs related to maintenance.

In the following, some general observation and discussion points are included based on the work covered in this section related to current strategies, maturity, important areas and obstacles for standardisation in addition to data management.

- **Current strategies**. While strategies for inspection and monitoring are defined in the standards, the full extent and value-creation of performing monitoring activities are generally provided on a high level, i.e., few or no details are provided.
- **Maturity**. In general, inspection techniques are considered mature in the offshore industry, contrary to structural monitoring systems. Furthermore, a framework that includes requirements of structural monitoring systems and the application of SHM on offshore structures is lacking.
- **Important areas**. Important areas for standardisation include: execution, verification, calibration and documentation of structural monitoring systems and associated data processing techniques; optimization of inspection and maintenance programs by utilizing data obtained from structural monitoring systems; benefits of SHM application of offshore structures with respect to type of structure and material; definition of common failure modes for specific types of offshore structures that can be detected with the use of SHM; and, integration between different parts of the SHM process.
- **Obstacles.** There are several obstacles for including SHM in offshore standards. First, SHM is case specific; it is challenging to generalize the application of SHM for a group of structures. Second, SHM is a complex field of engineering that includes many areas of research. Consequently, it is a multi-disciplinary field of engineering that requires highly competent personnel and strong cooperation across internal business units. Lastly, the experience with structural monitoring systems in the offshore industry is low compared to other industries, mainly because offshore structures are remotely located and experience harsh environments (installing structural monitoring systems on offshore structures are costly).
- **Data management**. General and high-level considerations concerning data quality assessment, assurance of data-driven algorithms and models and assurance of digital twins, sensors systems and simulation models are included in recently developed recommended practices (RPs) by DNV [24]–[28]. Furthermore, ISO 8000-8 describes important subjects related to data quality [29], whereas cyber security is covered in references [30], [31]. These documents provide general definitions and frameworks that may be coupled with the application of SHM on offshore structures.

4.4 Summary

An overview of existing codes and standards for digital solutions and SIM is presented. The existing codes and standards, i.e., ISO, API and NORSOK, cover topics related to inspection and structural monitoring of offshore structures. Although the application of structural monitoring systems and SHM are considered mature from a scientific perspective, there is limited information (guidance or frameworks) in the existing codes and standards regarding these topics. However, information related to the process of inspection of offshore structures is well defined in existing codes, standards and recommended practices. In conclusion, there is a lack of codes, standards and recommended practices (RPs) that consider SHM of offshore structures.

5. SENSOR TECHNOLOGY FOR DATA COLLECTION

5.1 General

This section presents current information, methodologies and knowledge in the industry regarding the use of digital solutions for structural monitoring related to sensor technology for data collection. More specifically, this section covers data collection using sensor technology that is relevant for structural monitoring applications. Figure 5-1 shows an example of measurement equipment and sensor technology for data collection using a structural monitoring system.

Figure 5-1: An example of measurement equipment and sensor technology for data collection.

5.2 Background for using sensor technology

Before deciding on the use of measurement equipment and sensor technology, it is important to map critical elements related to the structural safety and their performance when exposed to hazardous events. Such a mapping also includes defining relevant structural failure modes. Table 5-1 presents an example of a mapping overview. This example should not be considered as a complete mapping but merely an example of how such a mapping can be performed. Reference is also made to [11], [32].

When considering structural monitoring systems, several objectives for performing structural monitoring can be present. Furthermore, thorough planning is required in the process of considering the application of structural monitoring systems. Relevant questions to consider include: why structural monitoring is needed; how the data collected can be recorded, stored, transferred and accessed; and, how the data collected can be used.

Table 5-1: Mapping overview.

1) Hazardous event or failure	2) Safety critical structural system(s)	3) Prevention, mitigation, or control	4) Failure mode or damage state	5) Inspection or monitoring parameter
Extreme weather (excessive loading) - Wave - Ice - Wind - Current	- Main structure (jacket, GBS, hull, mooring line, anchoring, foundation, etc.) - Risers and their supports	- Adequate air gap - Design using adequate safety margin - Structural redundancy	- Loss of stability - Loss of airgap - Member/joint failure - Foundation failure	<u>Visual</u> - Damage such as cracks, excessive deformation and/or loss of members - Leakage <u>Sensing</u> - Change in structural response - Actual metocean parameters and loading - Leakage
Loss of station keeping (control system dysfunctionality)	- Moorings - Positioning (drifting) - Risers	- Mooring load measurement - GPS perimeter warning - Redundancy (moorings and/or system backup)	- Mechanical damage - Rupture of risers (release of hydrocarbons)	<u>Visual</u> Loss of mooring lines <u>Sensing</u> Loss of position
Geotechnical hazards (earthquake, subsidence, scour)	- Foundation	- Surveys on the seabed - Robust foundation design - Inspections / measurements of subsidence and scour conditions	- Pile failure or pull out - Loss of stability - Loss of airgap	<u>Visual</u> Platform tilt <u>Sensing</u> - Airgap measurements - Tilt measurements by inclinometer
Corrosion / material degradation	- All structural members (topside, jacket, hull, caissons, GBS, mooring, risers, supports and appurtenances)	- Anodes / coating / corrosion protection - Corrosion allowance in design	- Crack formations - Loss of wall thickness on structural members - Buckling of structural members - Erosion and embrittlement	<u>Visual</u> Crack identification <u>Sensing</u> - Corrosion protection monitoring - Inspection, maintenance and repair (IMR) program
Change of use / additional dead load	- Primary structural members on the topside, jacket, jackup-rig and foundation	- Weight control - Reinforcement / structural modifications to withstand additional dead load	- Structural failure due to overload - Pile / foundation failure	<u>Visual</u> Extensive structural deformations, crack propagation, instability and/or loss of members <u>Sensing</u> Monitoring of change in structural response

Fire and blast	- Topside structure including accommodation module, MSF, fire / blast walls - Exposed critical structural members in the riser, hull, and legs - Piping and equipment	- Reduction/control of leak sources - Leak detection/ warning and deluge systems - Fire / blast walls - Sufficient structural capacity	- Loss of structural stiffness due to overloading - Loss of structural members - Blast damage om piping and equipment	
Ship collision and dropped objects	- Structural failure, component failure or system collapse (breach of hull, rupturing of riser and conductors, or main member failure)	- Sufficient structural capacity to withstand ship loading - Warning systems - Control of crane operations	- Loss of structural stiffness due to overloading (buckling / denting) - Loss of stability - Crack initiation - Breach of water-tight integrity	<u>Visual</u> Extensive structural deformations, crack propagation and/or loss of jacket members through dents / deformations <u>Sensing</u> Monitoring of change in structural response after ship collision
Fatigue	- Steel sub-structures and topsides main structural members (critical elements) - Caissons, risers and key appurtenances incl. supports - Hull integrity - Mooring - Concrete strength degradation through cracks and reduced reinforcement	- Design for adequate fatigue life - Ability for inspection and monitoring	- Crack propagation and through-member cracks - Loss of stability due to widespread fatigue damage	<u>Visual</u> Damage such as cracks and extensive deformations <u>Sensing</u> - Strain monitoring of members experiencing the highest stress concentrations - Inspections

Several references established in the industry provide a further insight into the current practice and development of topics related to inspection, monitoring and structural integrity of offshore structures that are considered important to include as a background for using sensor technology. Table 5-2 provides a summary of the most relevant references established in the industry that are used in this section of the report.

Table 5-2: References found in the industry relevant for inspection, monitoring and structural integrity of offshore structures.

Responsible	Content
ROMEO [33]	Monitoring technology and specification of the support structure monitoring problem for offshore wind farms (2018)
NGI [34]	Guidelines on structural health monitoring of offshore wind turbine foundations (2017)
Atkins [32]	Review and appraisal of current technologies of offshore applications (2009)

5.3 Sensor technology

Table 5-3 presents an overview of essential and matured measurement equipment and sensor technology applicable for offshore structures.

Table 5-3: Overview of sensor technology applicable for offshore structures.

Sensor type	Purpose and capability	Limitations	Possible applications and examples
Accelerometer	There are several different types of accelerometers. Furthermore, accelerometers can measure in 1, 2, or 3 directions, and they have different properties with respect to sensitivity, resolution and noise characteristics. Common types of accelerometers are force-balanced, micro-electromechanical system (MEMS), variable capacitance, piezo-electric or piezo-resistive.	- The sensitivity, resolution and noise characteristics of accelerometers must be considered with respect to the expected structural response and loading to produce usable data. - When attached to structural members they are in principle both measuring the components and systems accelerations.	- System identification (natural frequencies, mode shapes and damping). - Measurements of global displacements. - Measured fatigue accumulation. - Model and load calibration. - Uncertainty assessment. - Detection of anomalies (damage).
Acoustic emission (AE) sensor	The purpose of AE sensing is detection of anomalies in materials. In the offshore industry, the technique is primarily used to detect fatigue crack initiation and the monitoring of crack growth. Modern AE sensors and systems are accurate and can detect crack initiation and early stages of propagation.	- The system can be prone to background noise which can affect its accuracy and reduce probability of detection. - The system can be partially sensitive to any activity such as maintenance works in the local sensor vicinity.	Identification of crack initiation and crack growth.
Acoustic doppler current profiler (ADCP) sensor	ADCPs measure current and waves by considering how fast water is moving across an entire water column.	Loss of data/velocity information close to the boundaries of the water column.	Information of current and wave properties.
Dissolved oxygen probe	The dissolved oxygen probe is used to determine the concentration of oxygen in aqueous environments.		
Linear Variable Differential Transducer (LVDT)	An LVDT is an electrical transducer used to measure a linear position (displacement transducer). Linear displacements are the movement of an object in one direction along a single axis. The output signal of the linear displacement sensor is the measurement of the distance an object has travelled.	LVDT sensor devices are sensitive to electromagnetic interference. The reduction of electrical resistance can be improved with shorter connection cables to eliminate significant errors.	Measurements of relative displacements.
Electrical resistance (ER) probe	ER probes and instruments determine metal loss from corrosion or erosion by the electrical resistance method.	The ER method allows only the measurement of uniform corrosion but cannot identify localised corrosion phenomena.	Quantification of corrosion impact.

Global Positioning System (GPS) sensor	The GPS is a satellite-based radionavigation system that provides geolocation and time information to a GPS receiver. The technology is especially useful to any floating structure where exact positioning is important.	- Limitations in indoor conditions as the radio waves can be blocked by physical barriers. - The accuracy of the GPS depends on the sensor quality. However, high-quality sensors can provide accuracy in mm.	- Identification of position of floating structures. - Identification of elevational changes due to, e.g., subsidence.
Inclinometer / tilt sensor	Inclinometers, also called tilt sensors, measure the slope/angle/tilt of objects based on gravity in various applications.	The position relative to other sensors must be known to provide meaningful results.	Identification of platform tilt due to, e.g., subsidence.
Light Detection and Ranging (LiDAR) sensor	LiDAR sensing is a method for determining ranges (variable distance) by targeting an object with a laser and measuring the time for the reflected light to return to the receiver.	- High costs. - Unable to measure distances through heavy rain, fog and snow.	- Scanning of surfaces. - Identification of distances/contours.
Load cell	A load cell measures mechanical force, mainly the weight of objects.	Calibration / accuracy and maintenance (over time).	Monitoring of topside weight and mooring tendons on TLP.
Pore / earth pressure	Piezometers or pore pressure meters are pressure transducers that are able to measure the sub-surface piezometric level within groundwater level, soil, or rock. Pressure transducers are suitable for monitoring the pore and earth pressure at the pile surface during jacking/pile driving.	- Robustness and/or fragility of the sensor head. - Welding operations (slots for mounting).	Measurements of pressure at pile surface.
Scour sensor (acoustic)	Scour sensors are typically covered by echo sounders and sonars. Scour sensors can be used to perform scour depth measurements in an area around a bottom-fixed structure. When excessive sediment transport occurs, the sensor will indicate a change in elevation.	See acoustic emission sensors.	Identification of scour depth.
Strain gauge	A strain gauge is a sensor used to measure strains on an object, as the resistance in the sensor varies with applied force. The strain gauge converts force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured.	- The performance of a strain gauge can be affected by change in temperature and humidity. - The sensor must be installed on a clean surface. - The robustness of strain gauges can be limited.	- Measurements of strain/stress in structural members. - Strain levels in bolts and flanges.
Thermal imaging methods (Impedance tomography and thermography)	Thermal imaging is the process where a thermal camera captures and creates an image of an object by using infrared radiation emitted from the object in a process.	Difficulties in obtaining accurate data from objects that have less thermophysical and radiometric properties.	Corrosion and other external material degradation mechanisms including excessive deformation and damage.

Video camera	Video cameras are e.g., used for surveillance of the subsea system.		Video surveillance.
Wave radar	The wave radar measures wave heights and wave periods by radar technology.		Identification of wave properties.
Wave buoy	A wave buoy measures wave heights and directions. It contains an accelerometer that sits in fluid at the base and measures the heave of the ocean swells.	- Buoys can easily be damaged by boat traffic. - Buoy data is only relevant to operations conducted within their immediate vicinity.	Continuous identification of wave heights and wave directions.
Wind and humidity sensor	A wind sensor (anemometer) is an instrument used to measure the speed or velocity of gases in e.g., unconfined flows, such as atmospheric wind. Humidity sensors (hygrometers) work by detecting changes that alter electrical currents or temperature in the air.	Anemometers may get damage during strong winds.	Identification of meteorological properties such as wind speeds and directions.

5.4 Observations and discussions

From Table 5-2 and Table 5-3, it is observed that extensive measurement equipment and sensor technology appliable for offshore structures exist. Some general observation and discussion points are included in the following based on the work covered in this section.

- **Essential SHM factor**. An essential factor for successfully implementing SHM lies in the planning phase. The mapping of critical elements related to the structural safety and their performance when exposed to hazardous events (including failure modes) and the subsequent selection of structural monitoring systems (sensors, data acquisition system and data infrastructure system) are important.
- **Accuracy of measurement data and data quality**. Important properties of a structural monitoring system are the accuracy of the measurement data and data quality. This is of importance with respect to the resulting data post-processing and analysis to be performed. Furthermore, high data quality reduces uncertainty. Accuracy of measurement data and data quality have been highlighted as important areas to consider by the industry.
- **Data management**. The ability of a structural monitoring system to log, store, transmit and/or process data is important. Data sampling, streaming and integration are essential for how data can be further processed. Continuous (live) data processing and analysis are beneficial with respect to early warning detection and damage detection, whereas late data processing (months or years after the actual measurements) is beneficial for mode trend analysis, model updating, risk analysis and calibration tasks to mention a few. Proper data management has been highlighted as an important area by the industry with respect to considering the use of structural monitoring systems.
- **Network configuration**. Wireless sensors and structural monitoring equipment have several benefits. However, battery capacity and synchronization are still identified as issues. Although the wireless sensor and structural monitoring technology is experiencing rapid development, cabled structural monitoring systems are, in many cases, still more reliable. This depends, however, on the requirements to be fulfilled for the structural monitoring system under consideration and the subsequent analysis to be performed.

- **Data integration (fusion)**. Integration of data from multiple systems and vendors can be challenging due to 1) different data formats and 2) the costs associated with making different systems communicate with a common system. Consequently, recognised (common) data formats should be considered for data storage. An important benefit of a structural monitoring system throughout the measurement campaign is to be able to access all data easily from recognised formats in one system by proper data management.

5.5 Summary

An overview of data collection using sensor technology relevant for structural monitoring applications is presented. Although extensive measurement equipment and sensor technology applicable for offshore structures exist, there are increasing challenges related to data management. The most important factor for successfully implementing SHM lies in the planning phase. Particularly, mapping of critical elements related to the structural safety and identification of failure modes are important to consider when designing a structural monitoring system.

6. A FRAMEWORK FOR STRUCTURING THE USE OF DIGITAL SOLUTIONS AND SHM FOR INTEGRITY MANAGEMENT

6.1 General

This section presents recognised and state-of-the-art digital and automated solutions to enhance structural integrity using data analytics. More specifically, the section covers specific advanced methods and algorithms for processing the data obtained from structural monitoring systems.

6.2 The framework

There are many methodologies, methods and algorithms in the literature that are applicable for SHM of offshore structures. Consequently, a framework that includes digital solutions for structural monitoring, integrity management and damage detection is established. The framework provides a coupling between a digital twin of the offshore structure under consideration and measurements obtained from structural monitoring. The framework consists of the following levels:

- Pre-study and design of structural monitoring systems
- Level 1 – Screening and diagnosis
- Level 2 – FE model updating
- Level 3 – Load model updating
- Level 4 – Quantification of uncertainties
- Level 5 – Detection of changes (damage detection)

The framework is based on the SHM process [2]–[4], however, structured in a different manner to obtain a value that is specific for the offshore industry. An overview of the framework is shown in Figure 6-1.

The framework is based on utilizing a digital twin [26], which in this context is a numerical FE model of the structure under consideration. Using this framework, each level contributes and creates *additional* value and increases the quality of the digital twin. Each level is applied to assess whether proceeding to the next level will create value for the asset owner. Consequently, it is recommended that these levels are performed in a chronological order instead of directly going to a specific level without having performed the preceding levels.

In the following, each of the framework levels are explained and methods, methodologies and algorithms within each level are presented together with relevant references. It should be noted that the framework is based on an extensive theoretical foundation, which has been developed during the last 15-20 years and published in numerous conference proceedings and journal articles. For further details of the framework, reference is made to [35]–[37].

Level	Pre-study & SHMS design	Level 1 Screening and diagnosis	Level 2 FE model updating	Level 3 Load model updating	Level 4 Uncertainty assessment	Level 5 Change & damage detection
Description	Definition of objectives, and the ambition level Optimal sensor placement studies on synthetic data Technical specification for SHMS Liaison during fabrication and installation Factory assurance test (FAT) Site assurance test (SAT) Commissioning	Based on short-term or continuous measurement Quality assurance of data System identification to detect measured modal parameters Comparison with existing structural integrity model	Preparation of FE model to represent current condition (as-is model) Sensitivity studies to identify governing parameters affecting the modal parameters Determining which parameters to include in the model updating Justification of parameter changes by comparison with weight reports, soil measurements, etc.	Long-term measurement representing governing loads Virtual sensing to enhance the information from a few sensors to cover the global structure Updating of load model by calibrating governing load parameters Utilizing rainflow counting for comparison of measured and predicted stress history curves	Quantification of uncertainties influencing fatigue loading: - FE model - Year-to-year load variation - Measurements - Expansion process Quantification of bias & CoV values consistent with RBI method Risk based inspection planning (RBI)	Predictive maintenances, including for example fatigue counter Warning system for structural integrity Optimization of operational conditions (system control, smart structures)
		Digital Twin development				
Benefit	**A structural health monitoring system (SHMS) fit for purpose**	**Correspondence assessment of the modal parameters between the FE model and the actual structure**	**Improved response model representation** **Optimized operation & maintenance** **Vibration assessment**	**Improved load model representation** **Optimized operation & maintenance**	**Quantification and reduction of uncertainties** **Updated inspection plan** **Optimized operation & maintenance**	**Continuous assessment of structural integrity (predictive maintenance, detection of changes, warning system etc.)**

Figure 6-1: Framework for structuring the use of digital solutions.

6.3 Pre-study and design of structural monitoring systems

6.3.1 Description

The pre-study and design of structural monitoring systems is the fundamental part of the framework, in which the operational evaluation involving the use of a digital twin and structural monitoring is performed. The operational evaluation defines the purpose and the goal of the project. The choices made in this activity will affect the possibility of realizing the values in the subsequent levels 1-5 of the framework.

The following activities are included, but not limited to, in the pre-study:

- Definition of the objective, scope of work and limitations of the project for the application of a digital twin and structural monitoring (ambition level).
- Performing optimal sensor placement studies on synthetic data.
- Establishing technical specifications of the structural monitoring system.
- Evaluation of operational and environmental conditions under which the structural monitoring system functions, including any limitations on acquiring data.
- Evaluation of life-safety and economic justifications.
- Establishing liaison during fabrication and installation.
- Determining Factory Assurance Test (FAT) and Site Assurance Test (SAT).
- Clarifications regarding data management and cyber security.

The benefit of this part of the framework is a digital twin and structural monitoring system that is fit for purpose in correspondence with the ambitions of the project. Other relevant knowledge for this part of the framework is included in [38].

6.3.2 Framework level summary

An operational evaluation involving the use of a digital twin and structural monitoring is considered in the fundamental part of the framework, i.e., the pre-study and design of structural monitoring systems. The benefit of this part of the framework is the design of a digital twin and structural monitoring system that provide value for the asset owners in the desired subsequent levels 1-5 of the framework.

6.4 Level 1 – Screening and diagnosis

6.4.1 Description

The first level of the framework is the screening and diagnosis level. The purpose of this level is to assess whether the digital twin used for structural integrity management corresponds to the actual structure. Before deciding on the strategy for any digital twin updates and improvements, it is essential to evaluate the performance of the existing digital twin by studying its ability to predict the actual structural behaviour. This knowledge enables a diagnosis to be made.

In general, the screening is based on a correlation study of the dynamic response. Hence, the objective is to correlate the dynamic behaviour of the digital twin with the measured condition of the structure. To facilitate a quick and cost-effective screening phase, it is crucial that the structural monitoring system and sensor setup is kept sufficiently simple. This also minimize costs related to the measurement campaign in addition to pre- and post-processing of the data obtained.

Therefore, the strategy adopted in this level of the framework focuses on a simple structural monitoring system with a limited measurement period. It should be noted, however, that more advanced structural monitoring systems can equally well be considered. A simple structural monitoring system could consist of a few sensors (e.g., two tri-axial accelerometers) at different locations on the structure performing a few hours of measurements under adequate load excitation. A measurement campaign with such a simple structural monitoring system could be performed in a one-day survey. Following this strategy allows for sufficient information of the real structural behaviour to be obtained using temporary equipment and installation. A “fingerprint” of the structure can be generated based on the measurement data obtained using experimental modal analysis (EMA) or operational modal analysis (OMA). Using EMA and OMA allows the identification of modal parameters, such as natural frequencies, mode shapes and damping of the structure.

6.4.2 Methods and algorithms

6.4.2.1 Pre-processing of data

Pre-processing of data is needed to ensure adequate data quality of the data before being applied for analysis. Such pre-processing includes, but are not limited to:

- Adding sensor sensitivities, if relevant.
- Optimization and/or synchronization of sensor channels including data cleansing (choosing data to include or reject).
- Checking of consistency and quality of the data through visual and statistical checks.
- Applying signal processing techniques such as detrending, filtering, resampling and / or smoothing. Signal processing techniques are further described in [39].

6.4.2.2 Analysis of data

Analysis of data can range from simple comparisons between a digital twin and the data obtained directly from the structural monitoring system to more advanced methods for experimental and operational modal analysis.

Approach 1

The least advanced approach considers a direct comparison. A direct comparison between *predicted* displacements and stresses of a digital twin and *measured* displacements and strains (converted to stress) obtained from a structural monitoring system can be performed at specific locations on a structure. Such a comparison could be performed directly in the time domain or using statistics.

A direct comparison can provide a general evaluation of the digital twin performance against the real behaviour of the structure. However, this comparison is not considered adequate as a complete validation of the digital twin.

Approach 2

Approach 2 considers EMA and OMA. EMA refers to the process of identifying the modal parameters, such as natural frequencies, mode shapes and damping, from measurements of the applied force (input) and the vibration response (output). OMA, however, concerns with estimating the modal parameters of a structure by only considering the vibration response (output only) [40]. OMA allows for taking advantage of the vibration from operational and environmental loads, which makes the identification of modal parameters of large structures, such as offshore structures, possible. Consequently, methods and algorithms for OMA is presented in the following. However, it should be noted that the methods and algorithms for EMA are in many cases similar to OMA.

Table 6-1 presents well-known and recognised system identification algorithms for performing OMA. The table includes relevant references that describe each method in detail.

Table 6-1: System identification methods for OMA

Method	Relevant reference(s)
Frequency Domain Decomposition (FDD)	[41], [42]
Enhanced Frequency Domain Decomposition (EFDD)	[43]
Data-driven stochastic subspace identification (DD-SSI)	[44]
Covariance-driven stochastic subspace identification (COV-SSI)	[45]

The frequency domain decomposition (FDD) and enhanced frequency domain decomposition (EFDD) are frequency domain methods, whereas the data-driven (DD) and covariance-driven (COV) stochastic subspace identification (SSI) are time domain methods. For an overview and description of these methods and other methods for OMA, it is referred to [40].

The benefit of approach 2 is that the modal parameters can accurately be identified from measurements of the vibration response. By accurately identifying the modal parameters in approach 2 allows a more reliable comparison between the actual structural behaviour and the digital twin than by considering approach 1.

6.4.3 Level 1 summary

The correspondence of the modal parameters between the digital twin (FE model) and the available measurement data is established in the first level of the framework through a screening and diagnosis. This correspondence is established by comparing the modal parameters obtained from measurement data with the modal parameters of the digital twin. If there is a low correspondence in the modal parameters, the force distribution in the digital twin may not be correct and the digital twin should be calibrated and updated. The approach for a calibration and updating is presented in the next level of the framework.

6.5 Level 2 – FE model updating

6.5.1 Description

The second level of the framework concerns finite element (FE) model updating. FE model updating aims at minimizing the discrepancy between the modal parameters of the digital twin and the real structure. FE model updating can be performed by optimizing the parameters affecting the modal parameters, which is typically parameters related to stiffness, mass and boundary conditions of the structure under consideration. Consequently, the FE model updating process is generally formulated as an optimization problem.

The identified or measured modal parameters are applied as the target for the FE model updating. The identification of the modal parameters is typically performed in level 1 of the framework. If the model updating is based on a few modal parameters, a simple structural monitoring system as defined in level 1 can be used. However, if the model updating requires many modal parameters, a comprehensive structural monitoring system is needed and should be considered in level 2 of the framework. In general, obtaining a digital twin that accurately represents the true behaviour requires the identification of several modal parameters. The FE model updating procedure should depend on both natural frequencies and modal assurance criterion (MAC) numbers as the modal properties of the structural system. A MAC value of 1.0 represents a perfect correlation between the measured and predicted mode shapes.

6.5.2 Methods and algorithms

6.5.2.1 Approach 1

The least advanced approach considers manual trial and error for FE model updating. In this approach, the parameters of the FE model are manually adjusted to best fit the modal parameters obtained from the measured data. By applying this approach, it is challenging to establish the optimal and most probable set of parameter values that would lead to the least discrepancy between the analytical and identified modal parameters obtained from the digital twin and structural monitoring, respectively. However, fair improvements can still be achieved.

6.5.2.2 Approach 2

Approach 2 considers advanced model updating algorithms. Contrary to manual trial and error, these algorithms apply mathematical formulations, which allow for an optimal set of parameters to be found in a highly efficient manner. There are several model updating methods that are available in the literature. Table 6-2 presents a selection of well-known and recognised methods for performing model updating that has been applied to large civil engineering structures. The table includes relevant references that describe each method in detail.

Table 6-2: Model updating methods

Method	Relevant reference(s)
Sensitivity-based model updating	[46], [47]
Bayesian parameter estimator-based model updating	[48], [49]
Bayesian-based model updating	[47], [48]

In general, the choice of method to use depends on the structure under consideration and the complexity of the model updating to be performed. For an application of sensitivity-based model updating, including the implementation of the theoretical framework using Abaqus and Python on a numerical benchmark study, it is referred to [50], [51]. The application of sensitivity-based model updating of an offshore structure is presented in [52]. Furthermore, references are made to applications relevant to offshore structures that are related to Bayesian model updating, see [53], [54].

6.5.3 Level 2 summary

FE model updating ensures that the static and dynamic characteristics of the structure are more precisely represented in the digital twin, provided that the resulting change in parameter values is considered reasonable from an engineering perspective. Consequently, using FE model updating ensures that the distribution of force and stress flows are more accurately represented in the digital twin, resulting in an improvement in locating the most critical hot spots. However, the FE model updating of the digital twin with respect to modal parameters does not ensure that the wave load modelling is correct.

6.6 Level 3 – Load model updating

6.6.1 Description

The third level of the framework concerns load model updating. In general, the idea of calibrating a load model to measured conditions is defined as an optimization problem, where relevant load parameters are selected as the governing variables in the optimization. The objective of the calibration is to minimize the discrepancy between the measured and the predicted response by calibrating the load modelling part of the FE analysis.

The performance of the digital twin is not only related to its ability to represent the structural static, quasi-static and dynamic characteristics accurately; the load modelling part is of equal concern when evaluating the performance of a digital twin for fatigue prediction. To obtain a digital twin for fatigue re-assessment or lifetime extension purposes, it is important that the load model accurately represents real conditions.

Load calibration requires long-term measurement data, which can be obtained from, e.g., wave radars, to represent the wave loading part. Additionally, strain gauges can supplement measured global platform displacements generated from accelerometer data. Consequently, a permanent structural monitoring system that includes accelerometers, strain gauges and wave radars may be needed in this level of the framework.

To ensure a proper load calibration, it is essential that the load calibration is performed in a way consistent with the method adopted for the fatigue re-assessment analysis which follows. Wave load calibration can be performed by calibrating the wave load model parameters, e.g., the C_d and C_m values in Morison's equation. The goal of the wave load calibration is therefore to identify the set of hydrodynamic parameters that provide a minimum discrepancy between the measured and predicted stress history curves. It is observed that the load modelling parameters from codes and standards typically yield conservative fatigue estimations.

6.6.2 Methods and algorithms

6.6.2.1 Methods

There are several methods that can be considered relevant for load model updating for offshore structures. Table 6-3 summarizes the relevant methods together with references, where relevant. The references describe each method and associated algorithms in detail.

Table 6-3: Load model updating methods.

Method	Description	Relevant reference(s)
Method 1	Load updating by trial and error	
Method 2	Load identification	[55]–[59]
Method 3	Virtual sensing	[60]–[66]
Method 4	Load updating by objective function optimization	[36]
Method 5	Bayesian-based load updating	[54], [66]

Method 1 considers manual trial and error for load updating. In this method, the input parameters for the digital twin are manually adjusted or calibrated to obtain a best-fit. Method 2 includes load identification, which is considered a method that can be a part of load model updating. Furthermore, method 3 takes into account virtual sensing. Virtual sensing covers several algorithms that use available information from measurements extracted on a few locations on the structure to estimate the stress at all other locations in the structure. For offshore structures, the purpose of virtual sensing is to determine stresses and strains in all elements and joints of the structure above and below the mean sea level (MSL) from measurements of the structure in a limited number of sensor locations above the MSL. For virtual sensing to be effective, it is important that levels 1 and 2 have been performed. If levels 1 and 2 have not been performed, the quality and confidence in the virtual sensing will be low due to higher uncertainties. Methods 4 and 5 consider load updating by the optimization of an objective function and Bayesian-based load updating, respectively. The relevant references included for methods 4 and 5 describe these methods in detail.

6.6.3 Level 3 summary

Load model updating ensures that the load model is more precisely represented in the digital twin. Consequently, a wave load calibration can reduce conservatism in the adopted wave load model and thus facilitate potential lifetime extension with respect to fatigue prediction. To ensure a proper load calibration, it is essential that the load calibration is performed in a way consistent with the governing procedures provided in relevant codes, standards and recommended practices.

6.7 Level 4 – Quantification of uncertainties

6.7.1 Description

The fourth level of the framework concerns the quantification of uncertainties. The question of how much the prediction model has improved, i.e., the digital twin with a calibrated wave load model, can be answered in terms of quantification of the uncertainties of the updated prediction model performance against measurements. The benefits associated with this level of the framework are mainly 1) to quantify the confidence in the digital twin and its performance and 2) a cost reduction related to inspection-planning activities and documentation of the improved understanding of the safety level. An additional benefit is the improved estimation of the probability of failure (PoF) for the structure under consideration for extreme events.

If the inspection planning is based on RBI methods, the model uncertainties can be quantified in terms of bias (typically calibrated to a bias of 1.0) and the associated Coefficient of Variation (CoV) values. The assessment of the uncertainties should be consistent with the RBI approach adopted by the asset owner, e.g. according to DNV-RP-C210 [67]. Several uncertainties need to be quantified from the data, i.e., measurement noise, numerical noise, model bias and other uncertainties including, but not limited to, environmental variations (year-to-year sea state variations). It should be noted that the uncertainty associated with observed stochastic variables can be quantified, but the uncertainty associated with the unobserved stochastic variables needs to be covered by the RBI approach considered (e.g., quantification of nominal stresses is based on observations, whereas the additional uncertainty from nominal stresses to hot spot stresses is covered by the RBI approach considered).

One of the value creations from a reduction in the uncertainties of the prediction model in terms of reduced CoV values is a reduction in the number of hot spots to be inspected and an increase in the time between inspections. Consequently, a reduction in the number of surveys to be performed in the lifetime of the structure can be achieved.

6.7.2 Methods and algorithms

In general, the quantification of uncertainties associated with the use of structural monitoring systems shall be determined in a format that is consistent with the future use of the calculated uncertainty, such as following an RBI approach or any other probabilistic approaches. For detailed descriptions related to the quantification of uncertainties, it is referred to [35], [53], [54], [57], [58], [66].

Here, there are two formats for quantifying the uncertainties: plain and future formats. The plain format consists of quantifying the uncertainties related to the CoV and bias, see [35]. This format shall be consistent with the adopted RBI approach. The future format, however, consists of quantifying the uncertainties determined by Bayesian-based methods, see [54], [57], [58].

There are two methods that can be considered relevant for quantifying the uncertainties related to offshore structures. Table 6-4 summarizes the relevant methods together with references, where relevant. The references describe each method and associated algorithms in detail.

Table 6-4: Methods for quantification of uncertainties.

Method	Description	Relevant reference(s)
Method 1	RBI – standard approach	[67]
Method 2	RBI – SHM approach	[68]

Method 1 considers the standard approach to RBI, which is based on historical data. Method 2 considers recent data obtained using a structural monitoring system. For considerations regarding the estimation of the PoF relevant for extreme analysis, it is referred to [69], [70].

6.7.3 Level 4 summary

The improvement of the prediction model, i.e., the digital twin with a calibrated wave load model, is established in the fourth level of the framework by considering the quantification of uncertainties. The value creation of this level of the framework lies in the potentially significant reduction of uncertainties and hence quantifying the quality of the digital twin. Furthermore, as the uncertainties are closely related to the safety, the safety level is improved and verified by measurements. Additionally, a reduction in the uncertainties also results in a potential reduction of inspection costs.

6.8 Level 5 – Detection of changes (damage detection)

6.8.1 Description

The fifth level of the framework concerns detection of changes. At this level, it is considered to continue the structural monitoring from the preceding levels. A continuation of the structural monitoring beyond the period required for levels 1-3 and 1-4 facilitates 1) continuous monitoring of the actual accumulated fatigue damage in elements and joints (hot spots) of the structure, and 2) detection of changes that are not caused by operational and environmental variability. By continuous and permanent structural monitoring, the normal variation in the modal properties of the structure due to operational and environmental changes can be established. This allows the detection of changes that are *not* caused by operational and environmental variability but are rather caused by structural damage or deterioration.

In general, only the accelerometers are required for the continuation of measurements, i.e., measurements from strain gauges are not strictly needed once updating and calibration of the digital twin have been performed. However, it is recommended to continue measurements from strain gauges where possible. The fatigue damage can be updated continuously or after specified periods, e.g., yearly or bi-yearly. The advantage of continuous monitoring related to fatigue is that the structure is only "punished" by the actual occurring fatigue damage. Consequently, any conservatism in the future load description taken from codes and standards can gradually be removed, which can result in enhanced lifetime extension.

The value creation from continuous and permanent structural monitoring lies in establishing the actual accumulated fatigue damage for the structure and the potential of detecting abnormal changes related to or caused by structural damage. Realising the need for advanced damage detection can be exemplified by imagining a storm in which an extreme wave event has occurred, and the structural integrity of the platform needs evaluation. The asset owner then needs sufficient reliable information to support critical decision-making whether it is safe to continue operation, or the platform should be shut down and evacuated due to critical structural damage. A more complete and detailed description of this part of the framework is presented in [37].

6.8.2 Methods and algorithms

A large number of methods and algorithms exist for detecting changes. Some methods and algorithms may be useful for specific applications for damage detection, but no general approach for robust and general damage detection exists today.

The purpose of this section is to highlight technologies that have been developed in recent years in the context of other state-of-the-art work, which has the potential to extend and improve aspects of the presented framework with a view to increase autonomy, insight and robustness. Each of these developments is built upon increasingly data-centric ideas; in other words, they consider how to most effectively make use of, and learn from, data collected from a structure. The methodologies, methods and algorithms cover the related areas of statistical modelling, machine learning and artificial intelligence.

Table 6-5 summarizes the relevant methods together with references, where relevant. The references describe each method and associated algorithms in detail.

Table 6-5: Method for load estimation and detection of changes (damage detection).

Method	Description	Relevant reference(s)
Method 1	Integration of methods	[54], [57], [71]
Method 2	Damage detection	[72]–[80]

Table 6-5 summarizes two methods that are relevant for asset management. Method 1 concerns an integration of methods that adopt novel technologies for analyses of all five levels in one integrated analysis. One benefit of this method is that it solves the limitations of some of the former methods presented in cases of non-linear and/or non-stationary system behaviour. Another benefit is the potential for further reduction of uncertainties by a detailed quantification of the uncertainties. Method 1 facilitates root cause analysis and assessing knowledge gaps. In addition, the method has the potential for aiding damage detection. It is also important to highlight that this method concerns load estimation, where it is aimed at improving the estimation of the loading experienced by a given structure. If successful, this method is considered a route to further reducing uncertainty in the fatigue damage calculations beyond what is presented in the previous levels of the framework. Method 2 concerns online damage detection based on state-of-the-art and novel methodologies, methods and algorithms. It should be noted that a framework for damage detection should follow the principles according to Rytter's hierarchy [81], [82].

Further detailed descriptions of each method and the associated algorithms presented in Table 6-5, including additional references not included in the table, are presented in [37].

6.8.3 Level 5 summary

Actual accumulated fatigue damage and detection of changes, or damage detection, is performed in the fifth level of the framework by considering continuous and permanent structural monitoring of the structure under consideration. The value creation of this level of the framework lies in increased lifetime extension possibilities and the potential of detecting abnormal changes related to or caused by structural damage. The core aim of integrating new technology into an asset management setting is to increase knowledge, in the sense that the asset owner can make more informed decisions about the usage and maintenance of a structure.

6.9 Summary of the framework

The state-of-the-art recognised digital and automated solutions that can enhance the structural integrity of offshore structures include experimental and operational modal analysis, virtual sensing, FE model updating, wave load calibration, quantification of uncertainties from measured data and RBI planning analysis. The recognised digital and automated solutions also include state-of-the-art methods for detection of changes (damage detection) that exploit recent advances in machine learning (ML) and artificial intelligence (AI).

A framework for how digital solutions and SHM for integrity management can be structured is established. The presented framework, which consists of a pre-study and five levels, provides a coupling between a digital twin and measurements obtained from structural monitoring. This coupling facilitates a direct performance evaluation of the digital twin against measurements and creates the basis for improving the performance of the digital twin to capture the actual condition of the structure more accurately.

7. VALUE CREATION AND EXAMPLES OF PRACTICAL IMPLEMENTATION

7.1 General

There has been a lot of focus on digitalization and digital twins throughout the last decade. Although this is not a new terminology, there may still be vague and conflicting definitions of what a digital twin is and what it is not. Typically, a digital twin consists of several layers of information linked to a 3D model, which individually or combined may contribute to an increased value within different disciplines. In general, the first step to creating a digital twin is to establish a 3D model, such as for example a FE model, that represents the geometrical features of the actual (physical) structure. This section focuses on discussing the value creation enabled by using SHM on offshore structures, as well as providing examples of practical implementation based on the framework presented in Section 6.

7.1.1 Structural health monitoring

SHM introduces a new layer of information to a digital twin by connecting the virtual and actual (physical) world. This can be done by using the framework presented in Section 6. The value of using SHM typically depends on several factors, such as the experience of the user and the complexity of the technology used.

There are several quantifiable benefits of using SHM in structural integrity management. Whilst some of the value creation may be estimated and quantified upfront, it is important to highlight that the use of SHM can be compared to an insurance policy. An SHM system comes with a cost but will in return generate valuable information throughout the lifetime of a structure, which can be used in a case of an unexpected future event.

The use of SHM on offshore structures provides value in terms of change management, decision-making, predictive maintenance and risk control. These factors result in a safer and cost-optimized operation, see Figure 7-1. Other examples of value creation using SHM systems include supporting sustainability by allowing for optimization of operational performance and life-cycle management.

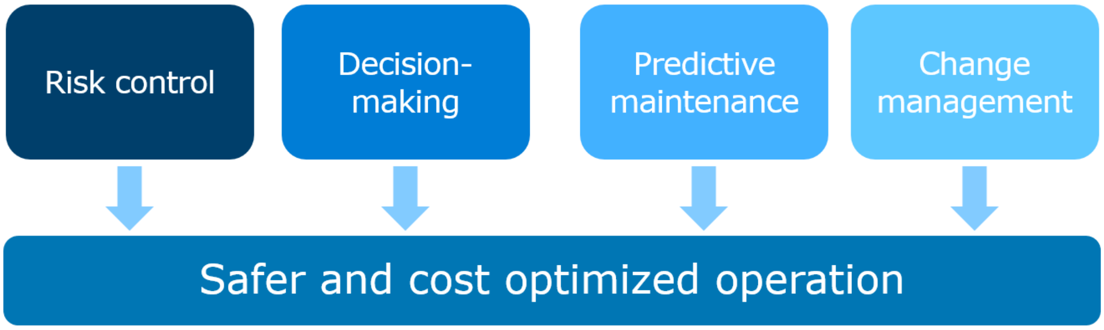

Figure 7-1: Value creation and benefits of using SHM on offshore structures.

7.1.2 Safer operation and cost reduction

As the name SHM indicates, it concerns gaining a better understanding of the actual health of the structure under consideration. This information provides the opportunity to detect changes (damage) at an early stage, which would not be possible without this information. Also, as illustrated in Figure 7-1, the information obtained from an SHM system may be used to achieve a safer operation by informed decision-making, which also feeds into change management.

Having a better understanding of the actual structural condition is also valuable in lifetime extension projects. Such information may lead to a significant cost reduction with regard to optimization of inspections. In some cases, such information may also allow for cost-efficient reuse of existing structures instead of performing decommissioning.

The continuous use of information obtained from SHM allows for several benefits, as presented in Table 7-1, with the purpose of reducing cost and increase safety, by focusing on the efforts and investments for the areas of actual concern of the structural integrity. SHM provides valuable information in time of need, for example, during abnormal operational and environmental events. Furthermore, SHM provides information on the actual behaviour of the structure, which is valuable when considering parts of the structure that are difficult to access and costly to inspect, such as structural beam members, joints and supports (grouted pile-sleeve connections) below water. Table 7-1 summarizes the value creation obtained by using SHM for offshore structures.

Table 7-1: Value creation obtained by using SHM for offshore structures.

CAPEX	OPEX
Real-life design verification	Actual safety and risk
Design basis and optimisation	Predictive maintenance
Implement new learnings/knowledge gaps	Unexpected events - instant information
	Minimize shutdown time
	Detection of changes (damage)
	Capture unexpected behaviour
	Root cause analyses
	Lifecycle history
	Warning systems
	Decision-making

7.2 Examples of practical implementation

The following sections present examples of practical implementation of the framework for lifetime extension of various types of structures and events. In general, the information and guidance provided in Section 6 and Appendix 1, respectively, are based on extensive experience with fixed offshore structures. However, the information and guidance are also applicable for floating structures, bridge systems (between topsides), crane pedestals and other structures related to piping and process disciplines in addition to abnormal events.

7.2.1 Fixed loadbearing structures

Description and purpose

With respect to lifetime extension and optimization of inspection plans, the use of SHM is very valuable. By using measurements in a structured framework as presented in Section 6, the actual behaviour of the structures and the response and load models may be better understood. Hence, it is possible to reduce uncertainties, which are directly linked to safety and risk levels. Combining structural monitoring with advanced analysis will usually lead to considerable benefits in lifetime extension projects with an optimized inspection plan as the outcome.

Methodology statement

Pre-study and design of structural monitoring systems

For a lifetime extension project, an evaluation should be performed whether to opt for a short-term structural monitoring system, which only allows for levels 1 and 2, or a long-term (continuous) structural monitoring system, which allows for levels 3, 4 and 5. The selection of sensors and the design of a structural monitoring system will typically depend on factors such as the complexity of the structure, expected outcome of the project and project budget. See Section 6.3 and Appendix 1 for more information and guidance.

Level 1

Level 1 includes performing measurements to identify the modal parameters of the structure such as the natural frequencies, mode shapes and damping. These measurements are typically performed using accelerometers by considering either short-term or long-term structural monitoring.

Comparing the measured modal parameters to those of the initial FE model will give the user a good indication of the FE model performance and whether model updating in level 2 is necessary. If there is a good match between the measurements and the FE model, it is fair to assume that the force flow and dynamics of the FE model are well represented in the linear domain.

Level 2

Level 2 considers updating of the FE model (response model), see Section 6.5 for several methods for model updating. Updating the FE model to the measured modal parameters ensures that the static and dynamic characteristics of the real structure are correctly represented, thus ensuring that the distributions of the force and stress flows in the structure are correctly represented. The FE model should be calibrated against a minimum of the first 3 or 4 modes to obtain adequate confidence in the updated FE model.

Another benefit of having an updated FE model that represents the measured modal parameters is that it may allow for potential virtual sensing. This is a process where stresses in all elements and joints of the structure are determined from a limited number of sensors.

Level 3

In addition to updating the response model (level 2), the load model may be updated in level 3, see Section 6.6 for methods of load model updating.

Updating the load model may include strain gauges and wave radars, among other sensor types. However, strain gauges are not considered necessary for performing load model updating or performing an expansion process. However, only considering displacements through accelerometers will result in higher uncertainties.

Level 4

This level quantifies the uncertainties in the updated response and load models and links the uncertainties in a format that is consistent with the format required for a given method for RBI planning. The outcome of this level is a reduced CoV that can be used for optimizing inspection plans. The outcome also increases the confidence in the updated FE model since the actual uncertainties between the FE model and real-life measurements are quantified. An additional benefit is the estimation of the real probability of failure (PoF) for the structure under consideration for extreme events.

Level 5

Level 5 comprises a broad range of methods for detecting changes (damage and degradation). An example could be a continuous fatigue counter, i.e., using continuous measurements to update fatigue calculations and inspection plans based on the actual performance of the considered structure (predictive maintenance). Another example could be the detection of changes in grouted sleeve-pile connections. There are several ongoing developments and development projects investigating this field, see [37]. However, to gain benefits of level 5, it is recommended to obtain control of the previous levels 1-4.

7.2.2 Floating structures

The use of SHM on floating structures can give valuable information in connection with overload monitoring and measurement of the actual fatigue damage at strategic locations. In addition, by combining data from a few sensors installed at selected locations on a floater with data from a FE model of the structure, insight into all areas of the structure can be obtained. This insight can be used for structural integrity management in terms of assessing the potential for lifetime extension, optimization of inspections and warning of extreme events. Furthermore, phenomena such as springing (wave resonance) and whipping (wave impact) can be assessed. Demonstrations of value creation for floating structures are provided in the references [63], [83], [84].

7.2.3 Bridge systems, crane pedestals and other structures

The use of SHM for assessing bridge systems, crane pedestals and other structures can add value with respect to lifetime extension related to fatigue, damage detection and root cause analysis. It should be noted that other structures may also include piping and process equipment.

The value creation depends on the chosen structural monitoring system with respect to short-term or long-term monitoring. An example where a short-term structural monitoring system can be applicable is for crane pedestals. A short-term structural monitoring system can provide a root cause analysis of excessive vibration or unexpected structural behaviour. An example where a long-term structural monitoring system can be applicable is for bridge systems between topside structures. A long-term structural monitoring system and the subsequent analysis of data can provide documentation of the integrity of the bridge bearings. Furthermore, detailed information regarding the degradation of the bearings over time and potential warnings in case of unexpected behaviour can be provided. For all cases, information from the structural monitoring systems may provide early warnings, documentation of structural integrity and support to predictive maintenance.

7.2.4 Abnormal events

The use of SHM for assessing abnormal events can add value with respect to 1) the potential verification of higher capacity (strength) and safety of the structure and 2) damage detection with the benefit of supporting critical decision-making such as evacuation and decision-making for cost optimization, loss prevention and increase of safety. Abnormal events include extreme environmental events (wind and wave loading, sudden drop, earthquake, and other), sudden occurring damage caused by operational events, ship impact and others.

8. REFERENCES

[1] ISO, "Petroleum and natural gas industries – Specific requirements for offshore structures – Part 9: Structural integrity management (ISO 19901-9:2019)," 2019.

[2] C. R. Farrar and K. Worden, "An introduction to structural health monitoring," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 365, no. 1851, pp. 303–315, 2007, doi: 10.1098/rsta.2006.1928.

[3] C. R. Farrar and K. Worden, *Structural Health Monitoring: A Machine Learning Perspective*. Wiley, 2012.

[4] B. T. Svendsen, "Numerical and experimental studies for damage detection and structural health monitoring of steel bridges," Norwegian University of Science and Technology, 2021.

[5] PSA, "Regulations relating to health, safety and the environment in the petroleum activities and at certain onshore facilities (the Framework Regulations)," 2019.

[6] PSA, "Regulations relating to conducting petroleum activities (the Activities Regulations)," 2020.

[7] PSA, "Regulations relating to design and outfitting of facilities, etc. in the petroleum activities (the Facilities Regulations)," 2020.

[8] PSA, "Regulations relating to management and the duty to provide information in the petroleum activities and at certain onshore facilities (the Management Regulations)," 2020.

[9] PSA, "Regulations relating to technical and operational matters at onshore facilities in the petroleum activities, etc. (the Technical and Operational Regulations)," 2020.

[10] "NORSOK Standard - In-service integrity management of structures and marine systems (NORSOK N-005:2017)," 2017.

[11] DNV, "Comparison of API, ISO, and NORSOK offshore structural standards," 2011.

[12] ISO, "Petroleum and natural gas industries - General requirements for offshore structures (ISO 19900:2019)," 2019.

[13] ISO, "Petroleum and natural gas industries - Specific requirements for offshore structures - Part 1: Metocean design and operating considerations (ISO 19901-1:2015)," 2015.

[14] ISO, "Petroleum and natural gas industries - Specific requirements for offshore structures - Part 3: Topsides structure (ISO 19901-3:2014)," 2014.

[15] ISO, "Petroleum and natural gas industries - Specific requirements for offshore structures - Part 4: Geotechnical and foundation design considerations (ISO 19901-4:2016)," 2016.

[16] ISO, "Petroleum and natural gas industries — Fixed steel offshore structures (ISO 19902:2020)," 2020.

[17] ISO, "Petroleum and natural gas industries — Concrete offshore structures (ISO 19903:2019)," 2019.

[18] ISO, "Petroleum and natural gas industries — Floating offshore structures — Part 1: Ship-shaped, semi-submersible, spar and shallow-draught cylindrical structures (ISO 19904-1:2019)," 2019.

[19] ISO, "Petroleum and natural gas industries - Site-specific assessment of mobile offshore units - Part 1: Jack-ups (ISO 19905-1:2016)," 2016.

[20] "NORSOK Standard - Integrity of offshore structures (NORSOK N-001:2020)," 2020.

[21] "NORSOK Standard - Actions and action effects (NORSOK N-003:2017)," 2017.

[22] "NORSOK Standard - Design of steel structures (NORSOK N-004:2021)," 2021.

[23] "NORSOK Standard - Assessment of structural integrity for existing offshore load-bearing structures (NORSOK N-006:2015)," 2015.

[24] DNV, "DNV-RP-0497 - Data quality assessment framework," 2021.

[25] DNV, "DNV-RP-0510 - Framework for assurance of data-driven algorithms and models," 2021.

[26] DNV, "DNV-RP-A204 - Qualification and assurance of digital twins," 2021.

[27] DNV, "DNV-RP-0317 - Assurance of sensor systems," 2021.

[28] DNV, "DNV-RP-0513 - Assurance of simulation models," 2021.

[29] ISO, "Data quality - Part 8: Information and data quality: Concepts and measuring (ISO8000-8:2015)," 2015.

[30] ISO, "Information technology - Security techniques - Information security management systems - Overview and vocabulary (ISO/IEC 27000:2018)," 2020.

[31] NIST, "Framework for improving critical infrastructure cybersecurity," 2014.

[32] Atkins, "Structural integrity monitoring - Review and appraisal of current technologies for offshore applications," 2009.

[33] ROMEO, "D4.1 Monitoring technology and specification of the support structure monitoring problem for offshore wind farms," 2018.

[34] NGI, "Guidelines for structural health monitoring for offshore wind turbine towers and foundations," 2017.

[35] U. T. Tygesen, M. S. Jepsen, N. Dollerup, and A. Pedersen, "The true digital twin concept for fatigue re-assessment of marine structures," 2018.

[36] U. T. Tygesen, K. Worden, T. Rogers, G. Manson, and E. J. Cross, "State-of-the-art and future directions for predictive modelling of offshore structure dynamics using machine learning," in *Conference Proceedings of the Society for Experimental Mechanics Series*, 2019, pp. 223–233, doi: 10.1007/978-3-319-74421-6_30.

[37] U. T. Tygesen, E. J. Cross, P. Gardner, K. Worden, B. A. Qadri, and T. J. Rogers, "Digital transformation by the implementation of the true digital twin concept and big data technology for structural integrity management," 2021.

[38] J. B. Hansen, R. Brincker, S. Mathiasen, A. Jørgensen, M. B. Knudsen, and U. Tygesen, "Combining GPS and integrated sensor signals," in *4th International Operational Modal Analysis Conference (IOMAC)*, 2011, pp. 127–133.

[39] S. Smith, *Digital signal processing: A practical guide for engineers and scientists*. 2002.

[40] C. Rainieri and G. Fabbrocino, *Operational Modal Analysis of Civil Engineering Structures*. New York, NY: Springer New York, 2014.

[41] R. Brincker, L. Zhang, and P. Andersen, "Modal identification from ambient responses using frequency domain decomposition," in *Proceedings of the International Modal Analysis Conference (IMAC)*, 2000, pp. 625–630.

[42] R. Brincker, L. Zhang, and P. Andersen, "Modal identification of output-only systems using frequency domain decomposition," *Smart Mater. Struct.*, vol. 10, no. 3, pp. 441–445, 2001, doi: 10.1088/0964-1726/10/3/303.

[43] R. Brincker, C. E. Ventura, and P. Andersen, "Damping estimation by frequency domain decomposition," in *Proceedings of the International Modal Analysis Conference (IMAC)*, 2001, vol. 1, pp. 698–703.

[44] P. Van Overschee and B. De Moor, *Subspace Identification for Linear Systems*. Boston, MA: Springer US, 1996.

[45] L. Hermans and H. van der Auweraer, "Modal testing and analysis of structures under operational conditions: industrial applications," *Mech. Syst. Signal Process.*, vol. 13, no. 2, pp. 193–216, 1999.

[46] M. I. Friswell and J. E. Mottershead, *Finite Element Model Updating in Structural Dynamics*, vol. 38. Dordrecht: Springer Netherlands, 1995.

[47] E. Patelli, Y. Govers, M. Broggi, H. M. Gomes, M. Link, and J. E. Mottershead, "Sensitivity or Bayesian model updating: a comparison of techniques using the DLR AIRMOD test data," *Arch. Appl. Mech.*, vol. 87, no. 5, pp. 905–925, 2017, doi: 10.1007/s00419-017-1233-1.

[48] K.-V. Yuen, *Bayesian Methods for Structural Dynamics and Civil Engineering*. Chichester, UK: John Wiley & Sons, Ltd, 2010.

[49] T. Lauwagie, J. Guggenberger, J. Strobbe, and E. Dascotte, "Model updating using operational data," in *Proceedings of ISMA 2010 - International Conference on Noise and Vibration Engineering and USD 2010 - International Conference on Uncertainty in Structural Dynamics*, 2010, pp. 2669–2678.

[50] B. T. Svendsen, Ø. W. Petersen, G. T. Frøseth, and A. Rønnquist, "Improved finite element model updating of a full-scale steel bridge using sensitivity analysis," *Struct. Infrastruct. Eng.*, vol. 0, no. 0, pp. 1–17, 2021, doi: 10.1080/15732479.2021.1944227.

[51] B. T. Svendsen, "FE model updating in Python." 2020, doi: https://doi.org/ http://doi.org/10.5281/zenodo.4243875.

[52] D. Augustyn, U. Smolka, U. T. Tygesen, M. D. Ulriksen, and J. D. Sørensen, "Data-driven model updating of an offshore wind jacket substructure," *Appl. Ocean Res.*, vol. 104, no. August, p. 102366, 2020, doi: 10.1016/j.apor.2020.102366.

[53] P. L. Green, U. T. Tygesen, and N. Stevanovic, "Bayesian modelling of offshore platforms," in *Conference Proceedings of the Society for Experimental Mechanics Series*, 2016, vol. 3, pp. 15–22, doi: 10.1007/978-3-319-29754-5_2.

[54] T. J. Rogers, K. Worden, G. Manson, U. T. Tygesen, and E. J. Cross, "A Bayesian filtering approach to operational modal analysis with recovery of forcing signals," in *Proceedings of ISMA 2018 - International Conference on Noise and Vibration Engineering and USD 2018 - International Conference on Uncertainty in Structural Dynamics*, 2018, pp. 5181–5194.

[55] N. Perišić, P. H. Kirkegaard, and U. T. Tygesen, "Load identification of offshore platform for fatigue life estimation," in *Conference Proceedings of the Society for Experimental Mechanics Series*, 2014, vol. 5, pp. 99–109, doi: 10.1007/978-3-319-04570-2_11.

[56] N. Perišić and U. T. Tygesen, "Cost-effective load monitoring methods for fatigue life estimation of offshore platform," 2014.

[57] D. J. Pitchforth, T. J. Rogers, U. T. Tygesen, and E. J. Cross, "Grey-box models for wave loading prediction," *Mech. Syst. Signal Process.*, vol. 159, p. 107741, 2021, doi: 10.1016/j.ymssp.2021.107741.

[58] D. J. Pitchforth, T. J. Rogers, U. T. Tygesen, and E. J. Cross, "A grey-box model for wave loading prediction with uncertainty propagation," in *Proceedings of ISMA 2020 - International Conference on Noise and Vibration Engineering and USD 2020 - International Conference on Uncertainty in Structural Dynamics*, 2020, pp. 3611–3622.

[59] B. Nabuco, S. D. Amador, E. I. Katsanos, U. T. Tygesen, E. D. Christensen, and R. Brincker, "Comparing measured responses of an offshore structure with operational modal analysis-assisted classical model approach," *J. Offshore Mech. Arct. Eng.*, vol. 143, no. 3, pp. 1–8, 2021, doi: 10.1115/1.4048879.

[60] M. Tarpø, "Stress Estimation of Offshore Structures," Aarhus University, 2020.

[61] A. Skafte, J. Kristoffersen, J. Vestermark, U. T. Tygesen, and R. Brincker, "Experimental study of strain prediction on wave induced structures using modal decomposition and quasi static Ritz vectors," *Eng. Struct.*, vol. 136, pp. 261–276, 2017, doi: 10.1016/j.engstruct.2017.01.014.

[62] B. Nabuco, M. Tarpø, U. T. Tygesen, and R. Brincker, "Fatigue Stress Estimation of an Offshore Jacket Structure Based on Operational Modal Analysis," *Shock Vib.*, vol. 2020, 2020, doi: 10.1155/2020/7890247.

[63] F. Bigot, F.-X. Sireta, E. Baudin, Q. Derbanne, E. Tiphine, and Š. Malenica, "A Novel Solution to Compute Stress Time Series in Nonlinear Hydro-Structure Simulations," 2015, doi: 10.1115/OMAE2015-42014.

[64] A. Skafte, U. T. Tygesen, and R. Brincker, "Expansion of mode shapes and responses on the offshore platform Valdemar," in *Conference Proceedings of the Society for Experimental Mechanics Series*, 2014, vol. 4, pp. 35–41, doi: 10.1007/978-3-319-04546-7_5.

[65] D. Augustyn, R. R. Pedersen, U. T. Tygesen, M. D. Ulriksen, and J. D. Sørensen, "Feasibility of modal expansion for virtual sensing in offshore wind jacket substructures," *Mar. Struct.*, vol. 79, no. June 2020, pp. 1–17, 2021, doi: 10.1016/j.marstruc.2021.103019.

[66] E. Dascotte, J. Strobbe, and U. T. Tygesen, "Continuous stress monitoring of large structures," in *5th International Operational Modal Analysis Conference (IOMAC)*, 2013, pp. 1–10.

[67] DNV, "DNV-RP-C210 - Probabilistic methods for planning of inspection for fatigue cracks in offshore structures," 2021.

[68] D. Augustyn, U. T. Tygesen, M. D. Ulriksen, and J. D. Sørensen, "Data-driven design and operation of offshore wind structures," in *Proceedings of the Twenty-ninth International Ocean and Polar Engineering Conference (ISOPE)*, 2019, pp. 491–498.

[69] J. Tychsen, S. Risvig, H. F. Hansen, N.-E. O. Hansen, and F. Stevanato, "Summary of the impact on structural reliability of the findings of the Tyra Field Extreme Wave Study 2013-15," 2016.

[70] J. Tychsen and M. Dixen, "Wave kinematics and hydrodynamic loads on intermediate water depth structures inferred from systematic model testing and field observations - Tyra Field Extreme Wave Study 2013-2015," 2016.

[71] T. J. Rogers, K. Worden, and E. J. Cross, "On the application of Gaussian process latent force models for joint input-state-parameter estimation: With a view to Bayesian operational identification," *Mech. Syst. Signal Process.*, vol. 140, p. 106580, 2020, doi: 10.1016/j.ymssp.2019.106580.

[72] T. J. Rogers, K. Worden, R. Fuentes, N. Dervilis, U. T. Tygesen, and E. J. Cross, "A Bayesian non-parametric clustering approach for semi-supervised Structural Health Monitoring," *Mech. Syst. Signal Process.*, vol. 119, pp. 100–119, 2019, doi: 10.1016/j.ymssp.2018.09.013.

[73] T. J. Rogers, K. Worden, R. Fuentes, N. Dervilis, U. T. Tygesen, and E. J. Cross, "A semi-supervised Bayesian non-parametric approach to damage detection," in *9th European Workshop on Structural Health Monitoring (EWSHM)*, 2018, no. 1, pp. 1–12.

[74] L. A. Bull *et al.*, "Foundations of population-based SHM, Part I: Homogeneous populations and forms," *Mech. Syst. Signal Process.*, vol. 148, p. 107141, 2021, doi: 10.1016/j.ymssp.2020.107141.

[75] J. Gosliga, P. A. Gardner, L. A. Bull, N. Dervilis, and K. Worden, "Foundations of population-based SHM, Part II: Heterogeneous populations – Graphs, networks, and communities," *Mech. Syst. Signal Process.*, vol. 148, p. 107144, 2021, doi: 10.1016/j.ymssp.2020.107144.

[76] P. Gardner, L. A. Bull, J. Gosliga, N. Dervilis, and K. Worden, "Foundations of population-based SHM, Part III: Heterogeneous populations – Mapping and transfer," *Mech. Syst. Signal Process.*, vol. 149, p. 107142, 2021, doi: 10.1016/j.ymssp.2020.107142.

[77] G. Tsialiamanis, C. Mylonas, E. Chatzi, N. Dervilis, D. J. Wagg, and K. Worden, "Foundations of population-based SHM, Part IV: The geometry of spaces of structures and their feature spaces," *Mech. Syst. Signal Process.*, vol. 157, no. February, 2021, doi: 10.1016/j.ymssp.2021.107692.

[78] M. H. Faber, S. Tølbøll Glavind, J. G. Seplveda Astudillo, and J. Qin, "Big Data Techniques for Probabilistic System Representations," 2019.

[79] B. T. Svendsen, G. T. Frøseth, O. Øiseth, and A. Rønnquist, “A data-based structural health monitoring approach for damage detection in steel bridges using experimental data,” *J. Civ. Struct. Heal. Monit.*, no. 0123456789, 2021, doi: 10.1007/s13349-021-00530-8.

[80] R. Brincker, U. Tygesen, M. Faber, E. Katsanos, M. Tychsen, and H. Stang, “Innovative structural health monitoring and risk-informed structural integrity management (InnoSHM).” Innovation Fund Denmark – Grand Solutions. Case number: 0175-00028A, 2020.

[81] A. Rytter, “Vibrational Based Inspection of Civil Engineering Structures,” University of Aalborg, Denmark, 1993.

[82] K. Worden and J. M. Dulieu-Barton, “An Overview of Intelligent Fault Detection in Systems and Structures,” *Struct. Heal. Monit.*, vol. 3, no. 1, pp. 85–98, 2004, doi: 10.1177/1475921704041866.

[83] R. Hageman, P. Aalberts, M. Shaik, and H. van den Boom, “Development of an Advisory Hull Fatigue Monitoring System,” Nov. 2013, doi: 10.5957/SMC-2013-T43.

[84] R. Hageman, P. Aalberts, R. Leeuwenburgh, and N. Grasso, “Integrity Management of Mooring Systems,” Apr. 2019, doi: 10.4043/29560-MS.

APPENDIX 1
CONSIDERATIONS FOR IMPLEMENTATION OF THE FRAMEWORK (SIMPLIFIED GUIDANCE)

General

This appendix provides considerations to include for the implementation of the framework presented in Section 6, These considerations can be considered as a simplified guidance, which gives the users, operators and asset owners an overview of the activities that must be considered related to the purchase and use of SHM systems for offshore structures.

In the following, a simplified guidance for each of the framework levels is presented. It should be noted that the simplified guidance for each of the framework levels should not be considered complete since several additional considerations may be relevant depending on the specific structure under consideration.

Pre-study and design of structural monitoring systems

Table A-1 summarizes the simplified guidance provided for the pre-study and design of structural monitoring systems.

Table A-1: Guidance for the pre-study and design of structural monitoring systems.

ID	Description
Pre-testing of the structural monitoring system	
1	The asset owner needs to define the ambitions for the monitoring strategy since the value generation and project pricing are highly dependent on which of the levels 1-5 are to be accomplished. Once the purpose and goal of the structural monitoring system are defined, different monitoring strategies can be tested in a numerical FE model.
1.1	The supplier should evaluate the required number of sensors and the optimal sensor placement for the structural monitoring system. The sensor locations should be carefully evaluated to ensure that they provide valuable information in fulfilling the purpose and goal of the structural monitoring system.
Technical specifications	
2	Technical specifications should include details of the sensor types, the number of each sensor type and the location of each sensor. Furthermore, the technical specifications should include technical requirements for each sensor type and data acquisition system indicating the quality of the individual sensors (performance specifications) and the quality of the raw data received from the measurement system. Methods and algorithms to find the optimal sensor placement can be applied.
2.1	Data must always be synchronized in time with high precision (typically within milliseconds as a minimum) to obtain value for levels 1-5.
2.2	For level 3 and 4 applications, the accuracy related to displacements measured from accelerometers or similar sensors are of utmost importance. The supplier should prove that the sensors measure accurate displacements by comparing them to a reference, such as a laser, showing performance from DC and up, covering all the frequencies of interest. Care should be taken when measuring displacements from accelerometers in the low frequency range, i.e., down to 0.03 Hz or lower.
2.3	For strain gauge installation, the supplier should fasten the strain gauges with an adequate approach such as micro-welding or similar to secure a robust system.
2.4	For levels 3-5 applications, detailed time-dependent information of the environmental loading is required. For waves, the wave elevation and wave direction should be measured in the time domain, typically at 10 Hz or more, to enable calibration of the wave load model.
Purchase, fabrication, installation and commissioning (relevant for levels 3-5)	
3.0	Based on the technical specifications and definition of the requirements for the documentation, the user can invite suppliers for tendering. The below items highlight the most important activities to ensure sufficient quality of the purchased structural monitoring system.
3.1	A review of the supplier’s data sheets and data quality documentation should be performed prior to purchase.
3.2	FAT at the supplier’s workshop should be performed to ensure that technical requirements are met and that the data quality is as accurate as required.

3.3	Third party verification of the structural monitoring system may be required depending on the user documentation requirements.
3.4	SAT offshore should be performed to ensure that the installed system works as intended.
3.5	Commissioning of the system should be performed to ensure data flow.

Level 1 – Screening and diagnosis

Table A-2 summarizes the simplified guidance provided for level 1 of the framework.

Table A-2: Guidance for level 1.

ID	Description
Experimental and operational modal analysis (screening and diagnosis)	
1	To perform a screening and diagnosis, high-quality data must be available together with an accurate description of the sensor locations.
1.1	The optimal sensor placement defined in the pre-study must capture the most relevant (fundamental) modes of the evaluated structural system.
1.2	Identification of the most relevant (fundamental) modes affecting the structural integrity should be performed using appropriate methods for EMA/OMA.
1.3	When assessing the fundamental natural frequencies, the associated mode shapes are of key importance since the force flow in the structure is significantly related to the modes. Consequently, a comparison using MAC or other related criteria should be performed.
1.4	The modal parameters obtained from the EMA/OMA should be compared to the modal properties of the digital twin (FE model) to assess the performance of the model. A diagnosis can be established by comparing the natural frequencies and modes shapes obtained from the EMA/OMA to the digital twin (FE model). For significant deviations, it is recommended to calibrate the structural parameters of the digital twin to achieve the best fit between the measurements and the digital twin.

Level 2 – FE model updating

Table A-3 summarizes the simplified guidance provided for level 2 of the framework.

Table A-3: Guidance for level 2.

ID	Description
Preparation of the digital twin (FE model)	
1	The digital twin should represent the as-is condition, i.e., with no conservative assumptions regarding scour, marine growth, masses and/or other parameters related to the structural representation. These parameters should reflect the actual conditions as experienced during the measurement period in the best possible way. Furthermore, future structural representations should be re-evaluated in order to obtain the best representation of the actual condition.
1.1	A sensitivity study should be performed to determine the parameters of the digital twin that are most sensitive to changes. In other words, determination of the parameters that influence the natural frequencies and MAC numbers of the modes used in the FE model updating.
1.2	Awareness is needed regarding the fact that the sensitivity study can be misleading in case the parameters of the digital twin do not represent the actual physics. As an example: the parameters in a soil model will only be sensitive if the model represents the physics measured.
Assessment of uncertainties and FE model updating	
2	Both natural frequencies and MAC numbers should be used in the FE model updating to obtain improved structural dynamic behaviour and force flow.
2.1	A suitable approach should be selected to determine an appropriate combination of parameters to use in the FE model updating.
2.2	Bounds on all parameters should be considered in the FE model updating to ensure that the parameters attain values within a reasonable range from an engineering point of view. Additionally, parameter uncertainty bounds could also be assessed, which can lead to a limited but reasonable change in parameter values. The approach depends on the method chosen for the FE model updating.
2.3	In complex FE models, the order of modes may change during the model updating. Hence, an approach should be selected to ensure the identification of correct modes during the model updating.
Validation of parameters	
3	For an additional assessment of the validity of the updated digital twin (FE model), the final parameter values should be checked against relevant documentation such as weight reports, geotechnical reports, and other relevant reports with structural information.

Level 3 – Load model updating

Table A-4 summarizes the simplified guidance provided for level 3 of the framework.

Table A-4: Guidance for level 3.

ID	Description
Measurement period	
1	The measurement period should be sufficiently long to capture the governing loads relevant for the structural analysis to be performed.
1.1	For fatigue analysis of offshore structures, a measurement period that considers an entire winter season may be adequate. However, longer measurement periods may provide a benefit in terms of a reduction of the uncertainties quantified in level 4.
Virtual sensing (measurements)	
2	When performing a load model updating, the forces in the entire structure should be considered. This can be achieved by using the virtual sensing technique to expand the information to all locations in the structure.
2.1	For virtual sensing of fixed offshore structures, the measured displacements along with the measured time-varying sea surface elevation is required. Furthermore, a calibrated digital twin (FE model) obtained in level 2 is required to expand the information into all other locations of the structure.
2.2	It is important to select locations that represents the global force flow through the structure for evaluation purposes. For fixed structures, structural elements above and in the splash zone should be selected together with elements near the seabed.
2.3	In virtual sensing, it is important to include the governing modes at all time increments. The following modes should be included for wave load calibration: • Dominant (fundamental) dynamic modes. • Quasi-static modes representing the wave load acting on the structure.
Prediction model	
3	The prediction model should be represented by an updated digital twin (FE model) from level 2. For the analysis approach adopted for the prediction model (deterministic, transient, or spectral fatigue), the selected approach should correspond with the prediction model to be used in the subsequent structural analysis in level 4.
3.1	A sensitivity study should be performed to assess that the governing parameters in the analysis do not affect the results significantly. Examples of considerations in a sensitivity study could be the length of the time steps in the transient analysis, the number of seeds representing the wave loads acting on the structure and grid size, to mention a few.
3.2	The governing parameters affecting the load on the structure should be identified. For a fixed offshore structure, the governing load for fatigue is the wave load and, hence typically, the parameters in the Morison equation should be calibrated.

Comparison of measurements and predictions	
4	To assess the performance of the load model in the prediction model, the stresses in selected elements should be compared to measured strains converted to stresses. The measured strains (converted to stresses) are typically extracted from the virtual sensing for the selected elements. The performance should be assessed in stress range history plots with stress increments on one axis and the number of counts on the other axis, covering data from several months of measurements.
4.1	The fit between data from virtual sensing and the prediction model will clearly indicate the performance of the prediction model. In case the correspondence cannot be achieved by changing the load model parameters (e.g., the Morison equations) within physical ranges, then the load model is most likely not representable with respect to fundamental physical parameters.

Level 4 – Quantification of uncertainties

Table A-5 summarizes the simplified guidance provided for level 4 of the framework.

Table A-5: Guidance for level 4.

ID	Description
Uncertainty of governing assumptions	
1	When assessing the uncertainty of the FE model and the loading of the structure, it is important to be aware of governing uncertainties contributing to the overall CoV on fatigue loading. Below are some examples of significant uncertainties affecting the CoV for a model governed by wave loading. For each uncertainty identified, the bias should also be determined. It should be noted that the definition and quantification of the contributing uncertainties shall be consistent with the structural reliability format adopted in the RBI. The different RBI methods require different quantification of uncertainties. Hence, the uncertainties can be treated differently from one RBI format to another.
1.1	*CoV measurement* is the uncertainty related to the measured data from the structural monitoring system, i.e., the measurement uncertainty.
1.2	*CoV virtual sensing* is the uncertainty related to the virtual sensing approach, i.e., the uncertainty in the virtual sensing based on the assumption of known measured data.
1.3	*CoV long-term* is the uncertainty contribution from the year-to-year sea state variations. This uncertainty can be estimated by assessing the variation of the significant wave height, $H_{S,}$ and the impact on the stress ranges. Hence, this uncertainty is important for inspection programs with short inspection intervals.
1.4	*CoV limited* is the uncertainty related to conditions where structural monitoring system measurements only have been carried out on a limited number of measured sea states (e.g., a few months during a winter period).
1.5	*CoV FEM* describes the fit between the updated load model and the virtual sensing model. Hence the CoV FEM is significantly affected by the parameters applied in Morison's equation.
1.6	*Other uncertainties.* Several other uncertainties exist that contribute to the overall uncertainty CoV on fatigue loading. However, if these uncertainties are below approximately 0.03, the contribution may be considered minor.

Level 5 – Detection of changes (damage detection)

Table A-6 summarizes the simplified guidance provided for level 5 of the framework.

Table A-6: Guidance for level 5.

ID	Description
Damage accumulation	
1	The actual accumulated fatigue damage in the structure considered can be determined from measurements by utilizing virtual sensing.
1.1	The uncertainty associated with fatigue damage results should be evaluated by performing a level 4 uncertainty assessment to ensure that the accumulated fatigue damage is reliable.
Change and damage detection	
2	Awareness is needed for the consideration of change and damage detection regarding detectability. Furthermore, an assessment of the chosen approach regarding the possibilities for local and global change and damage detection is needed, in addition to an assessment of how early such changes can be detected.
2.1	Different approaches exist for setting threshold values to classify an observation. Awareness with respect to operational and environmental variability is needed, which can cause false-positive indications of damage (indication of damage when in fact there is no damage in the system).
2.2	Awareness is needed when machine learning models are trained solely on numerical data and testing is performed based on experimental data. Furthermore, changes caused by operational and environmental conditions, together with measurement noise, may mask changes caused by damage.
Abnormal events	
3	In the case an abnormal event or incident has occurred, the processed data from the structural monitoring system can be used for decision-making by comparing with expected critical limits for extreme events.

APPENDIX 2
QUESTIONNAIRE

This appendix contains the questionnaire that has been given to all the external companies that have contributed to this report. The questionnaire contains two parts: part 1 and part 2. Part 1 considers sensor technology for data collection, whereas part 2 considers methodologies, methods and algorithms for data analysis.

Part 1

THE USE OF DIGITAL SOLUTIONS FOR STRUCTURAL MONITORING AND DAMAGE DETECTION OF FLOATING AND FIXED STRUCTURES

	Name of sensor	Description/purpose	Comments:
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Part 2

RAMBOLL

THE USE OF DIGITAL SOLUTIONS FOR STRUCTURAL MONITORING AND DAMAGE DETECTION OF FLOATING AND FIXED STRUCTURES

	Name of technique	FSS (X)	GBS (X)	TS (X)	SSH (X)	O&G (X)	WIND (X)	Description/purpose	System components/sensors What inputs/data are needed and from which sensors?	What is the technical outcome by applying this technique?	What is the value of this outcome?	Comments
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												

Please mark which industry/industries the technique is used in.
Fixed steel structures/jackets (FSS), Gravity Based Structures (GBS), topside structures (TS) and semi-submersible hulls (floaters) (SSH) within Oil & Gas (O&G) and Offshore Wind (WIND) industry

APPENDIX 3
ACKNOWLEDGEMENTS

General

This appendix contains acknowledgements of all the external companies that have contributed to this report through knowledge sharing, information and valuable discussions. In the following, a brief presentation of each company, including relevant contact information, is provided together with a short description of the specific contribution to this project.

Regulators

Company	**Health and Safety Executive (HSE)**	
Description	HSE sets the strategy, policy and legal framework for health and safety in Great Britain. The overarching, strategic principles for the system they guard are that those who create risks have a responsibility to manage them and that action should be proportionate to the risks that need managing. HSE uses a variety of methods to influence change and help people manage risks at work. These include: - Providing advice, information and guidance - Raising awareness in workplaces by influencing and engaging - Operating permission and licensing activities in major hazard industries - Carrying out targeted inspections and investigations - Taking enforcement action to prevent harm and hold those who break the law to account	
Company & study project contact(s)	Homepage / www.hse.gov.uk	Alex Stacey / alex.stacey@hse.gov.uk
Study project contribution	Informal input and valuable perspectives through interviews.	

Company	**Petroleum Safety Authority (PSA) Norway**	
Description	The PSA is a government supervisory and administrative agency with regulatory responsibility for safety, the working environment, emergency preparedness and security in the petroleum sector. PSA is responsible for determining parameters for the oil and gas industry and for ensuring that activities in this sector are pursued in a prudent manner. Authority has been delegated to PSA to establish detailed regulations for safety and the working environment in the industry, and to take administrative decisions in the form of consents, orders, coercive fines, shutting down operations, prohibitions, exemptions and so forth. PSA is also a directorate. In Norway's system of government administration, such bodies develop, manage, and communicate knowledge about their area of responsibility and technical expertise.	
Company & study project contact(s)	Homepage / www.ptil.no/en	Marita Halsne / marita.halsne@ptil.no Gerhard Ersdal / gerhard.ersdal@ptil.no
Study project contribution	Input and valuable perspectives through interviews and workshops.	

Operators

Company	**British Petroleum (BP)**	
Description	BP is one of the world's largest integrated oil and gas companies. The company is involved in almost every step of the oil and natural gas supply chain, from exploration to the sale and marketing of energy products. BP also engages in producing renewable energy through wind farms in addition to producing a variety of petrochemical products. BP operates worldwide (Europe, North and South America, Africa, Asia and Australia). BP has three main focus areas: low carbon electricity and energy; convenience and mobility; and resilient and focused hydrocarbons.	
Company & study project contact(s)	Homepage / www.bp.com	Philip Smedley / Philip.smedley@uk.bp.com
Study project contribution	Informal input and valuable perspectives through short interviews.	

Company	**Chevron**	
Description	Chevron is an integrated energy company covering everything from upstream exploration and production to midstream transportation, power and trading to downstream manufacturing and retail worldwide. Chevron is one of the largest oil companies in the United States. Production activities take place worldwide (North and South America, Europe, Africa, Asia and Australia). Chevron's purpose is to develop energy that enables human progress around the world through technology and innovation but also through their operational excellence platform. The purpose is executed with objectives in mind such as eliminating fatalities, serious injuries and illnesses; eliminating high-consequence process safety incidents and operating with industry-leading reliability; and using energy and resources efficiently.	
Company & study project contact(s)	Homepage / www.chevron.com	Sanjay Srinivasan / sanjay.srinivasan@chevron.com Robert Seah / rseah@chevron.com Moises Abraham / Moises.Abraham@chevron.com
Study project contribution	Informal input and valuable perspectives through short interviews.	

Engineering and service companies

Company	**Altera Infrastructure**	
Description	Altera (formerly a part of Teekay) provides critical infrastructure assets to the offshore energy industry. Their fleet consists of floating production, storage and offloading (FPSO) units, shuttle tankers, floating storage and offtake (FSO) units, long-distance towing and offshore installation vessels and a unit for maintenance and safety (UMS). Altera is represented by approximately 2300 employees and 46 vessels, operating in 6 countries through 10 offices.	
Company & study project contact(s)	Homepage / https://alterainfra.com	Bente Gussiaas / Bente.Gussiaas@alterainfra.com
Study project contribution	Informal input and up-front perspectives.	

Company	**DHI**	
Description	DHI is an independent and international consultant and research organization. They are also a governmental-approved research and technology organisation in Denmark. DHI's expertise spans all water environments, i.e., from rivers and reservoirs to oceans and coastlines in addition to cities and factories. They develop tailor made solutions and provide specialised services to solve specific water challenges within: aquaculture and agriculture; energy; climate change; coast and marine; surface and groundwater; urban water; industry; environment and ecosystems; product safety and environmental risk. DHI's knowledge is represented by 50 years of dedicated research and real-life experience from more than 140 countries with offices in more than 30 countries across the globe. DHI is approved by the Danish government as a technological service institute.	
Company & study project contact(s)	Homepage / www.dhigroup.com.com	Ole Svenstrup / osp@dhigroup.com
Study project contribution	Informal input and valuable perspectives through short interviews.	

Company	**DNV**	
Description	DNV is one of the world's leading classification societies and a recognized advisor for the maritime industry. DNV delivers renowned testing, certification and technical advisory services to the energy value chain including renewables, oil and gas, and energy management. DNV is one of the world's leading certification bodies, helping businesses assure the performance of their organizations, products, people, facilities and supply chains. DNV also provides digital solutions for managing risk and improving safety and asset performance for ships, pipelines, processing plants, offshore structures, electric grids, smart cities and more through platforms like Veracity. DNV is organised within business areas: Maritime, Energy systems, Digital solutions, Supply chain & product assurance, Business assurance and Accelerator.	
Company & study project contact(s)	Homepage / www.dnv.com	Ole Gabrielsen / Ole.Gabrielsen@dnv.com Francois-Xavier Sireta / Francois-Xavier.Sireta@dnv.com
Study project contribution	Input and valuable perspectives through knowledge sharing (questionnaire and informal discussions).	

Company	**FORCE Technology**	
Description	FORCE Technology is a technology consultancy and service company, which strives to create positive technological change and make the world more sustainable and safer. Since 1940, FORCE has helped companies through great technological advancements, from oil and gas, wind energy and space technology. Their core areas are: inspection, measuring and data acquisition; testing, calibration and analysis; and products, components and sensor systems. FORCE is also a governmental-approved research and technology organisation in Denmark, i.e., with a key role in the Danish innovation system as the link between technology and business. They seek to make new technological methods applicable to businesses and promote businesses uptake of new technology.	
Company & study project contact(s)	Homepage / www.forcetechnology.com/en	Julle Ekeborg / jue@force.no
Study project contribution	Input and perspectives through valuable knowledge sharing (questionnaire and informal discussions).	

Company	**Fugro**	
Description	Fugro is one of the world's leading geodata specialists, collecting and analysing comprehensive information about the earth and the structures built upon it. Through integrated data acquisition, analysis and advice, Fugro unlock insights from geodata to help clients design, build and operate their assets in a safe, sustainable and efficient manner. Fugro is represented around the globe, employing approximately 9000 employees in 61 countries. Their service ranges from marine site characterisation, land site characterisation, marine asset integrity and land asset integrity. Their offshore asset management services include: inspection, repair and maintenance services; monitoring and remote systems technologies; and diverse testing and engineering capabilities. Fugro operates in the Americas, Europe, Africa, Middle East, and Asia.	
Company & study project contact(s)	Homepage / www.fugro.com	Gordon Hamilton / g.hamilton@fugro.com
Study project contribution	Input and valuable perspectives through knowledge sharing (questionnaire and informal discussions).	

Company	**Kent PLC**	
Description	Kent is a leading international integrated energy services partner formerly known as Kentech. In 2021, Kentech acquired multiple businesses from SNC-Lavalin's oil and gas division, including the oil and gas and offshore wind, hydrogen, carbon and storage from the former Atkins business, Houston Offshore Engineering and Kentz. Today, Kent has more than 100 years of experience with a footprint representing 10 000 employees across 84 nationalities. They offer services such as construction, commissioning, modification and maintenance services to the energy industry across six continents.	
Company & study project contact(s)	Homepage / www.kentplc.com	Philip Walker / Philip.Walker@kentplc.com Matt Keys / Matt.Keys@kentplc.com
Study project contribution	Input and valuable perspectives through knowledge sharing (questionnaire and informal discussions).	

Company	**Light Structures**	
Description	Light Structures offers monitoring solutions to the maritime industry. Light Structures AS was founded in 2001 and evolved as a spin-off from the Norwegian Defence Research Establishment. The company is enjoying a steady growth in the shipping and oil & gas markets and is today the world's leading provider of fibre-optic hull stress and other structure monitoring systems. Light Structures offers different arrangements and frameworks to suit various requirements in the different sectors for customers and partners. Services include ice load monitoring systems and active fatigue management among others.	
Company & study project contact(s)	Homepage / www.lightstructures.no	Terje Sannerud / tsa@lightstructures.no
Study project contribution	Input and valuable perspectives through knowledge sharing (questionnaire and informal discussions).	

Company	**NetDesign**	
Description	NetDesign, a Nuuday company, has existed for more than 30 years and delivers end-to-end IT solutions and associated managed services, including transformation services of it-services, digital infrastructure, cyber security, collaboration platforms and customer engagement solutions.	
Company & study project contact(s)	Homepage / www.netdesign.dk	Thomas Thomsen Mølgaard / ttmo@netdesign.dk
Study project contribution	Informal input and up-front perspectives.	

Company	**ROSEN Group**	
Description	The ROSEN Group is a worldwide provider of cutting-edge solutions in all areas of the integrity process chain. The business is privately owned and consists of a team of more than 4 000 employees, operating in more than 120 countries. ROSEN's service portfolio comprises inspection and integrity as well as research and development solutions, including sensor and data acquisition technologies. ROSEN also supplies sophisticated instruments. They cover industries such as the oil and gas, hydrogen, mining and wind energy industries but also manufacturing, transportation and the process industries.	
Company & study project contact(s)	Homepage / www.rosen-group.com	Partha Dev / pdev@rosen-group.com
Study project contribution	Input and valuable perspectives through knowledge sharing (questionnaire and informal discussions).	

Institutes

Company	**Energy Institute (EI)**	
Description	EI is the not-for-profit chartered professional membership body bringing together expertise to tackle urgent global challenges. EI is a global, independent network of professionals spanning the world of energy, convening and facilitating debate, championing evidence and sharing fresh ideas, giving voice to issues of concern and where necessary challenging the industry they work with. The EI was set up in 2003 as a result of a merger between the Institute of Petroleum (IP) and the Institute of Energy (InstE). EI is licensed by the Engineering Council (UK) to offer Chartered, Incorporated and Engineering Technician status to engineers, and by the Society for the Environment to award Chartered Environmentalist status.	
Company & study project contact(s)	Homepage / www.energyinst.org	Cameron Stewart / cstewart@energyinst.org
Study project contribution	Informal input and up-front perspectives through their workshop on "Novel Monitoring & Inspection" (held November 2021).	

Company	**MARIN**	
Description	MARIN is a globally recognised institute for hydrodynamic and nautical research with 400+ specialists. As one of the world's leading maritime institutes, MARIN provides advanced expertise and independent research. Aiming to bridge the gap between design and operation, MARIN is involved in the entire lifecycle of the ship, from the initial concept development to design, construction and subsequently to the final operation. MARIN combines software, model test facilities, simulators, and full-scale monitoring capabilities to help the clients make ships and operations cleaner, safer and smarter during each phase of the lifecycle. MARIN has a complete range of model test facilities, software tools, simulators, numerical facilities, and measurement techniques to test, simulate and monitor ships and operations, including the human factor.	
Company & study project contact(s)	Homepage / www.marin.nl/en	Pieter Aalberts / p.j.aalberts@marin.nl Hannes Bogaert / h.bogaert@marin.nl
Study project contribution	Input and valuable perspectives through knowledge sharing (questionnaire and informal discussions including an associated presentation).	

Company	**SINTEF**	
Description	SINTEF is one of Europe's largest independent research institutes, which provides services such as research, expertise and software. As an R&D partner, SINTEF contributes to value creation and increased competitiveness within the public and private sectors. They apply their multidisciplinary approach in a wide range of projects, from small test and verification projects to multinational research programmes with several partners. SINTEF builds and operates important research infrastructure and they have over 100 laboratories that form the basis for their research. Research infrastructure includes zero-emission building, ocean basin, nano, CO_2, electrical engineering and full-scale aquaculture sites in addition to world-leading laboratories.	
Company & study project contact(s)	Homepage / www.sintef.no/en	Øyvind Helland / oyvind.hellan@sintef.no
Study project contribution	Informal input and valuable perspectives through short interviews.	

APPENDIX 4
THE SIM PROCESS

General

This appendix contains a detailed overview of the SIM process and two examples that illustrates the extent of monitoring activities provided in the ISO and NORSOK standards.

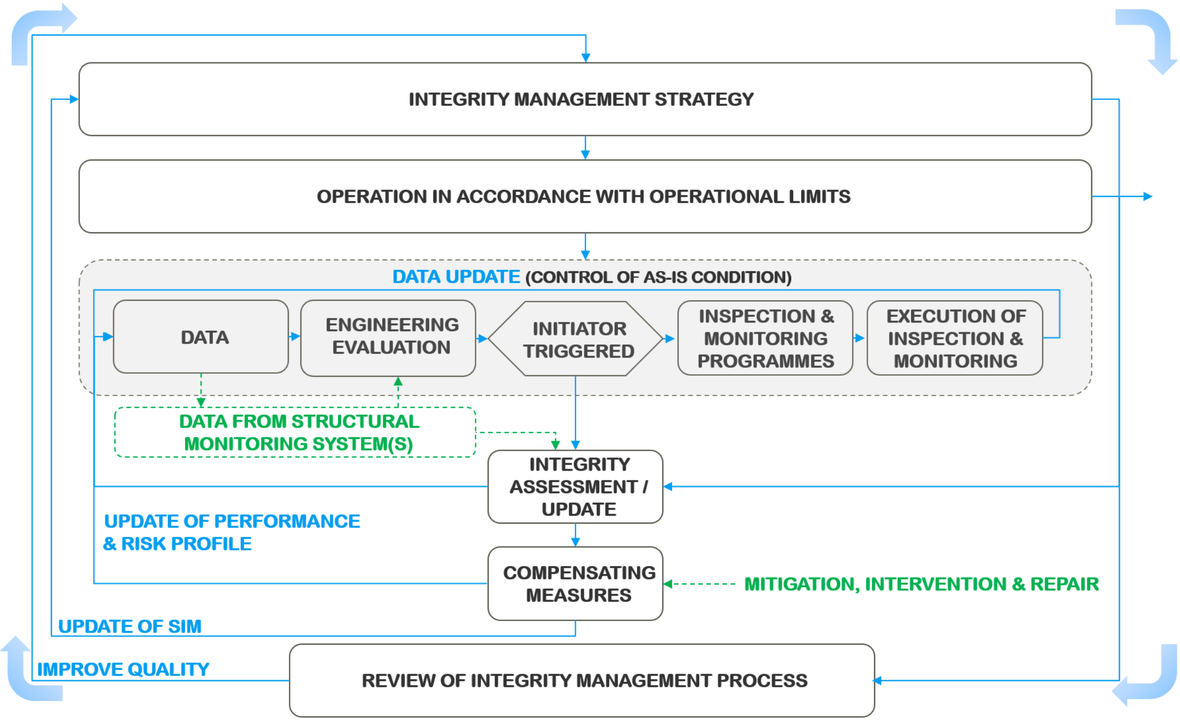

Figure A-1: A detailed overview of the SIM process.

Example 1

Standard ISO 19901-9 - Structural Integrity Management [1]
Selected parts - Clause 10.4 (Monitoring strategy) including Annex A.10.4 (informative) - Clause 11.4 (Monitoring program)
Reflections The stated clauses and associated annexes have been selected as they exemplify the level of details with respect to how monitoring is included, and how requirements and recommendations are provided. It should be emphasized that other detail levels are present in the standard, such as Clause 10.2 (Inspection strategy), where examples of inspections and associated (default) intervals are included. Furthermore, specific guidance on inspection techniques is stated in Annex A.10.2.4 (Inspection method). Clause 10.4.1 generally states that *"Monitoring may be used in combination with an inspection plan to enhance the level and quality of condition and operation data used to confirm fitness."* It should be noted that it is required that the monitoring program shall be documented within the inspection plan to confirm the monitoring program execution. Clause 10.4 defines different monitoring strategies that can be implemented to address expected degradation due to certain mechanisms. Such a monitoring strategy can be to monitor natural frequencies. It is highlighted that monitoring programs often require "*specialty equipment, continuous data recording, periodic calibrations, plus specialty software and personnel to evaluate the data.*" For monitoring natural frequencies, additional information is provided in Clause 10.4.4 and further detailed in Annex 10.4.4. Although examples are provided for the use and value-creation of this monitoring, no reflections and warnings are provided with respect to complexity. Furthermore, there is no specific guidance with respect to the equipment and technology to use, analysis methods to apply or how to perform validation. For the execution of the monitoring program, Clause 11.4 recommends that monitoring data be reviewed to determine whether anomalous conditions exist that would warrant further evaluation.

Example 2

Standards NORSOK N-005 [10] NORSOK N-006 [23]
Selected parts N-005: - Clause 6 (Data) - Clause 8.2 (Inspection and monitoring strategy) - Clause 8.11 (Monitoring/Program) - Clause 9.3 (Monitoring/Execution) - Annex B (Inspection Methods) N-006: - Clause 7 (Check of fatigue limit states) - 7.1, - Clause 8 (Check of ultimate limit states and accidental limit states) - 8.1 + 8.9
Reflections NORSOK N-005 and N-006 should be read and used together with SIM and assessment of existing structures. Similar to ISO 19901-9, Clause 6 in N-005 states that essential aspects of integrity management are the validity, extent and accuracy of the structure's data and inspection history. It is specifically required under the same clause that "*new techniques for improved inspection and monitoring and best practices shall be implemented, when relevant.*" While Clause 8.2 (N-005) defines the major activities to develop inspection and/or monitoring plans, they are all described on a high (general) level. Monitoring is further detailed in Clause 8.11 (N-005), where it is stated that: "*Monitoring can be used as a supplement to inspection to provide more information of the condition of a structure. This may be measurements of action effects by use of strain gauges, accelerometers may be used for monitoring of changes in response, leakage detection in confined spaces such as braces in floating structures and tethers, measurement of forces in anchor lines and tethers.*" The abovementioned is further detailed in Clause 9.3 (N-005), where more details are provided on value creation (specific examples are provided such as bridge monitoring and calibration/validation of analysis methods) and general requirements (e.g. technical skills, data management, etc.). A selection of inspection and monitoring methods are provided in Annex B.2 (N-005) for fixed steel structures (examples for other types of structures are provided in the associated annexes). These methods are described on a high (general) level. Reference is made to N-006, where an additional layer is added to the requirements and guidance on inspection and monitoring. Specific examples are provided in Clause 7.1 (fatigue limit states) and Clause 8.1 (ultimate and accidental limit states), where the specific use of monitoring to document the limit states are provided.