New Advances and Developments in Risk-based Inspection (RBI) of Marine Structures

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Marine structures such as ships and offshore platforms play an important role in the economic growth of many countries around the world. These structures are often exposed to severe environmental conditions such as high or low temperatures, high salinity, high or low pH values, etc. In such conditions, regular inspection of structures is very crucial and a methodology is needed to minimize the repair costs while assuring technical integrity and safety of operation. In recent years, the concept of risk-based inspection (RBI) has been widely used to optimize inspection activities for marine structures. This strategy aims to develop cost-effective inspection programs that concentrate efforts on those areas that are at highest risk of in-service failures, with a proportionate reduction in effort for low-risk areas. Up to now, several standards, guidelines and best practices have been developed for RBI of different marine structures by various international organizations, institutes and consultant companies, including ABS, API, DNVGL and ASME codes. In this paper, the state-of-the-art of RBI and its core elements, processes and common methodologies in the marine sector are reviewed, the most relevant standards and guidelines are identified and evaluated, and the new advances and developments in RBI of marine structures are outlined.

Keywords: Risk-based inspection (RBI), marine structures, maintenance, reliability.

1. Introduction

A significant number of structures such as oil and gas producing facilities and renewable energy platforms are being deployed in marine environments where operating conditions are severe, such as high wind speeds, large wave heights, strong currents, low visibility and so on. These severe conditions accelerate the normal degradation rate of the material and thus shorten the time to failure of marine structures. Failure of marine structures may result in loss of human life, severe environmental damage, and large economic consequences. Therefore, it is crucial to avoid these negative effects.

Regular inspection is the best means of protecting marine structures from damage or catastrophic failure. American Society of Mechanical Engineers (ASME) (2017) defines inspection as a quick check process whose frequency may vary from hours to months depending on necessity. An effective inspection program must identify defects that are likely to occur, and quantify their extent and severity. During the past decades, the inspection of marine structures has evolved from visual inspections by human operators to more detailed techniques based on nondestructive testing (NDT) using a variety of instruments. Additionally, in recent years, the use of computerized analytical methods has provided innovative solutions for detecting non-visible defects on surface or subsurface of the material.

Inspection resources, including monetary and human resources, are often scarce. Thus, inspectors have to prioritize available resources to areas where the needs are greater. *Risk Based Inspection (RBI)* is an efficient strategy used to prioritize inspection resources according to the degree of risk from the equipment. The British Standards Institution (BSI) (2016) defines RBI as an integrated technique that incorporates risk analysis information into inspection planning and execution. This strategy allows inspection efforts to be concentrated on those areas that are at highest risk of in-service failures, with a proportionate reduction in effort for low-risk areas. An RBI strategy mainly consists of two phases: (*i*) risk assessment, which aims to identify high-risk areas; and (*ii*) inspection planning, which aims to develop a preventive inspection program based on risk assessment results to reduce the risks to a tolerable level.

RBI concept was first developed by the U.K. Atomic Energy Authority during the 1960's. Later, in the mid-1980s, it was used to facilitate evaluation of potential hazards in chemical processing plants (Arunraj and Maiti, 2007). Since the early 1990's, RBI strategy has been increasingly applied to establish reliable and effective in-service inspection programs for

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offshore oil and gas structures (such as oil rigs, floating production, storage and offloading (FPSO) vessels, drill ships, and subsea pipelines) as well as fixed or floating offshore wind turbine support structures (such as monopiles, tripods, jackets, spar buoys, semi-submersibles, and tension leg platforms) (Marshall and Goldberg, 2009; Iqbal *et al.*, 2017; Shafiee and Sørensen, 2019). RBI has shown superior efficacy compared with the time-based inspection plans. The benefits of implementing RBI, as reported in the literature, include the reduced risk of damage to marine structures, improved defect detection, reduced inspection effort, prolonged lifetime and extended inspection intervals, increased structural reliability and overall availability, and improved legislative compliance (Straub *et al.*, 2006).

This paper reviews the current state-of-the-art of RBI and its core elements, processes and common methodologies in the marine sector. We also identify and evaluate the most relevant standards and guidelines developed in this regard by various international organizations, institutes and consultant companies. Some new advances and developments of RBI for marine structures (in oil and gas fields and offshore renewable farms) are also outlined.

The rest of the paper is organized as follows. Section 2 provides a brief overview of the RBI concept and approaches. Section 3 introduces the techniques used for the analysis of RBI programs. Section 4 identifies damage mechanisms to which the marine structures are vulnerable. Section 5 reviews and evaluate the related standards, guidelines and best practices. Section 6 outlines some new advances and developments in the field. Finally, the concluding remarks are given in Section 7.

2. RBI Concept and Approaches

RBI uses an analysis of the risks of failure for the development of the inspection plan. Risk is defined as the effect of uncertainty on objectives, where an effect is a deviation from what is expected (ISO 31000; 2009). Therefore, risk is a combination of the probability of occurrence of a hazard and the severity of that hazard. Risk analysis is defined as a systematic use of available information to determine how often a specified hazard may occur and the severity of its likely consequences. The purpose of risk analysis is to determine the priority of potential hazards so that preventive measures can be taken to reduce the overall risk and improve the safety. Generally, the risk analysis process consists of four components: hazard identification, risk assessment, risk management, and risk communication.

In the RBI approach, the components according to their risk levels are divided into different categories such as high-risk, medium-risk, or low-risk. High-risk components have a significant likelihood of failure and a high consequence of failure. On the contrary, low-risk components are those whose probability of failure and severity of consequences are negligible. The remaining components are considered to have a moderate level of risk of failure. For high-risk assets, a focused maintenance effort is required, whereas in areas of low risk the effort is minimized.

There are several approaches on how to perform RBI in the marine sector. However, our study shows that majority of these approaches follow a certain set of steps. These steps include: data collection, risk assessment, risk ranking, inspection planning, mitigation (if needed) and re-assessment. The data needed to conduct RBI analysis on marine structures include material properties, design parameters, degradation data, operational data, past failure data, historical inspection and maintenance records, as well as experts' opinions. The risk assessment in the RBI analysis can be done in either qualitative or quantitative manner. A qualitative risk assessment uses descriptive scales to categorize the risks, whereas a quantitative risk assessment provides a numeric estimate of the probability of occurrence and the magnitude of the consequences (Shafiee *et al.*, 2019). Thus, qualitative RBI analysis will be useful in situations when there is a lack of numerical data.

The accuracy of the results from a qualitative RBI analysis depends on the background and expertise of the risk analysts and maintenance team. Nevertheless, a quantitative RBI analysis is generally more precise than a qualitative RBI analysis because the results from a quantitative RBI analysis are presented in numerical forms and therefore it will be easier for inspectors to interpret the evaluations. A new class of RBI analysis approaches called '*semi-quantitative*' was also recently developed by integrating and taking advantage of both the quantitative and qualitative RBI analysis approaches (Dinmohammadi, 2018).

3. RBI Techniques

This section provides a brief overview of the qualitative, quantitative, and semi-quantitative techniques used for RBI analysis.

Fault tree analysis (FTA)

FTA is a top-down, deductive failure analysis technique in which an undesired state of a system (top event) is analyzed using Boolean logic to combine a series of lower-level events (O'Connor and Kleyner, 2012). The events are connected by various logic symbols (e.g. AND and OR gates), showing the relationship between successive levels of the tree. AND gate means that the output event will occur only if all the input events occur simultaneously, whereas OR gate means that the output event will occur if at least one of the input events occurs. FTA can also be used to determine the likelihood of occurrence of the top event. However, extensive calculations are required and sometimes discrepancies may exist between actual failure in practice and reliability estimations.

Event tree analysis (ETA)

ETA is an analytical technique used to identify and evaluate the sequence of events in a potential incident scenario following the occurrence of an initiating event. This technique can help determine whether an initiating event will develop into a serious incident or it can be controlled by safety systems and procedures available in the system. The method uses a forward logic, i.e., the analysis begins with the identification of potential initiating events, then, the subsequent possible events resulting from the initiating events are displayed at the second level, and finally, the process is continued to develop pathways or scenarios from the initiating events to potential outcomes.

Failure mode, effects and criticality analysis (FMECA)

FMECA is one the most widely used techniques for risk assessment in RBI. This method involves creating a series of linkages between failure modes of a system, their effects on the system performance, and the causes of the failure. Initially, the FMECA was called failure modes and effects analysis (FMEA). The letter 'C' stands for criticality, which indicates that the criticality (or severity) of various failure effects are considered and ranked. Nowadays, FMEA is often used as a synonym for FMECA. In this technique, the risk of each failure is prioritized based on the risk priority number (RPN). The RPN is calculated by multiplying together the values of three criteria, namely the probability of the failure occurrence (O), the severity of the failure (S), and the probability of not detecting the failure (D), i.e., RPN = O×S×D (Shafiee and Dinmohammadi, 2014). These three risk factors are evaluated using a ten-point scale from 1 to 10, so the RPN value for each failure mode will range between 1 and 1000. FMEA technique is most beneficial when carried out as an iterative process during the preliminary design stages, allowing for improvements and reliability monitoring.

Monte-Carlo simulation (MCS)

MCS is a mathematical technique that generates random variables for modelling risk of a certain system. The random variables or inputs are sampled based on their probability distributions such as exponential, Weibull, Normal, etc. Different simulations with a large number of iterations are run for generating paths and the outcome is arrived at by using suitable numerical computations. This technique can provide the RBI team with a range of possible events and the probability of occurrence for each event.

Reliability block diagram (RBD)

RBD is a graphical analysis technique used to represent the interconnections and relationships between system components and determine the reliability of the system as a whole. In this diagram, the components are represented by blocks connected with each other by lines which show the relation between the blocks. Systems in general can be divided into different configurations such as series, parallel, k-out-of-n, etc. In a series configuration, the entire system will fail if one of the components fails. A parallel configuration is used to show redundancy wherein the whole system can function properly as long as at least one of its components is working properly. For k-out-of-n configurations ($1 < k < n$), a system is considered functioning if at least k out of a total of n components are working properly.

Markov analysis (MA)

Markov model is a stochastic process with the property of being memoryless. In other words, a Markov model is a sequence of realized states that the transition probability to a state only depends on the current state and not on the history of states. Markov models can be either discrete or continuous. In discrete Markov models, the component is observed at discrete time points, while in continuous models there is continuous observation. In a study, Nielsen and Sørensen (2014) proposed a partially observable Markov decision process (POMDP) for risk-based planning of O&M in offshore wind farms.

Bayesian network (BN)

A BN is a technique used to combine traditional quantitative analysis with expert judgement by using a directed acyclic graph. This graph represents the conditional dependencies between failure root causes and symptoms. In this graph, nodes correspond to random variables and arcs between nodes represent probabilistic dependencies, which together define the joint probability distribution over all random variables of the model. In real-world situations, the nodes represent cause and effect variables and arcs connect the nodes. Montes-Iturrizaga *et al.* (2009) introduced a framework based on BN for RBI planning of offshore steel jacket structures subjected to various deterioration and damage processes. Atia *et al.* (2015) applied a BN updating method to optimize RBI plans based on structural fatigue reliability.

4. Damage Mechanisms in Marine Structures

Identification of damage (deterioration) mechanisms is an essential step in developing an effective RBI program for marine structures. A damage or deterioration mechanism is a process inducing micro and/or macro material changes over time that are harmful to the mechanical properties of the system. Examples of such mechanisms in marine structures include fatigue cracking, general corrosion, pitting corrosion, stress corrosion cracking, corrosion fatigue, scour, etc. In what follows, a brief description of these damage mechanisms is given.

- *Fatigue cracking* is one of the primary damage mechanisms in offshore steel structures, resulting from cyclic stresses that are below the ultimate tensile stress. In high-cycle fatigue situations, materials performance is commonly characterized by a curve called S-N. The S-N curve represents the relationship between the magnitude of the applied stress (S) and the number of cycles to failure (N).

The fatigue life of a structural component, N_f is measured by the number of stress cycles that can be applied to the specimen before it fails. Crack propagation has been found as an essential factor affecting the fatigue life. Many models have so far been developed to describe the fatigue crack growth process, e.g. Paris' law (also known as the Paris-Erdogan law) (Paris and Erdogan, 1963). The Paris' law is a power-function used to predict crack evolution in structures subject to fatigue stresses. The equation is given by:

$$\frac{da}{dN} = C(\Delta K)^m, \tag{1}$$

where a represents the crack length, N represents the number of load cycles, da/dN is the fatigue crack growth rate per cycle, and C and m are empirical constants which depend on material properties and operating environment. The range of the stress intensity factor, ΔK represents the difference between the stress intensity factor at maximum and minimum loads for a particular crack length. Therefore,

$$\Delta K = K_{\max} - K_{\min} = \Delta\sigma Y \sqrt{\pi a}\ , \tag{2}$$

where $K_{\max}$ and $K_{\min}$ are, respectively, the maximum and minimum stress intensity factors, $\Delta\sigma$ is the range of cyclic stress amplitude, and Y is a dimensionless parameter that depends on the crack and loading geometries.

- *Corrosion* is the deterioration and loss of a material and its critical properties as a result of chemical reactions between it and the surrounding environment. There are different types of corrosion, including: *uniform corrosion* which deteriorates the whole surface of the metal and makes the surface thin, *galvanic corrosion* which occurs with an electrolyte like seawater, etc.
- *Pitting corrosion* occurs because of random attacks making holes on particular parts of the metal's surface.
- *Stress corrosion cracking (SCC) or environmentally induced cracking* arises due to stress and corrosive environment and generates brittle and dry cracks in the material.
- *Corrosion fatigue* is a combination of cyclic stress and corrosion and occurs in the presence of a corrosive environment like saltwater.
- *Erosion* is a process where natural forces like water, wind, ice, and gravity wear away rocks and soil.
- *Scour* is a process of soil erosion, which takes place around the fixed-based offshore structures through the action of flowing water.
- *Erosion-corrosion*, also called flow-assisted corrosion, occurs due to the movement of corrosive liquids on metal surface which damages the material.

5. RBI Planning and Updating

Two approaches are often applied to plan RBI activities for damage mechanisms in marine structures. These include: the *defect sizing* approach and the *reliability index (β)* or *probability of failure (PoF)* approach. The defect sizing approach is suitable for RBI planning when deterioration mechanisms are treated independently (non-competing damages). In the defect size approach, the inspections are initiated when the defect size reaches a pre-determined threshold which is smaller than critical defect size. At each inspection, the defect might be found with a certain probability depending on the type of inspection technique applied. The ability to detect a defect is expressed using a statistical measure called '*probability of detection (POD)*' which represents the success of an inspection work. The ability to size a defect is also expressed using the '*probability of sizing (POS)*' which provides an indication of sizing accuracy.

The β (or PoF) approach can be applied to both competing and non-competing (e.g., accumulative) mechanisms. In this approach, an inspection is initiated when the structural reliability index β (or PoF) reaches a pre-determined threshold which is greater than target β (or lower than critical PoF) level. The relationship between β and POF are given by:

$$\beta = -\varphi^{-1}(\mathrm{POF}) \quad ; \quad \mathrm{POF} = \varphi(-\beta), \tag{3}$$

where φ represents the cumulative standard normal probability function.

An example of development of a defect (for example a crack) from an initial size to a critical size is indicated schematically in Figure 1. In this Figure, the defect size is shown on the vertical axis versus time on the horizontal axis. It is assumed that an inspection is performed when the defect size reaches a predetermined threshold (less than critical failure size). In each inspection, the initial defect distribution may have grown wider due to uncertainties in the damage growth parameters. In this example, it is assumed that some defects might not be found/detected. The inspection is assumed to be associated with a significant probability of detecting large defects. Thus, provided that some defects are not detected during an inspection, it is likely that large-size defects are not present at the considered hot spot. Due to the actual probability of detection, a narrower defect distribution after inspection is indicated in the Figure (as it is likely that the largest defects would have been detected if present). This also means that the probability of a failure in the nearest future can be considered to be lower than that assumed before the inspection. If no inspection is performed, the damage size will grow and reach to an unacceptable size, resulting in a structural failure.

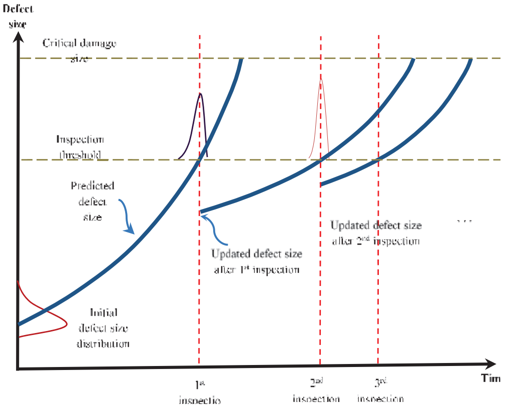

Figure 1. The defect growth behaviour under inspection.

6. RBI Guidelines and Best Practices

In this section, the most popular standards, guidelines and best practices developed by various international organizations, institutes and consultant companies for RBI analysis of marine structural assets are briefly reviewed.

American Bureau of Shipping (ABS)

ABS was founded in 1862 and its headquarters is located at Houston in Texas. ABS mainly provides risk assessment, safety, quality, and environmental consulting and certification services to the marine insurance industry. The ABS guidance on RBI for marine and offshore oil and gas industries was first published in year 2000 (ABS, 2000), and later in 2003, it was extended to offshore fixed-bottom and floating platforms (ABS, 2003).

The first step consists of the setup of an RBI team including individuals with experience and technical knowledge about maintenance and inspection, material degradation and failure analysis, reliability, structural integrity, risk analysis, process hazard assessment, and health and safety. Second, the RBI team identify and group the components that are subject to the inspection program and collect data for those components. Third, a risk-based prioritization screening is performed to identify the most critical components to the safety. This requires a risk assessment to be performed with considering consequences of failure from the anticipated degradation mechanisms as well as frequency of failure based on expected degradation rates. Forth, an inspection plan is developed based on the risk prioritization information so that the risk of failure is at or below acceptable levels. Fifth, the RBI program is executed and sixth, the results will be analysed. Finally, the observed degradation mechanisms and rates are used to update the RBI inspection plan.

American Petroleum Institute (API)

API is the largest U.S. trade association for the oil and natural gas industry. It has more than 650 corporate members from all segments of the industry, including production, refine, supply, pipeline operation, marine transport, etc. Up to now, the API has developed more than 600 standards and recommended practices on different issues within the petroleum and petrochemical sector. Its RBI recommended practices include: *API 580 "risk-based inspection"* (API, 2016a) and *API 581 "risk-based inspection technology"* (API, 2016b). These practices were developed based on the knowledge and experience of engineers, inspectors, risk analysts, and other personnel in the oil and gas and petrochemical industries. The API 580 is intended to provide guidance on developing a RBI program for fixed equipment and piping in the hydrocarbon and chemical process industries. API 581 divides the RBI analysis process into three parts: (1) determination of probability of failure (PoF); (2) analysis of consequences of failure (CoF); and (3) inspection planning using API 580 methodology.

Det Norske Veritas – German Lloyd (DNVGL)

DNVGL is an international certification body and classification society with main expertise in technical assessment, advisory, and risk management. It was created in 2013 as a result of a merger between two leading organizations in the field - Det Norske Veritas (DNV) and Germanischer Lloyd (GL). DNVGL is currently one of the world's largest technical consultancy to onshore and offshore wind, wave, tidal, and solar industries, as well as the global oil and gas industry. Regarding RBI analysis, DNVGL has developed two recommended practices:

DNVGL-RP-G101 "*risk based inspection of offshore topside static mechanical equipment*" (DNVGL, 2015): It provides guidelines and recommendations to describe a method for RBI analysis of offshore topsides static mechanical pressure systems when considering failures by loss of containment of the pressure envelope.

DNVGL-RP-C210 "*probabilistic methods for planning of inspection for fatigue cracks in offshore structures*" (DNVGL, 2015): It is a recommended practice providing guidelines on how to use probabilistic models in RBI planning of fatigue cracks in jacket structures, semi-submersibles and floating production vessels.

The cracks may have been detected during former inspections, but have been assessed to not require a repair before another inspection is performed. If there are such cracks in the structure, this information can be used as a basis for next inspection planning processes. All major structural damage mechanisms should be evaluated in the development of an RBI program for marine structures. However, DNVGL recommended practice mainly takes into account fatigue damage and the inspection is planned based on the calculated fatigue lives. In addition, when planning inspection process, it is important to assess the consequences of a potential fatigue crack at a considered hot spot. For this reason, the probability of a gross error is considered for planning the inspections for fatigue cracks.

Due to the nature of fatigue and number of uncertain parameters involved, there might exist some uncertainty as to when and where fatigue cracks will occur in a structure subjected to significant dynamic loading. The more information that is available, the better it is for predicting future behaviour with respect to fatigue cracking. For example if stress measurements have been performed over a sufficient period together with measured environmental data, it may be possible to reduce the uncertainty related to the long term loading significantly. In the DNVGL's RBI recommended practice, probabilistic analyses are performed for estimating the long term loading and fatigue limit. When inspection of the as built structure is performed and is properly reported, it may be possible to include fabrication quality in the assessment.

American Society of Mechanical Engineers (ASME)

In 1988, the ASME in cooperation with private industry and government agencies formed a multi-discipline research task force to develop and test efficient inspection programs based on risk assessment techniques. This effort resulted in the publication of a document in 1991 on the use of a generic RBI methodology for industrial applications (ASME, 1991). This methodology comprised a qualitative risk ranking as well as a quantitative assessment based on the FMECA technique to apply to individual components or equipment items. The use of operating experience databases and analytical damage models together with their probabilistic application was also recommended. The methodology was later adopted by various standard bodies, such as API and DNV, in the development of RBI standards. A number of subsequent publications also reported the application of the ASME's RBI methodology to the development of inspection programs in the fossil fuel, nuclear, petroleum, chemical and other industry sectors.

In 1992, the ASME published a second document about the application of the generic RBI methodology to nuclear power plant components (ASME, 1992). In 1994, the ASME published another document about fossil fuel-fired electric power generation station applications (ASME, 1994). It addressed the RBI analysis of components in fossil fuel-fired electric power generating stations. It considered application of the RBI methodology to all fossil power plant components contributing to plant unavailability, but the primary focus of inspection was on components that maintain a pressure boundary. Later in 2007, the ASME developed the PCC-3 code (ASME, 2007) based on API RP 580 to enhance its suitability for broader industry sectors including refineries and petrochemical facilities, oil and gas processing, pulp and paper, and power generation. However, this standard was specifically developed for applications involving fixed pressure-containing equipment and components.

7. New Advances and Developments in RBI

The methods and algorithms applied to RBI analysis of fixed-bottom and floating marine structures are evolving significantly. Bureau Veritas (BV) recently reported some of evolving technologies for RBI and integrity management of offshore jacket structures (Bureau Veritas, 2017). Jacket structures are one of the most common structures used for oil and gas development in offshore areas. They also are the most suitable foundation types for offshore wind turbines in depths of over 164 feet (50 meters). These structures should be designed with sufficient strength and stiffness to withstand the forces to which they may be subjected during operation in harsh and adverse environments. The typical forces on jacket structures include: wind and wave forces, forces due to current acting on the sea, tides, temperature forces, ice forces, and earthquakes. Therefore, it is crucial to develop and implement RBI plans with the aim of prolonging the life of jacket structures and/or achieving a high level of structural reliability.

With the development of advanced sensor technologies in the marine industry, new or more accurate information about the internal/external loadings to marine structures as well as condition of surrounding environment (such as temperature, humidity, wind speed) are becoming available. Emerging sensor systems can now monitor fatigue crack growth, applied and residual stresses as well as corrosion performance, and provide useful information about the structural damage development. On the other side, more information about the structural behaviour and accumulated fatigue damage becomes available from inspection activities at discrete time intervals or experience of inspectors accumulated over the lifetime of the structure.

Utilizing enormous amounts of "operational data" – collected either manually through inspections or with automation by means of condition monitoring systems (CMSs) – can increase the knowledge of the structural behaviour and reduce the prediction uncertainties related to the loadings. However, incorporating operational data into the RBI planning and updating of marine structures is not a straightforward task because such information cannot be directly applied to the assessment of changes in damage behaviour and then for updating the RBI program.

To the best of authors' knowledge, there is a strong need for the marine industry to shift from classical RBI planning systems to "real-time RBI" solutions that are capable of integrating different types of new data from a variety of sources, characterizing various forms of uncertainty in fracture mechanics parameters, damage prediction models, or monitoring data, and updating the RBI planning processes whenever any alternation in fatigue damage levels occurs, or when operating conditions change, or even when the platform is strengthened after some years of operation. In a research project funded by the UK's EPSRC, the first author is working on a real-time RBI model based on an advanced stochastic fracture mechanics approach coupled with (preposterior) Bayes' theorem to help wind energy industries gain benefit from real-time data and improve the performance of their RBI practices for offshore wind farm structures.

The number of floating marine structures is anticipated to have a significant growth in the near future. Floating structures have a number of important benefits including greater flexibility in the construction and installation procedures. However, as these structures are not fixed to the seabed and are deployed in harsher marine conditions, they will be subject to more extreme waves and wind-induced loads than fixed-bottom marine structures. Therefore, RBI will play a more critical role in maintaining the safe, efficient and economic operation of floating structures. Recently, ABS developed a guide for RBI analysis of floating offshore installations including hull, mooring, riser, etc. (ABS, 2018). This guide is a complete re-write of the previous ABS guide for surveys using risk-based inspection for the offshore industry which was published in 2003 (ABS, 2003).

8. Conclusion and Future Works

Over the last two decades, a great deal of attention has been focused on applying risk-based inspection (RBI) approaches to marine structures. RBI is a methodology that uses risk assessment information to prioritize and manage the efforts of an inspection program. The main objective of RBI is to focus the limited resources that are available for inspection on those structural members that have a high level of risk, i.e., the members with a high probability of failure and a high consequence of failure. Approaches such as fault tree analysis (FTA); event tree analysis (ETA); failure mode, effects and criticality analysis (FMECA); expert analysis and probabilistic modelling have been utilized for the purpose of RBI analysis and optimisation. Moreover, a number of standards, guidelines and best practices have been developed in this regard by various international organizations, institutes and consultant companies such as American Bureau of Shipping (ABS), American Petroleum Institute (API), Det Norske Veritas – German Lloyd (DNVGL), American Society of Mechanical Engineers (ASME), Bureau Veritas (BV), etc. Even though these guidelines provide multiple ways to perform RBI processes and policies, our review revealed that the majority of the RBI planning and decision-making procedures for marine structures follow a certain set of steps, including: data collection, risk assessment, risk ranking, inspection planning, mitigation (if needed) and re-assessment.

Currently, the RBI plans for marine structures can be either prepared for short-term, or long-term, or both. In short-term RBI plans, a detailed schedule is provided for few days of operation of the marine structure and then the schedule will be updated on a daily basis to reflect any changes that might occur in working conditions. The long-term RBI planning includes inspection plans that are prepared for several years of operation or the entire life of the marine structure and are updated typically on an annual basis. However, in recent years, with the development of advanced sensing and Internet of Thing (IoT) technologies, the marine industry in shifting toward real-time or near-real time RBI analysis in which the inspection plans can be updated instantaneously when any changes occur. Some efforts are currently underway in this direction.

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