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THE EVALUATION OF DAMAGE DETECTION AND STRUCTURAL HEALTH MONITORING FOR INTEGRITY MANAGEMENT OF OFFSHORE STRUCTURES

REPORT

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THE EVALUATION OF DAMAGE DETECTION AND STRUCTURAL HEALTH MONITORING FOR INTEGRITY MANAGEMENT OF OFFSHORE STRUCTURES
REPORT

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CONTENTS

ABBREVIATIONS

AG	Attributed Graph
CODAM	Corrosion and damage (database)
CPM	Cathodic Protection Measurement
CVI	Close Visual Inspection
DP	Dynamic Positioning
FMD	Flooded Member Detection
FPSO	Floating Production, Storage and Offloading unit
FSO	Floating Storage and Offloading unit
FSU	Floating Storage Unit
GBS	Gravity-Based Structure
GVI	General Visual Inspection
IE	Irreducible Element
MOU	Mobile Offshore Unit
NA	Not Applicable
NCS	Norwegian Continental Shelf
NDT	Non-Destructive Testing
NPD	Norwegian Petroleum Directorate
PBSHM	Population-Based Structural Health Monitoring
PSA	Petroleum Safety Authority
RBI	Risk Based Inspection
RNNP	Risikonivå Norsk Petroleumsvirksomhet
ROV	Remotely Operated underwater Vehicle
SHM	Structural Health Monitoring
VIV	Vortex-Induced Vibration

1. EXECUTIVE SUMMARY

Marine structures are complex structures that provide critical energy supplies to our society. Structural health monitoring (SHM) can provide information regarding the current state of the structural condition. There is a potential in using SHM systems on marine 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 optimisation of maintenance, lifetime extension, reduction of inspection costs and increased structural safety. Particularly, the motivation for increased structural safety is influenced by the current political situation in the world and the need for energy supplies.

This project is based on funding from the Petroleum Safety Authority (PSA) in Norway. The objective of the project is to obtain a general overview of common structural failure modes of offshore structures on the Norwegian Continental Shelf (NCS) in the context of SHM, and establish information regarding standardisation of SHM in industries other than the energy industry. To accomplish the objective, the main state-of-the-art SHM approaches to determine structural damage from the literature are described. Statistical information regarding failure modes of offshore structures on the NCS is collected and evaluated with respect to the damage detection possibilities using SHM. Furthermore, an overview of relevant codes and standards regarding SHM in industries other than the energy industry is established based on an extensive mapping.

The main state-of-the-art SHM approaches to determine structural damage are included in conventional SHM and population-based SHM (PBSHM). Conventional SHM includes the model-based, data-based and hybrid approaches. PBSHM involves information between structures to be transferred by considering data collected from a group of similar structures. In general, SHM and PBSHM aim to provide decision support or structural diagnosis of the structure under consideration.

Structural failure modes of offshore structures are established from the literature. From this review, a total of 10 significant structural failure modes are identified. Furthermore, statistical information regarding failure modes of offshore structures on the NCS is collected and the information is evaluated with respect to the damage detection possibilities using SHM. Results from the analysis of the corrosion and damage (CODAM) database are presented. The CODAM database is a database that contains reported incidents on offshore structures on the NCS in the period 1974-2021. By considering anomalies and causes in the context of SHM in this period, it is found that cracks and dents are the most common structural failure modes, with fatigue and vessel impacts/dropped objects as the most obvious causes, respectively.

An overview of relevant codes and standards regarding SHM in industries other than the energy industry is established based on an extensive mapping. From this mapping, it is observed that there is an increasing number of codes, standards and guidelines related to SHM that have been made available in recent years. Furthermore, these codes, standards and guidelines mainly cover structures and infrastructures such as buildings and bridges. Previous studies have shown that there is a lack of codes, standards and guidelines that consider SHM in the energy industry. Consequently, these observations indicate that the work related to SHM standardisation has come further in industries other than the energy industry. As such, there is a significant potential of standardizing SHM of marine structures in the energy industry.

Keywords: Structural health monitoring (SHM), damage detection, structural failure modes, structural integrity assessment, marine structures, standardisation.

2. INTRODUCTION

2.1 Types of offshore structures

The types of offshore facilities are generally divided into stationary and moveable facilities. More specifically, stationary facilities include permanently placed facilities, whereas moveable facilities include mobile offshore units (MOUs). For statutory requirements, permanently placed facilities must adhere to regional regulations, whereas MOUs adhere to flag state regulations combined with class society rules. In general, MOUs include structures that are not meant to be permanently placed on a field during the lifetime of the field. Permanently placed facilities, however, include structures that are placed on a field for the duration of the production period. Such structures include fixed and floating structures, where the floating structures also include semisubmersible and ship-shaped structures intended to be permanently placed on a field for the duration of the production period. Consequently, floating structures such as semi-submersible and ship-shaped structures can be considered permanently placed facilities and MOUs depending on the purpose of the use. An overview of the facilities and types of offshore structures is presented in Figure 1.

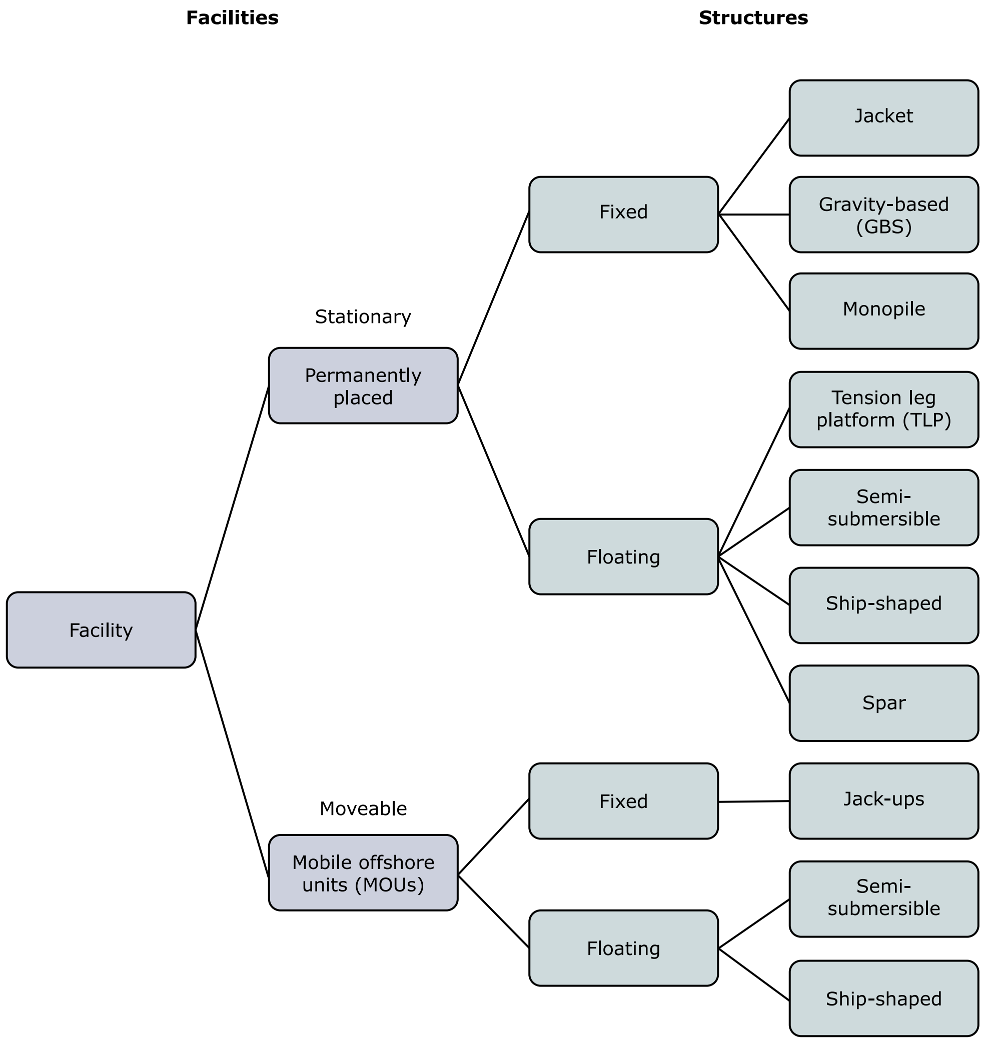

Figure 1: An overview of the facilities and types of offshore structures in the offshore industry.

The types of facilities used in the offshore industry mainly include fixed and floating structures. Fixed structures include jackets supported by piles or suction anchors, gravity-based structures (GBS), jack-ups and monopiles, whereas floating structures include semi-submersibles, tension leg, ship-shaped and spar structures.

Inspection and repair are essential to maintain the structural integrity and ensure safe operation of offshore structures. For permanently placed facilities. i.e., fixed structures and to some extent floating structures, inspection and repair must be performed in the offshore environment and normally underwater. For MOUs, however, inspection and repair are typically performed in a controlled environment at regular intervals since these units operate on a specific offshore location for a limited time. Consequently, inspection and repair are significantly different for permanently placed facilities and MOUs with respect to the regulatory regime and the environment.

2.2 Background

The Norwegian Petroleum Directorate (NPD) is responsible for managing and providing petroleum data from the Norwegian Continental Shelf (NCS), including relevant data regarding the facilities. Figure 2 shows the age distribution of permanently placed facilities on the NCS according to NPD. The facilities include fixed and floating structures but exclude subsea structures.

Altogether, 180 facilities are registered on the NCS. Figure 2 shows the facilities provided with data of the production start-up date, which include 163 of 180 facilities. Based on the facilities provided with data of the production start-up date, 95 facilities are still in service, 65 are not in service and three will be installed in the future (Johan Castberg FPSO, Njord A and Njord B). From Figure 2, it is observed that a majority of the facilities that are still in service were installed in the periods 1985-2005 and 2010-2020.

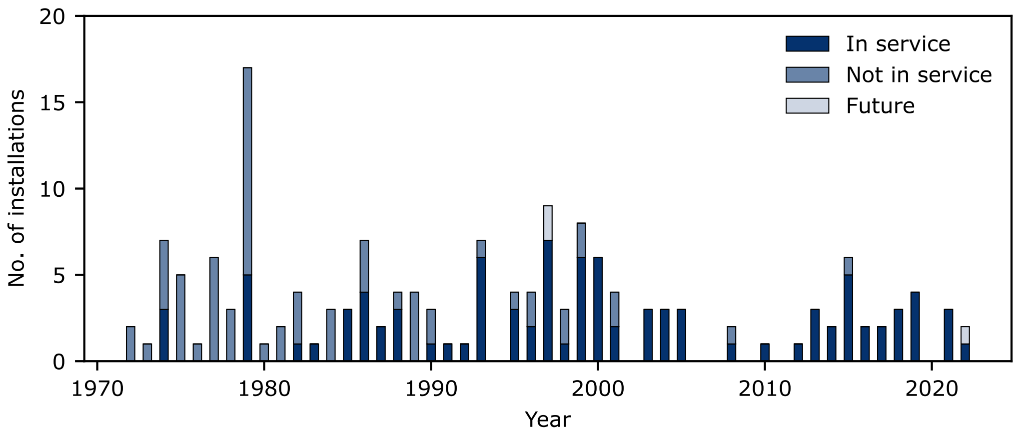

Figure 2: The age distribution of permanently placed facilities on the NCS according to NPD (2022). The age is set according to the date the facility was put into production (production start-up date).

Figure 3 shows the original design life distribution of the facilities still in service on the NCS. The figure shows the facilities that are provided with data of the original design life, which include 87 of 95 facilities. It is observed that a majority of the facilities are designed with original design lives of 20, 25 and 30 years.

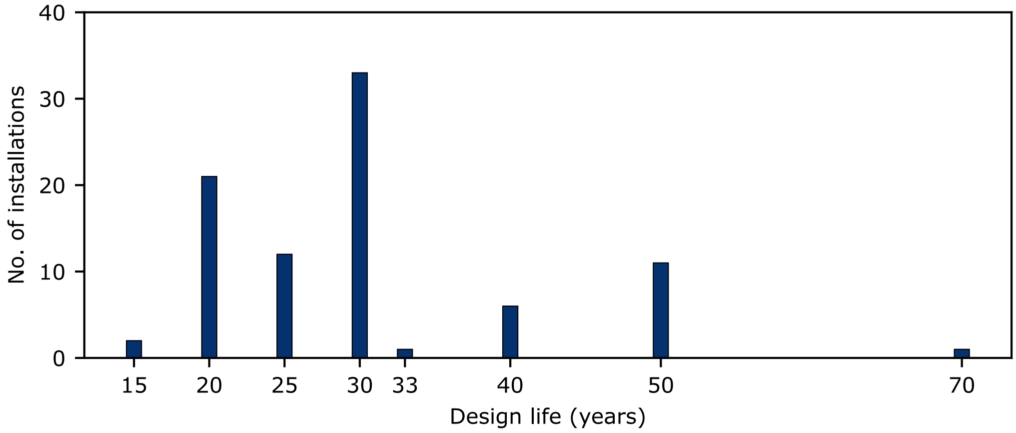

Figure 3: The original design life distribution of permanently placed facilities in service according to NPD (2022).

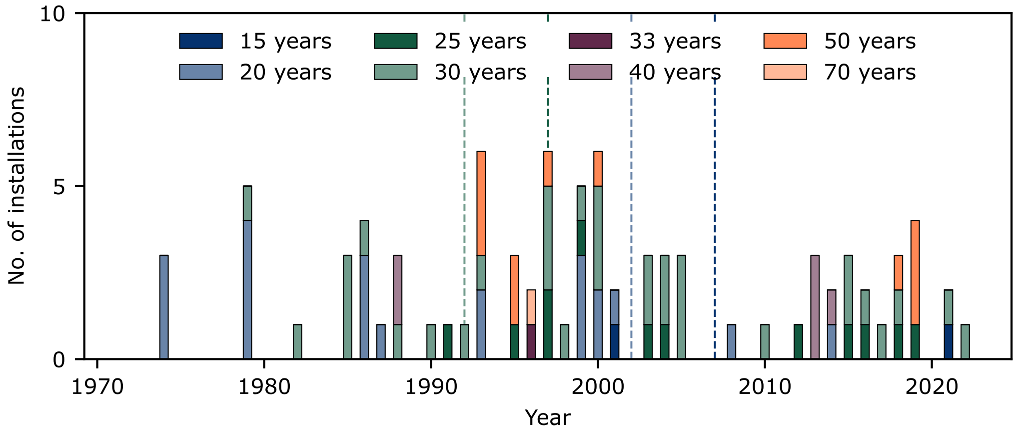

Figure 4: The age distribution of permanently placed facilities presently in service on the NCS with original design life according to NPD (2022). The dashed vertical lines indicate the design life limits of 15, 20, 25 and 30 years from year 2022 by colours according to the legend.

By considering the information provided in Figure 2 and Figure 3, the age distribution of permanently placed facilities in service with original design life can be obtained, as shown in Figure 4. The dashed vertical lines indicate the design life limits of 15, 20, 25 and 30 years from 2022. The respective facilities installed prior to these limits have exceeded their original design life. Altogether, 33 facilities (37.9%) in service have exceeded their original design life, whereas five facilities (5.8%) are approaching (within five years) their original design life.

The large number of facilities that are approaching or have exceeded their original design life on the NCS provides a significant challenge to the offshore industry. These facilities experience several incidents of different severity every year. Furthermore, lifetime extension is the preferred option for ensuring the continuous operation of these facilities. Consequently, increased decision support in terms of structural health monitoring (SHM) systems should be provided to ensure a safe and cost-optimised operation of the facilities in the future. However, there is limited information in existing codes and standards regarding the application of SHM. Therefore, the Petroleum Safety Authority (PSA) in Norway has initiated a project with the purpose of obtaining a general overview of common structural failure modes for facilities on the NCS and establishing information regarding standardisation of SHM in industries other than the energy industry. PSA has commissioned Ramboll to carry out this work.

3. THE PSA PROJECT

3.1 Objective

The objective of the project is to obtain a general overview of common structural failure modes of offshore structures on the Norwegian Continental Shelf (NCS), in the context of SHM, and establish information regarding standardisation of SHM in industries other than the energy industry.

3.2 Scope of work

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

- Describe and evaluate the main state-of-the-art SHM approaches to determine structural damage from the literature.
- Collect statistical information regarding failure modes of offshore structures on the NCS and evaluate the information with respect to the detection possibilities using SHM.
- Map and establish an overview of relevant codes and standards regarding SHM in industries other than the energy industry.

The project continues the study performed in 2021 for PSA Norway [1], which was carried out by Ramboll.

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:

- In the context of this project, the energy industry represents the offshore and oil and gas industries.
- The work presented mainly covers existing fixed and floating offshore structures. However, the work presented may also be relevant for new-build offshore structures and structures within the wind industry, such as wind turbines and the population of structures in wind farms.

4. STATE-OF-THE-ART APPROACHES FOR STRUCTURAL HEALTH MONITORING

4.1 SHM

Conventional SHM, referred to as the process of implementing an automated and online strategy for damage detection in structures [2], [3], is generally performed using three main approaches [4], [5]: model-based, data-based and hybrid. In general, these approaches provide some sort of decision support or structural diagnosis of the structure under consideration. These approaches are described in the following section according to [6]. Figure 5 summarises the SHM approaches.

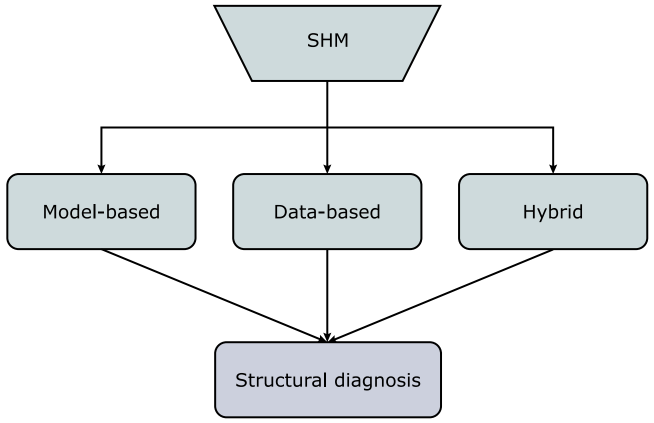

Figure 5: The main SHM approaches.

Figure 6 shows the model-based approach. The model-based approach is based on the calibration of finite element (FE) models and consists of two stages. In the first stage, a calibrated FE model (*reference* model) is established based on measurement data from the undamaged condition of the structure. In the second stage, a calibrated FE model (*damaged* model) is established based on measurement data from the damaged condition. Consequently, damage detection (structural diagnosis) is performed based on the change in the updated parameters of the structure.

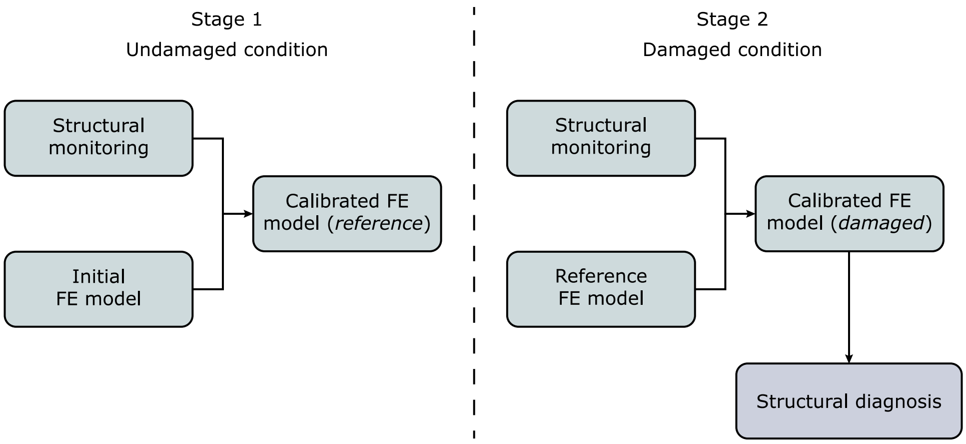

Figure 6: The model-based SHM approach.

The model-based approach is considered impractical for large and complex structures and is challenging to perform in practice. The main disadvantages include 1) difficulties in determining parameters of the FE model to be associated with damage, 2) uncertainties related to the FE models such as modelling inaccuracies, model simplifications and uncertainties in structural properties and 3) dealing with variability in operational and environmental conditions affecting the structural response. These challenges limit the possibility of detecting structural damage. Further details of the possibilities and limitations of the model-based approach are described in [6], [7].

Figure 7 shows the data-based SHM approach. The data-based approach, which generally relies on, but is not limited to, machine learning algorithms, builds a statistical model based only on experimental data to perform a structural diagnosis. As such, damage detection is performed by analysing features that are sensitive to damage using machine learning algorithms (unsupervised and supervised learning), which is referred to as statistical model development. Examples of features are modal properties (natural frequencies, mode shapes and damping), statistical parameters or any other quantity extracted from the measured response. In the context of SHM, unsupervised learning refers to circumstances where data are available only from the undamaged condition of the structure, which is often the case for marine structures in operation.

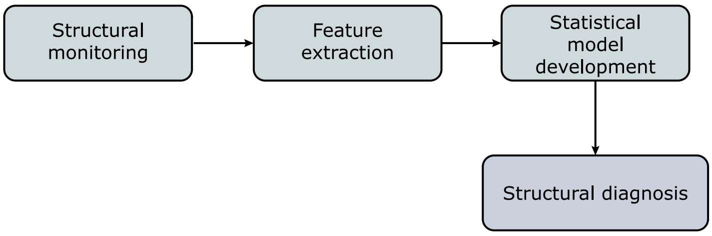

Figure 7: The data-based SHM approach.

The main disadvantages of the data-based approach are that 1) unsupervised learning is often required due to the lack of data from damaged conditions and 2) the process of separating changes caused by operational and environmental variability from changes caused by damage (data normalisation) must be considered. Despite these challenges, the data-based approach is considered practical, highly feasible and the preferred approach for most structures. Further details of this approach, including possibilities and limitations, are described in [6]–[8].

The hybrid SHM approach, shown in Figure 8, considers principles from the model-based and data-based SHM approaches. In general, the hybrid SHM approach integrates numerical models(s), experimental data and machine learning to perform a structural diagnosis.

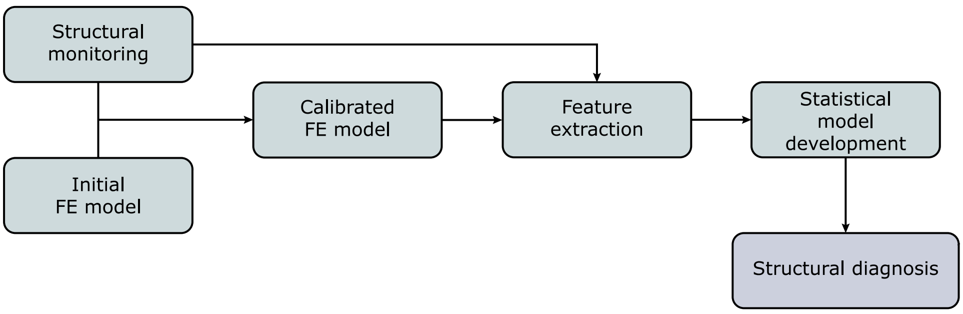

Figure 8: The hybrid SHM approach.

The hybrid SHM approach can overcome some of the limitations of the traditional SHM approaches. Although it has a large potential, it is a novel approach that has currently been applied to only a few structures. Further details of this approach, including practical implementations on a real structure, are described in [6], [7].

The data-based and hybrid SHM approaches can perform decision support or structural diagnosis in terms of statistical models, where machine learning algorithms are utilised to obtain the likelihood of damage. Furthermore, it should be noted that the purpose of SHM is to detect damage and inform actions, such as maintenance, inspection and repair.

4.2 Population-based SHM

Population-based structural health monitoring (PBSHM) has emerged in recent years [9]–[11]. The concept of PBSHM involves information between structures to be transferred by considering data collected from a group of similar structures (population). Groups of similar structures can include *homogeneous* and *heterogeneous* cases. The homogeneous case includes structures that are nominally identical, such as wind turbines within a wind farm, whereas the heterogeneous case includes structures that are of different design within the similar structure type, such as certain marine structures or bridges. In theory, a general population represents the behaviour of the group and can infer the presence of damage between structures. Consequently, the capability of SHM can be increased beyond that applicable to individual structures. However, it is crucial to understand the fundamentals of SHM and the accompanying approaches to understand PBSHM.

Figure 9 shows a simplified comparison of SHM versus PBSHM. The workflow of SHM differs from that of PBSHM. PBSHM is based on graph theory in mathematics.

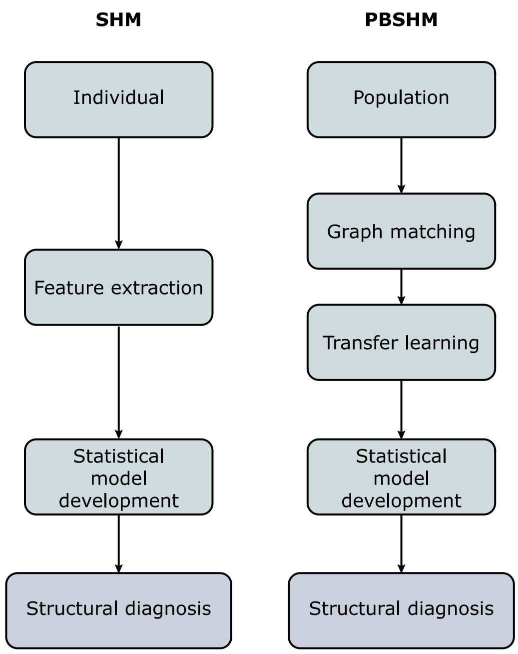

Figure 9: Comparison of SHM versus PBSHM.

In PBSHM, structures are represented in an abstract way based on Irreducible Element (IE) models, which capture the essential structural characteristics. The IE models are then converted to Attributed Graphs (AGs) and used as input to graph-matching machine learning algorithms to obtain a metric to assess structural similarity. The similarity is a measure of whether information can be transferred. Furthermore, similar structures are clustered to form communities. Within each community, a certain level of knowledge transfer is possible. Consequently, knowledge about normal operating conditions, damage states and numerical models can potentially be transferred between structures. As such, graph matching and transfer learning in PBSHM are analogous stages to feature extraction in conventional SHM.

4.3 Summary

Conventional SHM includes the model-based, data-based and hybrid approaches. PBSHM involves information between structures to be transferred by considering data collected from a group of similar structures. In general, SHM and PBSHM aim to provide decision support or structural diagnosis of the structure under consideration. Figure 10 shows a general overview and workflow of SHM and the decision-making process.

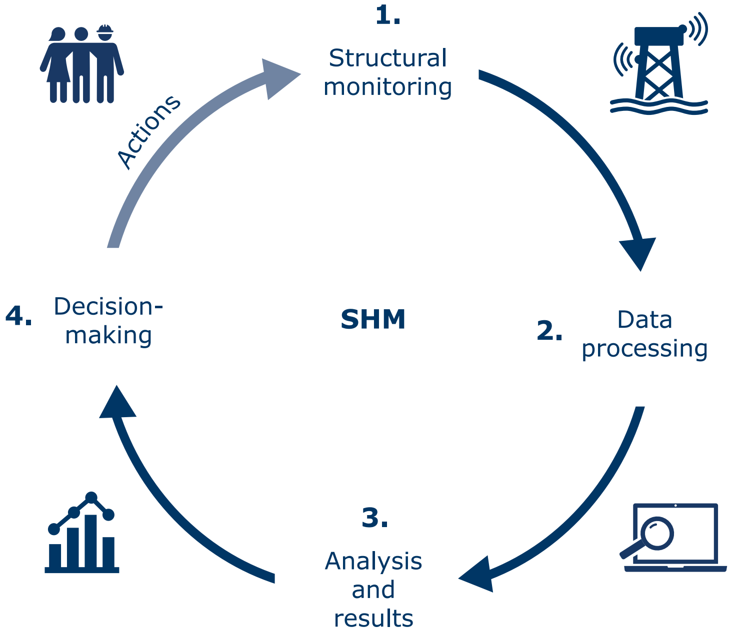

Figure 10: A general overview and workflow of SHM and the decision-making process.

By utilising parts of the different SHM approaches in a separate framework, value for operators and asset owners in the offshore industry can be obtained. Such a framework, which is based on the conventional SHM approaches, is proposed by Ramboll [1], [12]–[14]. The proposed framework, which consists of a pre-study and five levels, provides a coupling between a digital twin and measurements obtained from structural monitoring. The framework includes state-of-the-art methods that can enhance the structural integrity of marine structures, such as 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. In conclusion, the use of SHM on marine structures provides value in terms of risk reduction and optimisation of maintenance, lifetime extension, reduction of inspection costs and increased safety.

5. STRUCTURAL FAILURE MODES FOR OFFSHORE STRUCTURES

5.1 Structural failure modes according to the literature

Several structural failure modes and events occur for different offshore structures. Here, a structural failure mode is defined as a damage type or an unwanted (damaged) condition of the structure that *may* lead to failure of the structure. Table 1 summarises the most relevant significant structural failure modes and causes for offshore structures.

Table 1: Summary of relevant significant structural failure modes and typical causes for offshore structures.

	Global structure				
Failure mode	**Fixed**	**Floating**	**Loading systems[1]**	**Local structure[2]**	**Most likely (typical) cause**
Cracking (through thickness)	x	x	x	x	Fatigue and/or corrosion
Member separation	x	x	-	x	Fatigue and/or corrosion
Missing member	x	-	-	x	Fatigue and/or corrosion
Dents and bows	x	x	-	x	Vessel impact / dropped object
Grouted connection (slippage and failure)	x	-	-	-	-
Overloading (settlement and subsidence)	x	-	x	-	Settlement and subsidence
Scour (foundation)	x	-	x	-	-
Excessive/unexpected vibration[3]	x	x	-	x	Multiple reasons
Bridge bearing issues (interconnecting bridges)	-	-	-	x	Multiple reasons
VIV issues	x	-	-	x	Wind, wave, or current actions

[1] Loading systems include loading buoys and mooring lines, anchors and chains.

[2] Local structures include helidecks, bridges, crane pedestals, derricks, flare booms and topside modules.

[3] Vibration that includes, but are not limited to, springing, ringing and whipping effects.

The failure modes summarised in Table 1 are based on industry experience and a comprehensive overview of common structural failure modes of offshore structures [15], [16]. The failure modes are categorised according to occurrence on global and local structures. A global structure considers the primary structure of a fixed or floating structure, whereas a local structure considers the primary or secondary structure of a defined structure typically located on a topside. It should be noted that corrosion is not included as a failure mode but as a typical cause.

A total of 10 significant structural failure modes are defined. From Table 1, it is observed that fixed structures can experience most different failure modes (9 out of 10), whereas floating structures and loading systems can experience fewer different failure modes (4 and 3 out of 10, respectively). Moreover, local structures can experience many different failure modes (7 out of 10). Consequently, the potential for detecting different damage types using an SHM system is higher for global fixed and local structures than for floating structures and loading systems.

Table 2: Summary of accidental events that may cause significant damage to offshore structures.

	Global structure			
Event	Fixed	Floating	Loading systems[1]	Local structure[2]
Storm	x	x	x	x
Earthquake	x	-	x	x
Vessel impact	x	x	-	-

[1] Loading systems include loading buoys and mooring lines, anchors and chains.

[2] Local structures include helidecks, bridges, crane pedestals, derricks, flare booms and topside modules.

Table 2 summarises global accidental events that may cause significant damage to offshore structures. Note that local accidental events such as dropped objects, fires and explosions are not included in this summary. A total of three global accidental events that may cause considerable damage to offshore structures are identified: storms, earthquakes and vessel impacts. From Table 2, it is observed that fixed structures can experience significant damage in three events, whereas the floating structures, loading systems and local structures can experience significant damage only in two events.

There are mainly three databases that contain statistical information regarding structural failure modes of offshore structures on the NCS: the PSA database for trends in risk level (RNNP), the PSA incident database ("Hendelsesdatabasen") and the PSA corrosion and damage database (CODAM). In this study, statistical information regarding structural failure modes of offshore structures on the NCS from the CODAM database is considered.

5.2 Structural failure modes on the Norwegian Continental Shelf

5.2.1 The CODAM database

The corrosion and damage (CODAM) database contains reported incidents on offshore structures on the NCS. The database contains reported incidents on permanently placed facilities, i.e., structures that are placed on a field for the duration of the production period (fixed and floating structures). The database, which is publicly available, contains information on reported incidents from the mid-1970s and is administrated by the PSA.

In general, MOUs include structures that are not meant to be permanently placed on a field during the lifetime of the field, such as mobile drilling units and floating hotels. Such structures adhere to flag state regulations in combination with class society rules. In other words, these structures are typically classified as vessels and follow maritime rules and regulations. Such structures are not included in the CODAM database.

The results from the analysis of the CODAM database are presented in this section. The analysis is based on a reduced dataset, which is obtained by considering relevant structures in the context of SHM. As such, permanently placed facilities are considered, resulting in altogether 4639 incidents that have been reported in the period 1974-2021. These facilities exclude subsea structures. The objective of the analysis is twofold. First, obtain a general overview of incident reporting on the NCS and second, establish an overview of the structural failure modes considered relevant in the context of SHM. This objective is achieved by evaluating results from two time periods: period 1 (1974-2021) and period 2 (2000-2021).

5.2.2 An overview - general

To obtain a general overview of the incidents reported on the NCS, data from periods 1 (1974-2021) and 2 (2000-2021) are considered. Figure 11 and Figure 12 show the distribution of reported incidents from the CODAM database in periods 1 and 2, respectively.

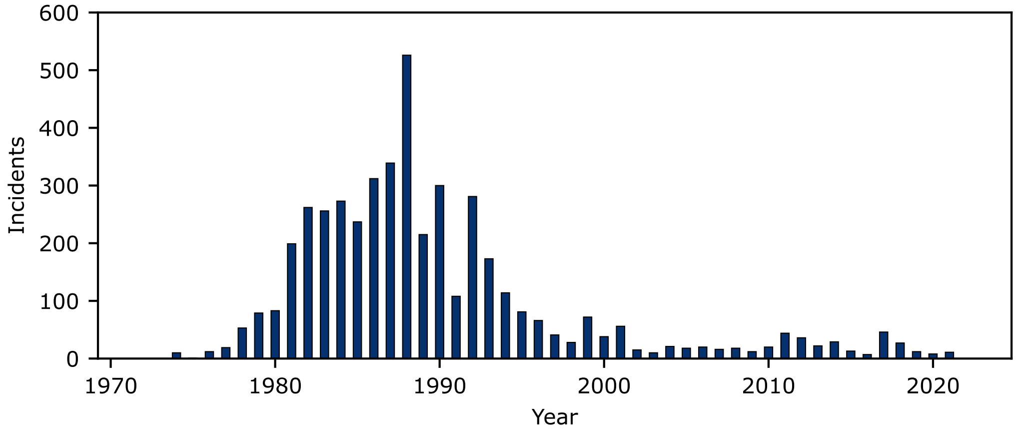

Figure 11: The distribution of reported incidents from the CODAM database in period 1.

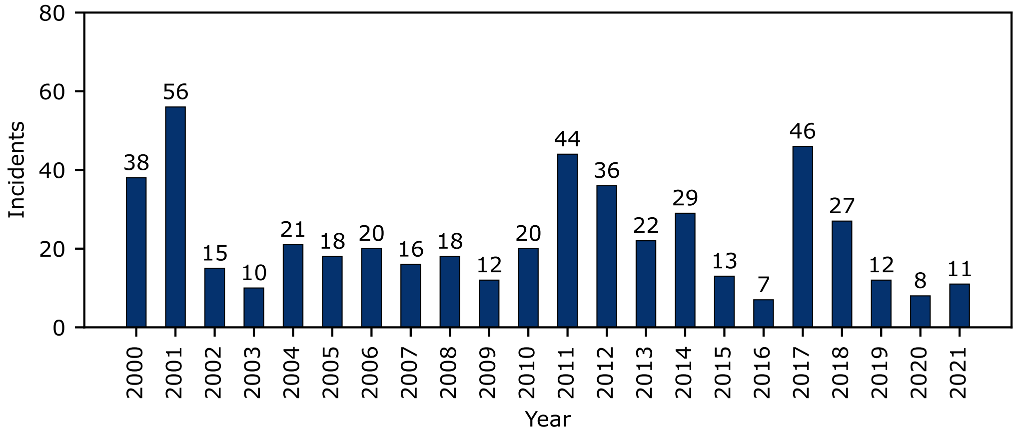

Figure 12: The distribution of reported incidents from the CODAM database in period 2.

Altogether 4639 incidents are reported for period 1 and 499 incidents for period 2. From Figure 11 and Figure 12, it is observed that the reported number of incidents increased from approximately year 1980 and was drastically reduced from approximately year 2000. This observation is discussed later in this section.

Figure 13 summarises the incidents reported in period 1 (1974-2021) categorised by *severity*. From Figure 13, it is observed that a majority of all reported incidents are categorised as insignificant. More specifically, 58.3% of all the incidents are categorised as insignificant, 38.4% are categorised as minor and 3.4% are categorised as major. It should be noted that there are no formal definitions of the severities. Hence, the severity of each reported incident is defined by the operator, which in turn may cause some inconsistency in the dataset.

In the following, most of the analysis results are presented in terms of the severity of the reported incidents. Furthermore, major trends in the reported incidents are considered more important than details of few incidents. Consequently, most of the analysis results are presented by considering data from the entire period, i.e., period 1 (1974-2021).

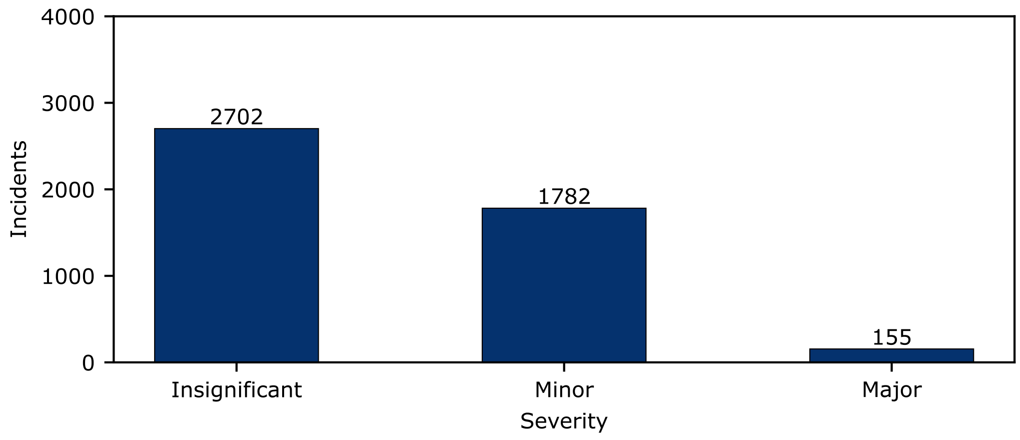

Figure 13: Incidents categorised by severity from the CODAM database in the period 1974-2021.

In the context of SHM, information on the type of *facilities* (permanently placed) that experience incidents is valuable. Figure 14 and Figure 15 summarise the reported incidents categorised by facility and grouped by severity in period 1 (1974-2021).

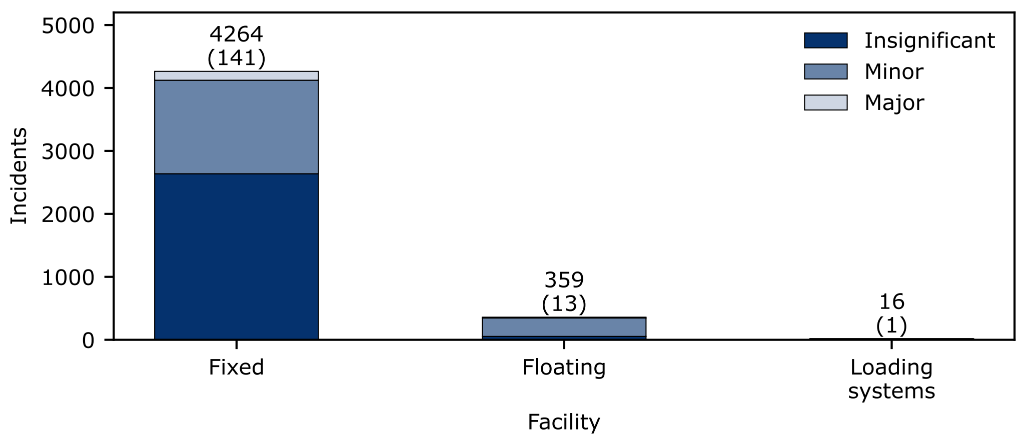

Figure 14: Incidents categorised by permanently placed facility and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

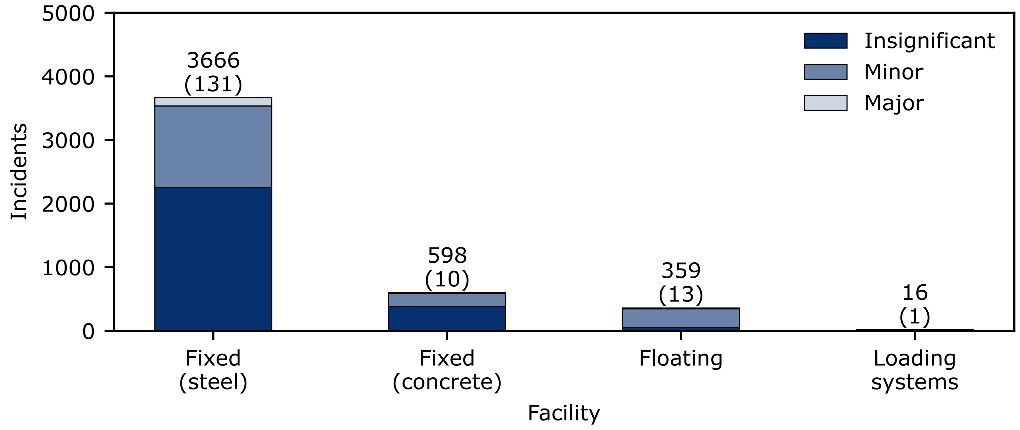

Figure 15: Incidents categorised by permanently placed facility (detailed) and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

From Figure 14, it is observed that 91.9%, 7.8% and 0.3% of all incidents occurred on fixed structures, floating structures and loading systems, respectively. Furthermore, Figure 15 shows that a majority of the incidents on fixed structures occurred for steel structures. This observation is reasonable since most of the facilities on the NCS are, in fact, steel structures. The percentage of incidents categorised as major are similar for fixed and floating structures, i.e., 3.3% and 3.6%, respectively.

Categorising the *structure types* into global and local structures is relevant in the context of SHM. Figure 16 summarises the reported incidents categorised by structure type and grouped by severity in period 1 (1974-2021).

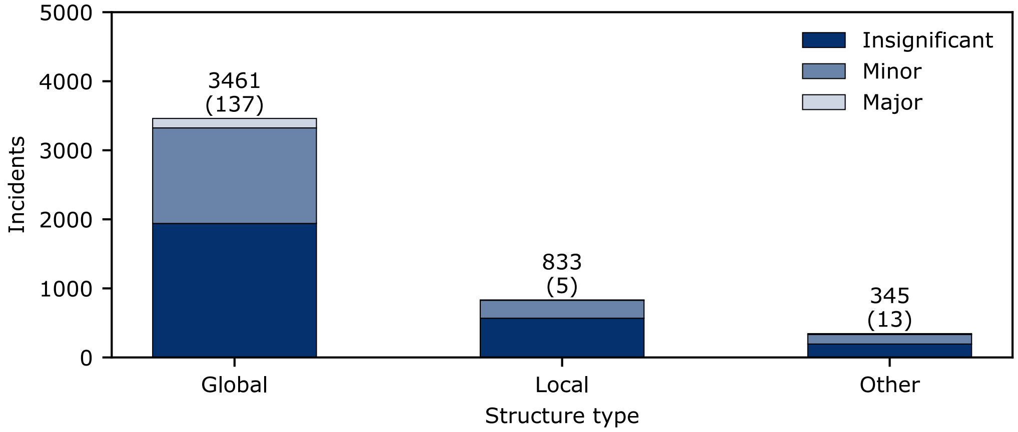

Figure 16: Incidents categorised by structure type and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

From Figure 16, it is observed that 74.6%, 18.0% and 7.4% are categorised in the global, local and other structure types, respectively. Hence, a majority of all incidents are reported on global structures. To obtain a detailed overview of the different structure types, the reported incidents categorised by global and local structure types and grouped by severity are summarised in Figure 17 and Figure 18, respectively.

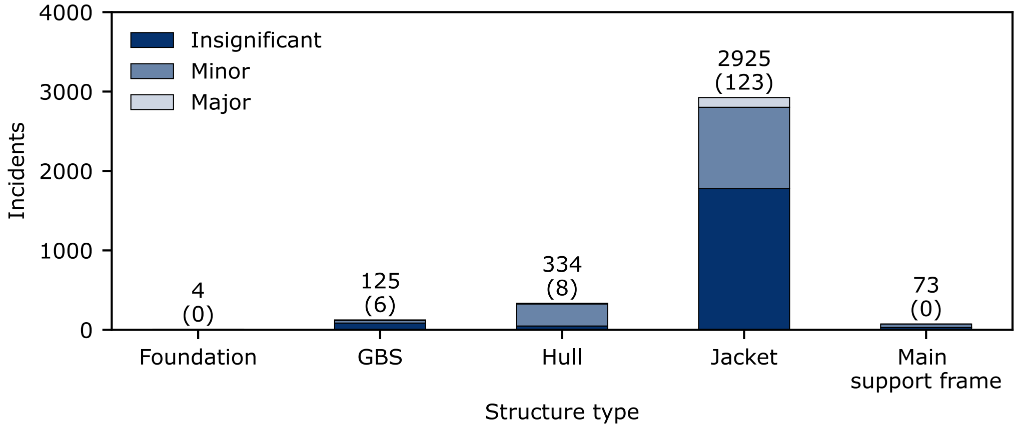

Figure 17: Incidents categorised by global structure types and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

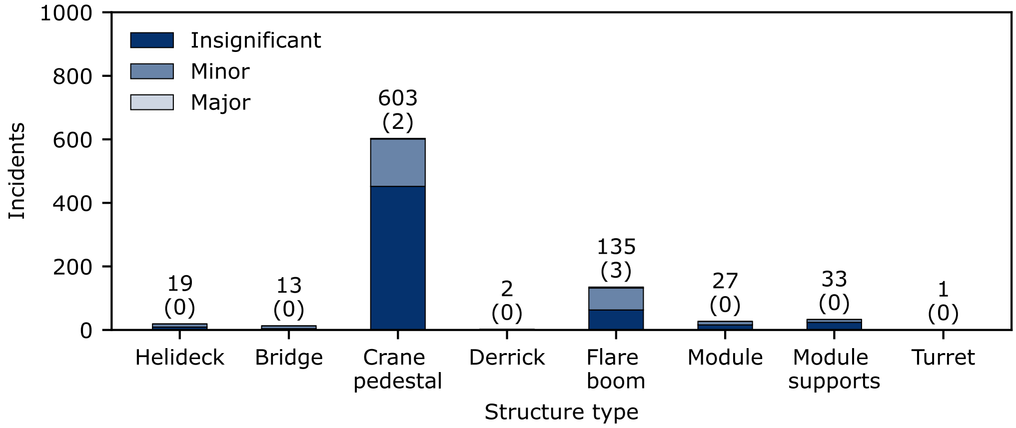

Figure 18: Incidents categorised by local structure types and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

From Figure 16, Figure 17 and Figure 18, it is observed that fewer major accidents are reported for local structure types than for global structure types. Furthermore, a majority of the incidents reported for the global structure types occur on jackets, whereas a majority of the incidents reported for the local structure types occur on crane pedestals and flare booms.

In the CODAM database, incidents are labelled according to the type of *material*. Figure 19 summarises the reported incidents categorised by material and grouped by severity in period 1 (1974-2021).

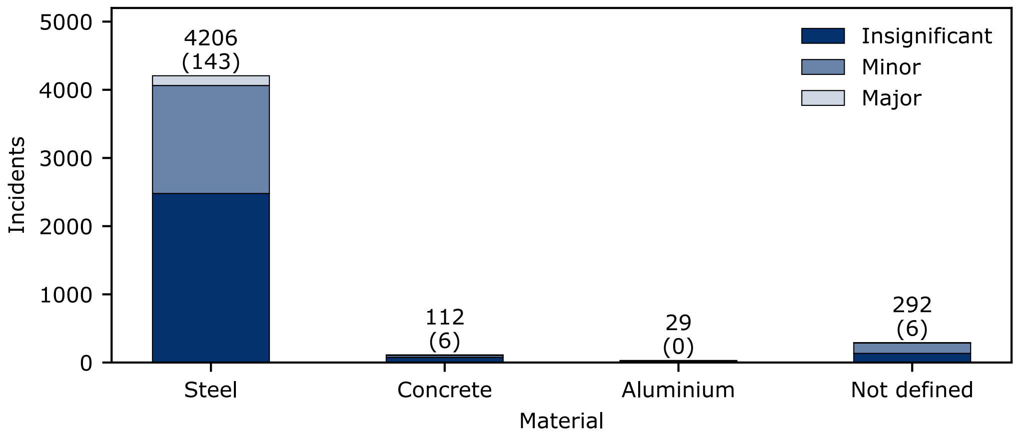

Figure 19: Incidents categorised by material and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

From Figure 19, it is observed that 90.7% of the reported incidents are categorised by steel, 2.4% by concrete and 0.6% by aluminium. The remaining incidents are not defined according to material. Hence, a majority of all incidents are reported for steel. However, the percentage of incidents categorised as major is higher for concrete (5.4%) than for steel (3.4%). This observation indicates that major accidents are more likely to occur in facilities with concrete than steel material.

The reported incidents categorised by *inspection type* and *inspection method* and grouped by severity in period 1 (1974-2021) are summarised in Figure 20 and Figure 21, respectively.

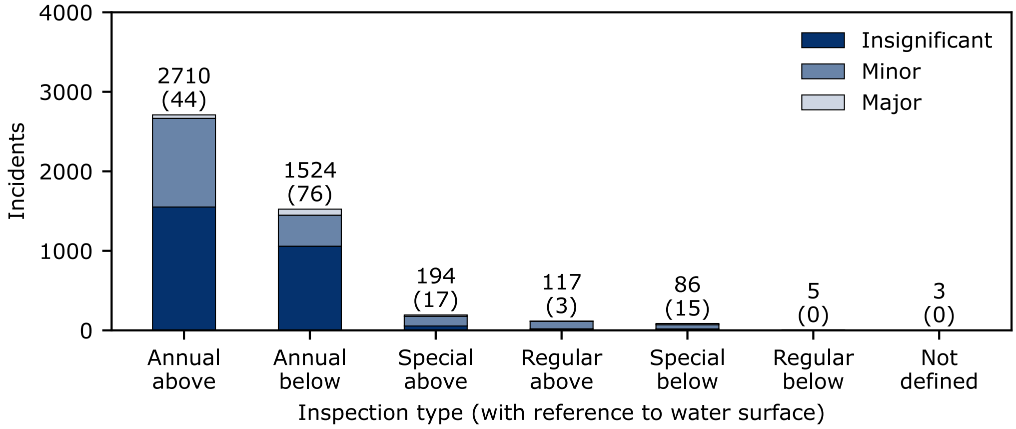

Figure 20: Incidents categorised by inspection type and grouped by severity from the CODAM database in the period 1974-2021. Note that the abbreviations "above" and "below" are provided with reference to the water surface, i.e., "above water" and "below water". The numbers in parentheses indicate major accidents.

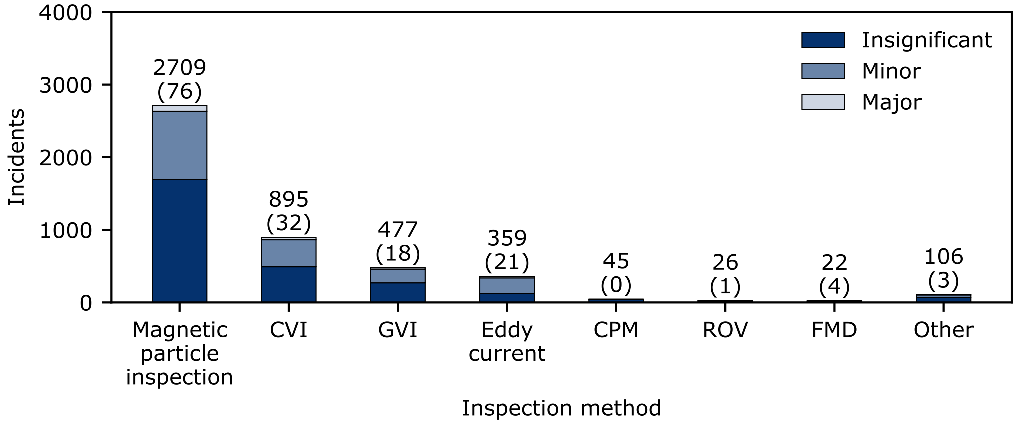

Figure 21: Incidents categorised by inspection method and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

From Figure 20, it is observed that a majority of all incidents (91.3%) is reported based on annual inspection types. Furthermore, the percentage of incidents categorised as major is higher for special inspection types (11.4%) than annual (2.8%) and regular (2.5%) inspection types. According to the CODAM database user manual, special inspections are relevant after accidental events such as vessel impacts, dropped object impacts, weather (storm) events and incidents that require attention before the next planned inspection. Consequently, the high ratio of major accidents related to the special inspection types is reasonable.

From Figure 21, it is observed that a majority of all incidents (58.4%) is reported based on the magnetic particle inspection method. Furthermore, 30.1% of all incidents are reported based on visual inspection methods, such as close visual inspection (CVI), general visual inspection (GVI) and remotely operated underwater vehicle (ROV) inspection. Consequently, visual inspection is a common and preferred inspection method. In conclusion, almost all inspection methods related to the reported incidents are performed using non-destructive testing (NDT) methods.

Figure 22 and Figure 23 show the distribution of reported incidents by grouped inspection type from the CODAM database in periods 1 (1974-2021) and 2 (2000-2021), respectively.

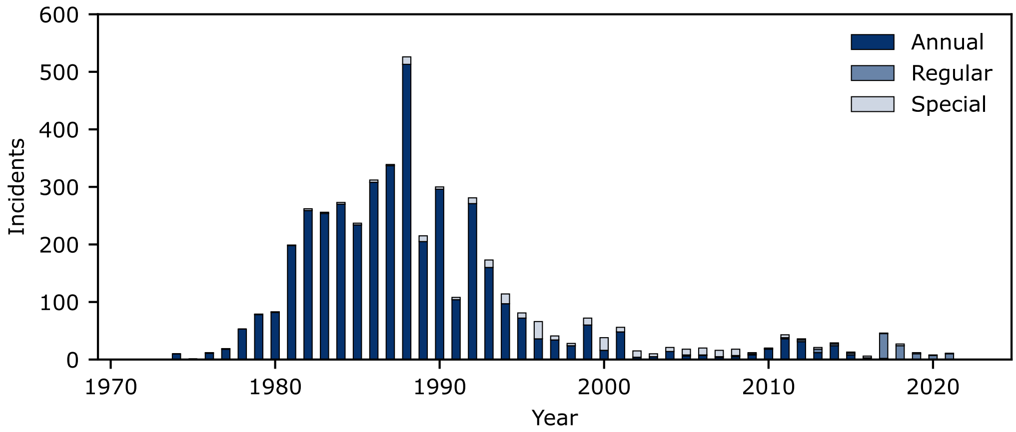

Figure 22: The distribution of reported incidents by inspection type from the CODAM database in period 1.

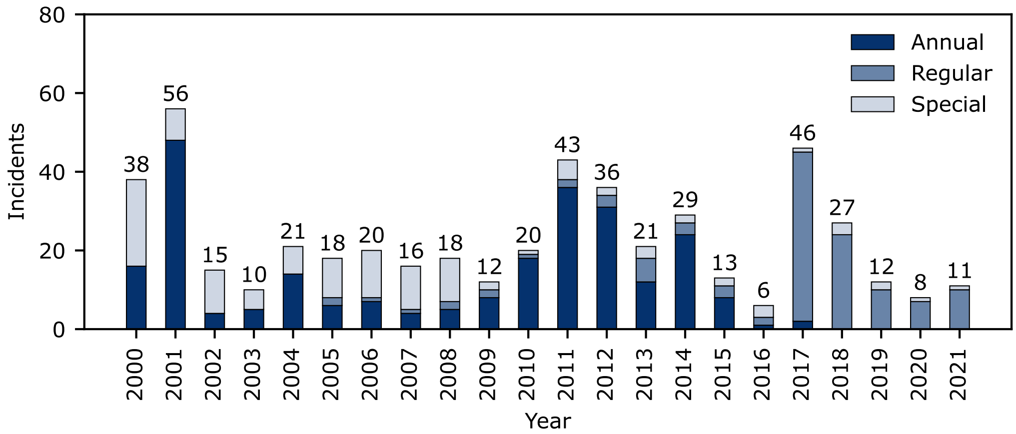

Figure 23: The distribution of reported incidents by inspection type from the CODAM database in period 2.

From Figure 22, it is observed that the reported number of incidents is drastically reduced from approximately year 2000. Furthermore, Figure 22 and Figure 23 show that the annual inspection types decrease, whereas the regular inspection types increase over time. The reported incidents categorised by annual inspection types are 91.3% for period 1 (1974-2021) but only 49.9% for period 2 (2000-2021). There are two possible reasons for this reduction. First, introducing risk and reliability-based inspection methods resulted in a decrease in the number of annual inspections performed and, consequently, a reduction in the number of reported incidents. Second, the general safety of offshore structures has increased over time. It should be noted that the regular inspection type, although not defined according to the CODAM user manual, is assumed to be the most likely inspection according to a defined inspection plan provided by the operator. Another interesting observation is the significant increase in the reported number of incidents around 1980. This increase coincides with the increasing number of facilities on the NCS in that period but also with the Alexander L. Kielland accident. This accident may have caused an awareness with respect to cracking caused by fatigue that lasted in a period of 10-15 years.

In the context of SHM, information on *facilities*, *structure types* and *material* of the reported incidents is useful to determine the applicability of SHM on offshore structures. Furthermore, information on *inspection type* and *method* is important for evaluating the potential of SHM systems to obtain complete up-to-date information about the current state of the structure's condition. Finally, *severity* is critical information since an SHM system is more likely to detect damage of high degrees of severity than low degrees of severity.

5.2.3 An overview – structural failure modes

To obtain an overview of the structural failure modes considered relevant in the context of SHM, data from periods 1 (1974-2021) and 2 (2000-2021) are considered. Figure 24 and Figure 25 show the distribution of reported incidents grouped by severities from the CODAM database in periods 1 and 2, respectively.

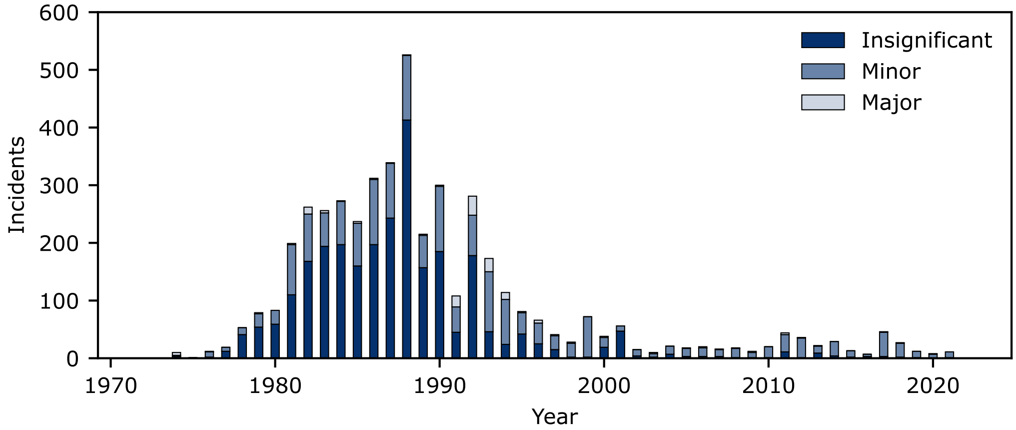

Figure 24: The distribution of reported incidents grouped by severities from the CODAM database in the period 1974-2021.

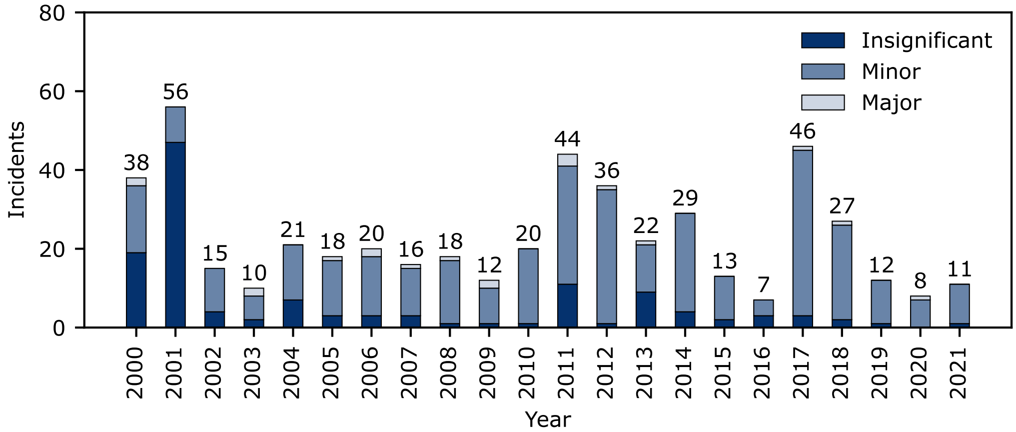

Figure 25: The distribution of reported incidents grouped by severities from the CODAM database in the period 2000-2021.

At the risk of repetition, a total of 4639 incidents were reported in period 1 (1974-2021), whereas 499 incidents were reported in period 2 (2000-2021). In period 1, 58.3% of all the incidents are categorised as insignificant, 38.4% as minor and 3.4% as major. In period 2, however, 25.7% of all the incidents are categorised as insignificant, 70.5% as minor and 3.8% as major. Hence, a majority of the incidents in period 1 is categorised as insignificant, whereas a majority of the incidents in period 2 is categorised as minor. Most importantly, there is an average of 0.86 major incidents per year in period 2 (2000-2021).

There are three possible reasons for the reduced number of reported incidents categorised as insignificant from period 1 to period 2: first, an increased reluctance to report insignificant damage by the operators an asset owners may have occurred over time; second, the use of inspection methods that identify damage categorised as insignificant may have been reduced; and third, optimized inspection programs that focus on damage types with a higher degree of severity than insignificant may have been implemented.

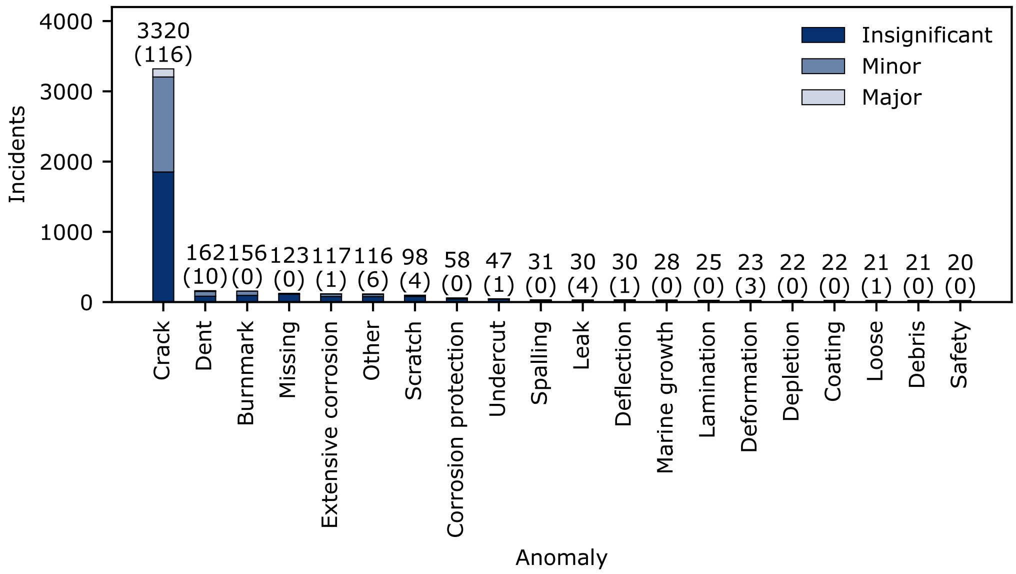

Figure 26: Incidents categorised by anomaly and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

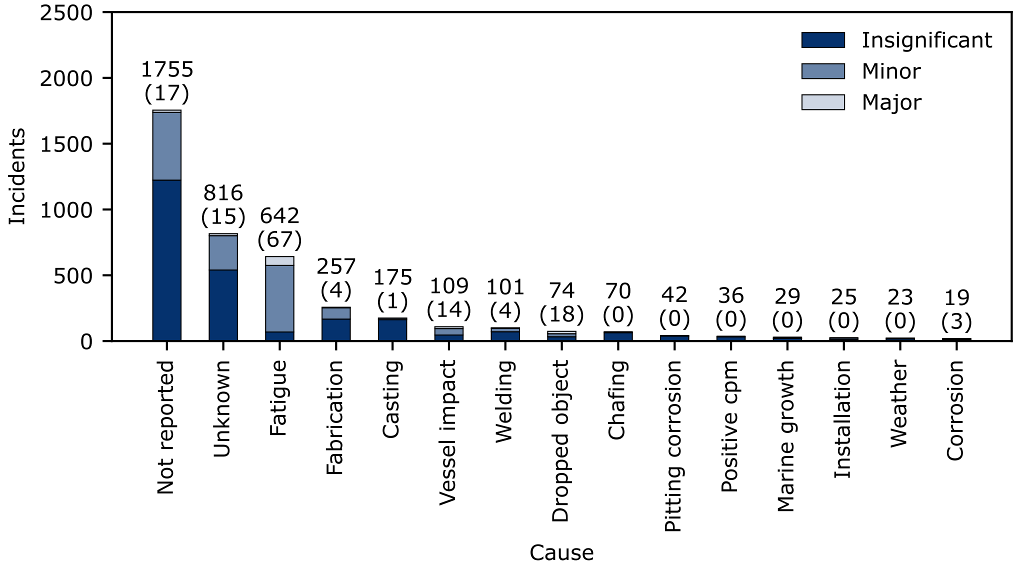

Figure 27: Incidents categorised by cause and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents.

Categorising the *structural failure modes* and *causes* is relevant in the context of SHM. Figure 26 summarises the reported incidents categorised by anomaly and grouped by severity in period 1 (1974-2021), and Figure 27 summarises the reported incidents categorised by cause and grouped by severity in the same period. Anomaly in CODAM is defined as the type of damage or incident that is being reported.

The 20 most common failure modes are shown in Figure 26. From this figure, it is seen that a majority of all incidents is categorised by crack as the anomaly, followed by dent. It is also observed that the number of major incidents is high for these anomalies. In the context of SHM, the incidents categorised as "crack", "dent", "missing", "other", "deflection", "deformation", "loose", and "scour" are the most interesting since these failure modes can develop and lead to failure being critical for the structural integrity.

The 15 most common causes are shown in Figure 27. From this figure, it is observed that a majority of the causes are not known, i.e., causes being categorised as "Not reported" or "Unknown". However, these causes have a relatively low percentage of major incidents. An important observation is that the rate of incidents categorised as major is high for fatigue (10.4%), vessel impact (12.8%) and dropped object (24.3%). This observation clearly indicates the importance of such causes with respect to structural integrity. It should also be noted that "weather" is an important cause in the context of SHM. This cause provides important information on how to perform structural monitoring related to the load, in addition to indicating the importance of conducting such monitoring.

There is a connection between the reported anomalies and the causes. Anomaly provides information on the structural failure modes, whereas the cause provides information on the damage potential and the corresponding effect on the structural integrity. From the results presented, and in the context of SHM, crack and dent are the most common structural failure modes, with fatigue and vessel impact/dropped object as the most apparent causes, respectively.

5.2.4 Other

The most common structural failure modes and causes related to structural and maritime systems on floating structures, i.e., semisubmersibles and ship-shaped units, such as floating storage units (FSU), floating storage and offloading units (FSO) and floating production, storage and offloading units (FPSO), are reported in [17], [18]. These papers cover structural failure modes and causes on the NCS in relation to permanently placed facilities and MOUs reported in the CODAM and RNNP databases. The reported failure modes are cracks, dents from wave actions (vertical and horizontal wave impacts), anchor impact on structures and vessel collisions. Additionally, causes (incidents) include failure of the dynamic positioning (DP) system, mooring system breakage and incidents related to stability and ballasting.

In general, MOUs can, to a certain degree, control the structural integrity from severe structural failure modes and causes due to **1)** built-in structural control systems and **2)** relocation to a controlled environment for inspection and repair. Built-in systems include DP monitoring, mooring system monitoring and stability and ballasting monitoring, in addition to well-developed operational procedures. The main focus of this report is on permanently placed facilities. Consequently, a further analysis of the data containing reported incidents for MOUs is not included.

5.3 Evaluation of damage detection possibilities using SHM

Based on the results obtained from statistical information regarding failure modes of offshore structures on the NCS presented in Sections 5.1 and 5.2, an evaluation with respect to the damage detection possibilities using SHM is performed. This evaluation is performed in terms of likelihood and presented in Table 3.

The results presented in Table 3 are based on a set of assumptions. First, it is assumed that the structural failure mode considered has reached a severe damage state. Second, it is assumed that sufficient monitoring is performed such that, where relevant, knowledge of the variability of operational and environmental conditions is known. Finally, the use of a fair and realistic (not overly costly) sensor setup is assumed. It should be noted that loading systems are not considered in this evaluation.

Table 3: Summary of the damage detection possibilities using SHM in terms of likelihood.

	Likelihood[1]								
	Fixed structures			Floating structures			Local structures		
Failure mode	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Cracking (through thickness)	x	-	-	x	-	-	x	-	-
Member separation	x	(x)	-	x	-	-	-	x	-
Missing member	-	x	(x)	NA	NA	NA	-	-	x
Dents and bows	x	(x)	-	x	-	-	x	(x)	-
Grouted connection (slippage and failure)	-	-	x	NA	NA	NA	NA	NA	NA
Overloading (settlement and subsidence)	x	(x)	-	NA	NA	NA	NA	NA	NA
Scour (foundation)	-	x	(x)	NA	NA	NA	NA	NA	NA
Excessive/unexpected vibration[2]	-	-	x	-	-	x	-	x	(x)
Bridge bearing issues (interconnecting bridges)	NA	NA	NA	NA	NA	NA	-	-	x
VIV issues	-	-	x	NA	NA	NA	-	-	x

[1] NA = Not applicable. X = main (primary) likelihood. (x) = possible (secondary) likelihood.

[2] Vibration that includes, but are not limited to, springing, ringing and whipping effects.

For the results presented in Table 3, the following additional assumptions and explanations are included:

- For the grouted connection failure mode, a severe damage state assumes displacement and movement in the structural element(s) of the grouted connection, such as movement in a jacket leg or similar.
- For excessive/unexpected vibrations in local and global structures, it is assumed that the sensor setup is defined with the purpose of detecting the failure mode in the given local and global structure. As such, a sensor setup is different for a local structure than for a global structure. It should also be noted that in cases where measurements are available from the baseline (undamaged condition), excessive/unexpected vibrations are likely to be identified. Examples of excessive/unexpected vibrations include, but are not limited to, ringing in fixed structures and springing and whipping in floating structures.
- Settlement and subsidence can be global and highly local. Global settlement and subsidence can cover a large area on the seabed, whereas highly local settlement and subsidence can cover small areas, such as only parts of jacket or GBS foundations. Furthermore, a realistic sensor setup may or may not include strain gauges. Strain gauges are vital for measuring overloading. Additionally, measuring tilt and the mean sea level using wave radars are beneficial for such a failure mode but is not always included in a realistic sensor setup. Consequently, this failure mode can be difficult to evaluate in terms of the damage detection possibilities using SHM.

- For the dent and bows failure mode, it is highly likely to identify the event from measurements *when* the event occurs, but it is less likely to determine the actual effect of the failure mode on the structural integrity from measurements *after* the occurrence of the event. Hence, the medium likelihood is included since the event itself can be identified from measurements. This evaluation is also valid for the settlement and subsidence failure mode.

From Table 3, it can be concluded that the structural failure modes that are most likely to be detected using SHM on *fixed structures* are missing members, grouted connections, excessive/unexpected vibrations and VIV issues. Furthermore, the structural failure mode that is most likely to be detected using SHM on *floating structures* is excessive/unexpected vibrations, whereas the failure modes that are most likely to be detected using SHM on *local structures* are missing members, excessive/unexpected vibrations, bridge bearing issues and VIV issues. The results presented in Table 3 are based on an evaluation performed using industry experience and knowledge and should, as such, only be viewed as guidance. Although some failure modes have a low likelihood of being detected using SHM, it is essential to emphasise that value creation from structural monitoring can still be obtained.

5.4 Summary

General observation and discussion points together with conclusions are included in the following, which is based on the work covered in this section.

- From the literature, a total of 10 significant structural failure modes of offshore structures are identified. Fixed global structures can experience the highest number of different failure modes. When considering permanently placed facilities, inspection and repair are required to be performed in the offshore environment and often underwater. For MOUs, however, inspection and repair are typically performed in a controlled environment at regular intervals since these structures operate on a specific offshore location for a limited time. Consequently, the potential benefits of using an SHM system on fixed structures (permanently placed) are likely to be higher than those for floating structures (permanently placed and MOUs) in terms of detecting structural damage.
- The objectives of the CODAM database analysis are to obtain a general overview of incident reporting on the NCS and establish an overview of the structural failure modes that are considered relevant in the context of SHM. These objectives are achieved by considering the periods 1974-2021 and 2000-2021. The main conclusions made from the analysis are based on major trends in the reported incidents, which are considered more important than the details of few incidents.
- From the results presented of the CODAM database analysis, it is found that a majority of all reported incidents are categorised as insignificant in terms of *severity*. Furthermore, an important observation is that there is an average of 0.86 major incidents per year in the period 2000-2021. When considering *facility* (permanently placed), most of the incidents are reported on fixed steel structures. When considering *structure type*, a majority of the incidents reported on the global structure types occur on jackets, whereas a majority of the incidents reported on the local structure types occur on crane pedestals and flare booms. Concerning *inspection type* and *method*, it is concluded that **1)** visual inspection is a common and preferred inspection method and **2)** almost all inspection methods related to the reported incidents are performed using NDT methods. Finally, by considering *anomalies* and *causes* in the context of SHM, it is found that cracks and dents are the most common structural failure modes, with fatigue and vessel impacts/dropped objects as the most obvious causes, respectively.

- RBI provides the likelihood, within a given uncertainty, of expected findings. Analysis results from the CODAM database show that annual inspection types decrease and regular inspection types increase over time. Findings, or reported incidents, that are *not expected* can potentially be established and evaluated using SHM. Consequently, the analysis results indicate the importance of obtaining decision support from SHM.
- In the context of SHM, measurements of the load (environmental conditions), in addition to structural response measurements, can increase the understanding of the actual structural behaviour. Parameters extracted from the structural response measurements can be parameterised as a function of the environmental conditions. Furthermore, including measurements of the load increases the understanding of **1)** the actual load that the structure is exposed to and **2)** the possible cause of the structural behaviour and/or damage detected.
- The CODAM dataset is incomplete in the sense that many structural failure modes are not reported in CODAM. There are few or no reported incidents of known structural failure modes, such as failure in grouted connections, excessive/unexpected vibration issues for global and local structures and bridge bearing issues.
- Significant damage affecting the structural integrity increases the likelihood of detecting damage using an SHM system. As such, highly localised damage such as minor cracks and dents are difficult to detect using SHM. Furthermore, a verification of the structural integrity after an accidental or extreme event can, in many cases, be performed when an SHM system is installed.
- From the evaluation of the damage detection possibilities using SHM, the structural failure modes that are most likely to be detected using SHM on *fixed structures* are missing members, grouted connections, excessive/unexpected vibrations and VIV issues. Furthermore, the structural failure mode that is most likely to be detected using SHM on *floating structures* is excessive/unexpected vibrations, whereas the failure modes that are most likely to be detected using SHM on *local structures* are missing members, excessive/unexpected vibrations, bridge bearing issues and VIV issues.

6. A GENERAL OVERVIEW OF STRUCTURAL HEALTH MONITORING STANDARDISATION

6.1 General

Codes, standards and guidelines bridge the gap between theory and practical applications. Although the application of structural monitoring systems and SHM are considered mature from a scientific perspective, it has not become common practice in the energy industry. One of the main reasons that the application of SHM has not become common practice in the energy industry is due to the lack of comprehensive codes, standards and guidelines that address the different parts of the SHM approaches. Consequently, information regarding standardisation of SHM in industries other than the energy industry is considered in this section.

It is essential to highlight that there is a distinction between the SHM approach and the decision-making process. The SHM approach concerns a system that acquires information and follows up the structural behaviour, whereas the decision-making process deals with the problem of choosing the best action to perform based on the acquired information. This distinction is shown in Figure 10.

6.2 SHM standardisation

This section presents an overview of relevant codes, standards and guidelines regarding SHM in industries other than the energy industry based on an extensive mapping. A general overview of the relevant codes, standards and guidelines relating to SHM is provided in Figure 28 and a detailed summary is presented in Table 4.

It is important to highlight that an extensive mapping is performed to include the most relevant codes, standards and guidelines related to SHM. However, the mapping is not exhaustive. As such, other codes, standards and guidelines related to SHM that are not included in this mapping may be available.

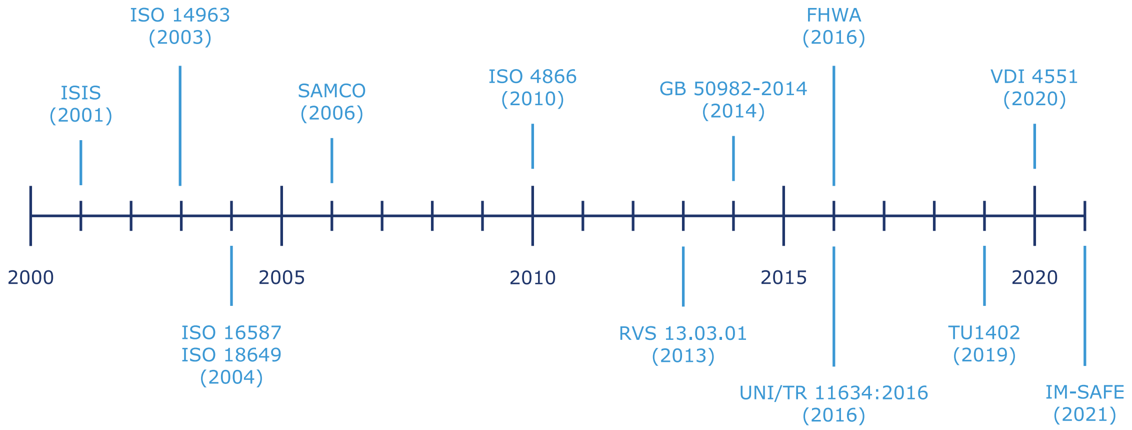

Figure 28: A general overview of relevant codes, standards and guidelines regarding SHM in industries other than the energy industry.

Table 4: Summary of relevant codes, standards and guidelines regarding SHM in industries other than the energy industry.

Code, standard or guideline	Year	Reference
VDI 4551 – Structure monitoring and assessment of wind turbines and offshore substations	2020	[19]
TU1402 – Quantifying the Value of Structural Health Information for Decision Support: Guide for Operators	2019	[20]
TU1402 – Quantifying the Value of Structural Health Information for Decision Support: Guide for Scientists	2019	[21]
TU1402 – Quantifying the Value of Structural Health Information for Decision Support: Guide for Practising Engineers	2019	[22]
TRB – Transportation Research Circular: Structural monitoring (Number E-C246)	2019	[23]
FHWA – Long-Term Bridge Performance (LTBP) Program Protocols, Version 1 (NO. FHWA-HRT-16-007)	2016	[24]
UNI/TR 11634:2016 – Guidelines for structural health monitoring	2016	[25]
GB 50982-2014 – Technical code for monitoring of building and bridge structures	2014	[26]
RVS 13.03.01 – Monitoring von Brücken und anderen Ingenieurbauwerken	2012	[27]
ISO 4866 – Mechanical vibration and shock – Vibration of fixed structures	2010	[28]
SAMCO – F08b Guideline for Structural Health Monitoring	2006	[29]
ISO 18649 – Mechanical vibration – Evaluation of measurement results from dynamic tests and investigations on bridges	2004	[30]
ISO 16587 – Mechanical vibration and shock – Performance parameters for condition monitoring of structures	2004	[31]
ISO 14963 – Mechanical vibration and shock – Guidelines for dynamic tests and investigations on bridges and viaducts	2003	[32]
ISIS – Guidelines for Structural Health Monitoring	2001	[33]

Two main observations are made from Table 4. First, an increasing number of codes, standards and guidelines have been made available in recent years. This increase indicates that SHM is developing and becoming more applicable to the industry. Second, most of the established codes, standards and guidelines mainly cover structures and infrastructures such as buildings and bridges. Further overviews and detailed information related to SHM standardisation, in addition to further information on the codes, standards and guidelines provided in Table 4, are found in [34]–[38]. Other relevant guidelines not included in Table 4 include [39], [40].

Relevant supportive literature in terms of standards and guidelines related to SHM is also provided in TU1402 – Quantifying the Value of Structural Health Information for Decision Support: Guide for Practising Engineers [22].

As previously indicated, an increasing number of standards and guidelines related to SHM are being developed. The IM-SAFE project [41] is a European project with the objective of preparing new standards for monitoring, maintenance and safety of transport infrastructure. Figure 29 shows an overview of the current state of standardisation according to the IM-SAFE project.

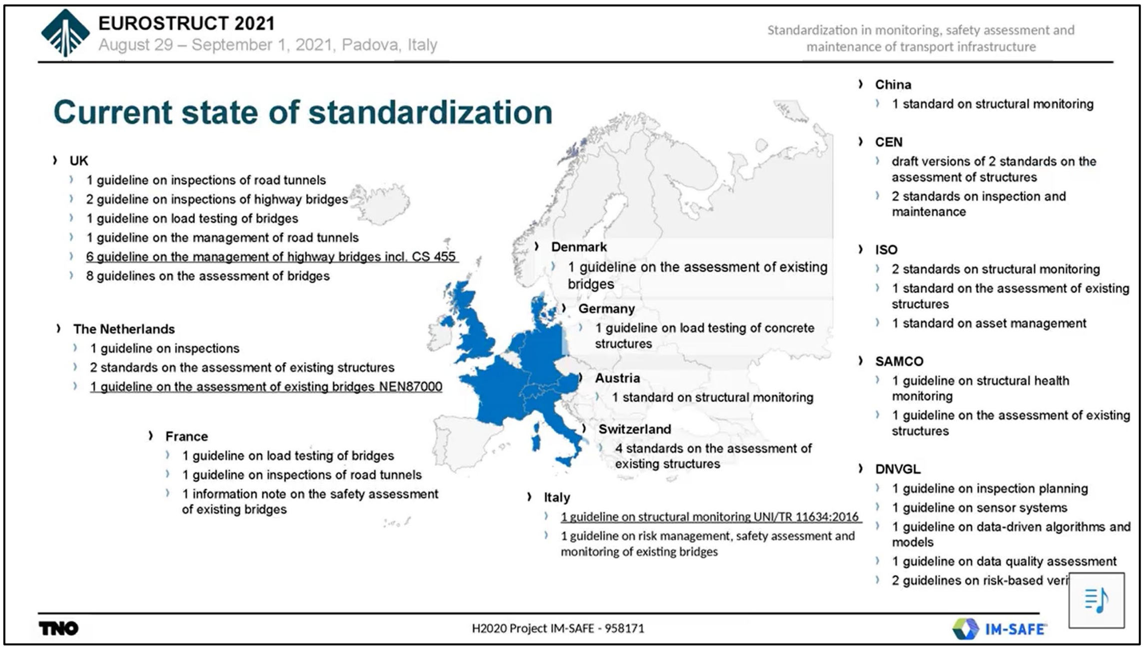

Figure 29: An overview of the current state of standardisation related to SHM according to the IM-SAFE project [41]**.**

6.3 Summary

General observation and discussion points together with conclusions are included in the following, which is based on the work covered in this section.

- An increasing number of codes, standards and guidelines related to SHM have been made available in recent years. These codes, standards and guidelines mainly cover structures and infrastructures such as buildings and bridges. There is a lack of codes, standards and guidelines that consider SHM in the energy industry [1]. Consequently, these observations indicate that the work related to SHM standardisation has come further in the structure and infrastructure industries than in the energy industry.
- There are several reasons for **1)** the low application of structural monitoring systems and SHM in the industries and **2)** the slow development of codes, standards and guidelines related to structural monitoring systems and SHM. First, there is limited information in the existing codes and standards regarding these topics. Second, many parties are involved in managing existing and new structures in the industry, such as asset owners, designers and contractors of various sizes and with different financial interests and technical skills. Third, there is a lack of understanding of the value creation and benefits that can be obtained using SHM. Finally, there are many different suppliers of structural monitoring systems and solutions in the market that can deliver equipment that ranges from low to high quality.

In general, there is a need for a standardisation of SHM that is acknowledged by public authorities and industrial stakeholders. Consequently, the development and adoption of SHM standards involve complex processes that require consensus and commitment from these participants. Although several codes, standards and guidelines have been developed, further standardisation across all industries is still needed for practical engineering applications.

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