Proceedings of OMAE 2002, 21st International Conference
Offshore Mechanics and Artic Engineering
Oslo, Norway, 23-28 June, 2002

OMAE2002-28609

ON THE SAFETY OF FIXED OFFSHORE STRUCTURES, FAILURE PATHS AND BARRIERS

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ABSTRACT

In order to ensure the safety of an offshore structure it is important to identify and maintain the barriers preventing hazardous events. Also, when monitoring the safety, the monitoring should be regarding how well these barriers are functioning, and utilise these to reassess the safety of the structure over time.

The purpose of this paper is to apply a well-known method in risk assessment, Haddon’s energy and barrier model, to a new area; structural safety. The purposes of this exercise are to look at the structural safety from a risk assessment point of view, and to use this to identify and give an overview of the existing barriers. Furthermore, the purposes are to evaluate the efficiency and redundancy of these barriers, and to use this to evaluate the safety of offshore structures.

This paper will analyse the safety of a fixed offshore structure through a qualitative approach. A possible event chart for a fixed offshore installation during operation in storms is established and analysed. Some of the root causes for potential structural failure are identified. These root-causes are kept on a general level, but considered in more detail than often seen in risk analysis. Hazards that are normally included in risk analysis, like boat collisions, fire, explosions, and dropped objects are not evaluated. Hazards that are evaluated are structural failure due to wave loading, fatigue damage, aging, and gross errors in design, fabrication, installation and operation.

In order to identify the barriers (hazard reduction strategies, physical barriers and vulnerable target protection strategies), the different failure paths in the event chart are then analysed using Haddon’s ten preventive strategies for reducing damage from hazards.

As an example a fixed offshore steel structure is used. A list of proposed barriers that influence the safety of such a fixed offshore installation are presented, and methods to measure these barriers are discussed.

INTRODUCTION

This work was initiated as a part of Norwegian Petroleum Directorate’s project to evaluate safety development on the Norwegian Continental shelf. Initially the trend in safety was measured by the number of injuries to personnel, the potential for major accident and work related illness. The potential for major accidents have been measured by measuring the number of incidents (as fire, well kicks, boat collisions and major cracks in structures). An alternative is to measure the condition of the barriers preventing accidents, and using this information to monitor the safety. This paper investigates the structural safety by the failure modes for a structure in storm, and possible barriers preventing an accident. A method to establish barriers is proposed, and examples for fixed offshore structures are presented.

The general use of barriers in Norwegian offshore regulation is rather new, and was introduced in the NPD regulations of 2001 (NPD 2001). In general, the requirements for the operators are that the barriers should be identified, the designed function should be known, and the barriers should be maintained or compensated for if missing or impaired.

The use of the terms barriers, defences and hazard reduction strategies may vary in different literatures, and will not in all cases be similar to the usage in the NPD regulation (NPD 2001). The attempt in this paper is to utilize the terms barriers and defences in accordance with Haddon (1980) and Kjellén (2000), and may differ from the usage of the same terms in the NPD regulation (NPD 2001).

In this paper all risk reduction strategies are called defences. The defences are divided into:

- Hazard reduction
- Barriers
  - Technical barriers
  - Administrative barriers
- Strategies related to the vulnerable target

The barriers are directly protecting the vulnerable targets in a hazard situation, and they are of primary interest for this study.

The same barriers will also be important in other situations, like identifying the main contributors to the safety, when establishing relevant hazards, failure modes and mitigations for quantitative risk analysis, and in assessment procedures for existing structures.

CAUSES FOR STRUCTURAL FAILURES

The following two conditions are usually regarded to represent the main causes for uncertainty in structural design:

- Normal uncertainty in environment, loading, strength, load and strength formulations, workmanship etc.
- Abnormal uncertainty:
  - Gross errors: Abnormal variations from the expected variation of human behaviour (e.g. design errors, welding error)
  - Accidental Loads
  - Unknown phenomenon (e.g. ringing, green water and vortex shedding has all resulted in unforeseen incidents).

Normal uncertainty can be modelled in a typical Structural Reliability Analysis (SRA), but structural reliability analysis cannot fully examine the gross errors uncertainties. Models of probability of gross errors and unknown phenomena into structural reliability analysis are still in its infancy. A typical Quantitative Risk Analysis (QRA) for a Northern European installations has well developed methods to analyse the following accidental loads, like blowouts, fire and explosions, dropped objects, ship impacts or other impacts. However the methods for assessing the abnormal variation in human behaviour and unknown phenomena in a quantitative risk analysis are not developed on a generally accepted level.

DESCRIPTION OF A PROPOSED METHOD

The general methodology proposed to identify barriers and defences in a structure in different hazardous situations are:

1: An event chart or fault tree is established taking into account as much information as possible about possible failure modes. This event chart should be updated based on known failures.

2: Defences and barriers are established using Haddon's ten preventive strategies (Haddon, 1980).

3: Contributing factors and root causes are established by evaluating the limitations and maintenance needs of these defences and barriers, and by evaluating the event diagram / fault tree.

3: The performance of the defences and barriers are measured with regards to dependence / independence, active / passive and how robust they are towards accidental loads.

As an example, this paper will describe an event chart / fault tree leading to structural failure of a fixed steel installation in a storm, and what additional considerations this may give to the accidental loads normally evaluated in QRA. Furthermore, the paper will analyse the possible strategies to limit these hazards (Haddon, 1980), and in light of these strategies analyse the primary contributors to the safety of an offshore structure.

QUALITATIVE RISK OF STRUCTURAL FAILURE

In many cases the probability of structural failure is evaluated in a QRA to be the probability of failure in overload due to extreme wave, current and wind load calculated by a SRA, together with typical Design Accidental Loads (DAL) like boat collision, fire and explosion. However, the probability of failure in extreme weather can be viewed to consist of more failure modes than what is usually modelled in a SRA. The event chart / fault tree in Figure 2 shows a slightly more detailed view on possible failure modes in extreme weather, but it does not give a complete picture.

The event chart / event tree in Figure 2 is limited, and can be expanded both in detail of the main cause of structural failure and in types of main failure modes. Additional main failure modes could be "Structural Failure in installation" and "Structural failure in fabrication". These failure modes do not apply to the structure in operation, and are not discussed further in this paper. The fabrication and installation process may result in errors that influence the risk of a structure in operation, and these possible errors will be included in the following discussion. However, it is worth mentioning that the event chart under these main failure modes will be similar to these showed in Figure 2, with degraded structure due to gross error as an important branch. It is also worth mentioning that all the major structural failures in Norway (Frigg DP1, Aleksander Kielland, Sleipner A-1) all are regarded to have a starting point at "degraded structure due to gross error", but in different main branches of the fault tree.

Examples of gross errors in design are calculation errors, drafting errors and design of installations not fit for their purpose (impossible to use) etc. Examples of gross errors in fabrication are bad welding, cracks, misalignment etc. Examples of gross errors in installation are burn-marks from removal of sea-fastening, damage on structure from piling hammer etc. Examples of gross errors in operation are errors in repair work, lack of inspection and repair etc.

Some of the branches in the event chart / fault tree in Figure 2 are rather easy to analyse with SRA, but others has proven to be very difficult to assess in a quantitative way. This applies especially to the gross error problem, but also accelerated fatigue causes problems. In general, history shows that the failure path starting with a gross error dominates the accident databases (Melchers 2001, Kvitrud et al 2001). Melchers (2001) states "... the risk associated with overloading-understrength-workmanship is relatively small compared to the risk associated with gross human error and structural abuse". Gross errors are not typically visible unless the structure is exposed to a high loading where the gross errors are the weakest links. These do, off course, not only occur in storm situations during operation, but could as well occur in other high loading situation in fabrication, transport, installation or operation phases. For Sleipner A1 this high loading occurred during fabrication, and for Frigg DP1 this high loading occurred during installation.

ENERGY MODEL AND PREVENTIVE STRATEGIES

The energy model, see Figure 1, represents an effort to systemise the analysis of accident causes in a way similar to that of analysing the cause of diseases (Kjellén, 2000). The hazard is energy exchange, which is mechanical, chemical, thermal, electrical, etc. The use of Haddon’s ten strategies for accident prevention, as shown in Table 1, into the energy model is a systemised development of this method.

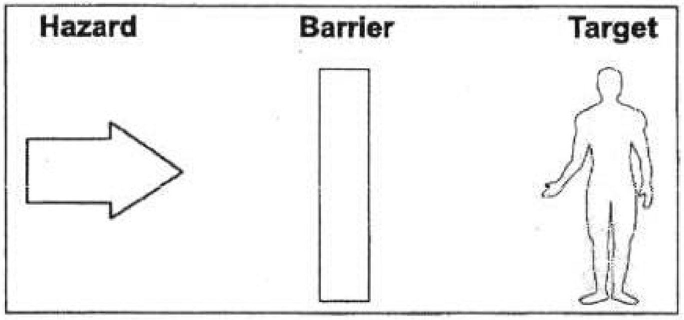

Figure 1: The energy model (Kjellén, 2000)

The energy model has three distinct merits. One lies in the support it offers in checking that all possible preventive measures have been identified. A second merit of the energy model is the support it offers in anticipating the consequence of accidents. A third important merit is the support the energy model offers in identifying hazards.

The energy model and Haddon’s strategies have had, according to Kjellén (2000), significant influence on the European legislation and standardisation work related to machinery safety and risk analysis. Due to this it is of interest to see how it will apply to offshore structures.

Based on the failure causes indicated earlier, the important strategies (defences) to secure the installations can be identified. A formal method of identifying these strategies (defences) is Haddon’s ten preventive strategies (Haddon, 1980). The strategies are directed towards reducing the hazard (e.g. fatigue failure in structures), towards physical barriers (e.g. sufficient strength in structure with one brace missing) and towards protecting the vulnerable target (e.g. evacuation equipment).

Table 1: Haddon’s ten preventive strategies (Kjellén, 2000)

Hazard (energy source)	Barriers	Vulnerable target
Strategies related towards the hazard:	Strategies related to barriers between hazard and target:	Strategies related to the vulnerable target:
1. Prevent build-up of energy 2. Modify the qualities of the energy 3. Limit the amount of energy 4. Prevent uncontrolled release of energy 5. Modify rate and distribution of energy	6. Separate in time or space the source and the vulnerable target 7. Separate energy source and the vulnerable target by physical barriers	8. Make the vulnerable target more resistant to damage from the energy flow 9. Limit the development of loss (injury or damage) 10. Stabilise, repair and rehabilitate the object of the damage.

BARRIERS IDENTIFICATION

The hazardous energies are defined as the by the event chart /fault diagram in Figure 2. Haddon’s strategies are applied to these hazards for a fixed offshore steel installation. Possible hazard reductions, barriers and vulnerable target protections are identified. The following hazards are analysed and the result are presented in Table 2:

- Overload due to Wave in deck.
- Overload due to wave, current and wind.
- Fatigue failure followed by wave, current and wind overload.
- Fatigue failure followed accelerated fatigue followed by wave, current and wind overload.
- Gross error in design, fabrication or installation followed by wave, current and wind overload.
- Aging (corrosion etc.) followed by wave, current and wind overload.

The vulnerable target in this example is the personnel on board of the offshore installation, but could also be the environment and economical interests.

The energy source in these cases is the waves, current and wind. According to Haddon’s strategies, the focus should be on the strategies related towards reducing the energy. In Table 2, only one general strategy is mentioned, as it is rather uncommon to reduce the wave, current and wind environment offshore. However, this has been done for many harbours by different methods.

The next step is to evaluate the barriers preventing accidents. On an offshore installation, with some degree of degradation, the barriers will be of prior importance for the safety during a storm. The identified barriers in Table 2 are:

- Air-gap with sufficient safety margin.
- Safety margin in global and local load capacity versus loading.
- Safety margin in fatigue capacity versus environmental loading.
- Reserve strength and ductility
- Residual strength and residual fatigue capacity
- Evacuation of personnel ahead of storm
- Restrict people from exposed areas and installations.
- Wave breaking walls around installation.
- Local wave breaking walls in topside.

In the last instance, when the accident has occurred, the strategies related to protection and evacuation of the vulnerable target should be evaluated. To some extent, this is equal to the protection and evacuation of the vulnerable target in other accident situations, as fire, blowout etc, but two interesting strategies that is structural related is identified in Table 2:

- Equipment for evacuation should be useable under large tilt.
- The structure should be designed in such a way that progressing total collapse allows time for evacuation.

The protections of the mentioned barriers will be of importance in order to ensure effective barriers in a hazard situation. Protection is performed by inspecting and maintaining the condition of these barriers. Table 2 identifies the following strategies:

- Subsidence monitoring and jack the platforms if needed.
- Environmental loading reduction measures e.g. reduced number of conductors, removing of marine growth.
- Inspection of structure (methods and intervals including first year inspection).
- Maintenance, repair and strengthening.
- Quality in the design, fabrication, installation and operation of the installation, ensured by experience transfer, updated regulations and standards, quality assurance, verification in design and fabrication, qualification of personnel, model tests and full scale tests etc.
- Corrosion protection (anodes, painting, coating etc.)
- Material selection.

All these groups of strategies should define the defences for a fixed offshore steel structure. The list may not be complete, and additions should be added when identified. When analysing the failure modes for topside and foundation failure, the identified barriers are to a large extent the same as already mentioned.

QUANTITATIVE MEASUREMENT OF BARRIERS

The main barriers for a fixed offshore steel structure are in general measurable by using results from standard structural calculations and structural reliability analysis.

- Air gap should be measured after installation, and monitored for installations that are exposed to subsidence.
- Safety margin in global and local load capacity versus loading is illustrated by utilization factors in design analysis.
- Safety margin in fatigue capacity versus environmental loading can be illustrated by fatigue damage usually calculated in fatigue design analysis.
- Reserve strength may be modelled by a Reserve Strength Ratio (RSR) analysis.
- Residual strength could be modelled by Damaged Strength Ratio (DSR, a RSR analysis with individual members damaged, also called RRF – Residual Resistance Factor).
- A method to measure residual fatigue capacity could also be established, but there is at present not established a standard methods for evaluating the residual fatigue capacity.

These factors are also commonly used in probabilistic analysis (structural reliability analysis) in order to establish a probability of failure. The barriers air-gap, safety margin, reserve strength, and residual strength are passive barriers. The barriers are not fully redundant. Air-gap and reserve strength could be evaluated as redundant, but the reserve strength when the wave has exceeded the air-gap will be small, and then the barrier will be ineffective. The safety margins and the reserve strength could to some extent be considered to be measurements of the same barrier.

Evacuation of personnel ahead of a storm may be used as an administrative barrier, and the effectiveness should be possible to estimate. The evacuation of personnel ahead of a storm is an active barrier that requires human intervention. In addition to the reliability of weather forecasts being uncertain, the human intervention will reduce the reliability of this barrier.

The monitoring of these barriers over time will be needed in order to establish a trend for the safety of these structures. Measuring the development of these barriers over time is not commonly performed, and has to be looked further into. The inspection methods and the interval between inspections and performed maintenance are generally known, but can in some cases be hard to trace back in time. The effect of inspections can be modelled in a probabilistic analysis (structural reliability analysis). The effect of inspection intervals and inspection method (by the POD curve) on the safety of the structure is quantified by a probability of failure. Inspections will give information on the state of marine growth, scour, and corrosion protection. Corrosion protection methods and material used should in general be known, and the effect should be able to measure.

The rest of the strategies for maintaining the defences and barriers are not quantifiable in the same manner. The quality in design, fabrication and installation is probably hard to trace back, and even if the information is well known there is no model for establishing the influence on the structural safety.

The manning situation, equipment and efficiency for evacuation and the expected time available for evacuation is consequence related, and will not be dealt with in detail here.

CONCLUSIONS

A reasonable goal is to create regulations that ensure an acceptable and equal level of safety on different offshore structures with the same manning situations. By identifying the defences contributing to the safety, it may be possible to develop a model to describe the safety of a structure based on these defences.

The method presented is based on the use of a fault tree / event chart to identify root-causes for possible structural failures in storms, then to use Haddon's ten preventive strategies to identify strategies preventing these failure paths. Haddon's ten preventive strategies are then used to establish proposed barriers and defences influencing the safety.

The following defences and barriers preventing structural accidents on fixed offshore structure are identified:

- Reduce wave, current and wind environment.
- Air-gap with sufficient safety margin.
- Safety margin in global and local load capacity versus loading.
- Safety margin in fatigue capacity versus environmental loading.
- Reserve strength and ductility
- Residual strength and residual fatigue capacity
- Evacuation of personnel ahead of storm
- Restrict people from exposed areas and installations.
- Wave breaking walls around installation.
- Local wave breaking walls in topside.
- Evacuation equipment should be able to be used under large tilt.
- The structure should be designed in such a way that progressing total collapse allows time for evacuation.

The protections of the mentioned barriers will be of importance in order to ensure effective barriers in a hazard situation. Protections of the barriers are performed by inspecting and maintaining the condition of these barriers. Table 2 identifies the following strategies:

- Subsidence monitoring and jack the platforms if needed.
- Environmental loading reducing measures e.g. reduced number of conductors, removing of marine growth.
- Inspection of structure (methods and intervals including first year inspection).
- Maintenance, repair and strengthening.
- Quality in the design, fabrication, installation and operation of the installation, ensured by experience transfer, updated regulations and standards, quality assurance, verification in design and fabrication, qualification of personnel, model tests and full scale tests etc.
- Corrosion protection (anodes, painting, coating etc.)
- Material selection.

This list may not be complete, and additions should be added when identified. The identified defences and barriers are similar to the general opinion in the structural engineering community, but are in this paper established using a formal risk approach.

If the method used in this paper is found to be an acceptable method to identify defences and barriers for structures, the method could also be applied to other types of installations like Semi-submersible, FPSO etc. The method could also be applied to identify defences and barriers for other types of failure causes like boat collisions, falling objects, fires and explosions.

The barriers are usually measurable, but are not easily converted into probability of failure formats. Further research on the correlation between the defences and barriers of a fixed offshore steel structure and a quantified safety-measurement is needed. The monitoring of these barriers over time will be needed in order to establish a safety trend of these structures. Measuring the development of these barriers over time is not commonly performed, and methods for evaluating the status of the barriers in an existing structure have to be established.

ACKNOWLEDGMENTS

The author would like to thank Arne Kvitrud and Urban Kjellén for valuable discussions. This work is a part of a PhD study at Stavanger University College financed by Norwegian Petroleum Directorate.

The opinions expressed herein are those of the author, and they should not be construed as reflecting the views of the Norwegian Petroleum Directorate.

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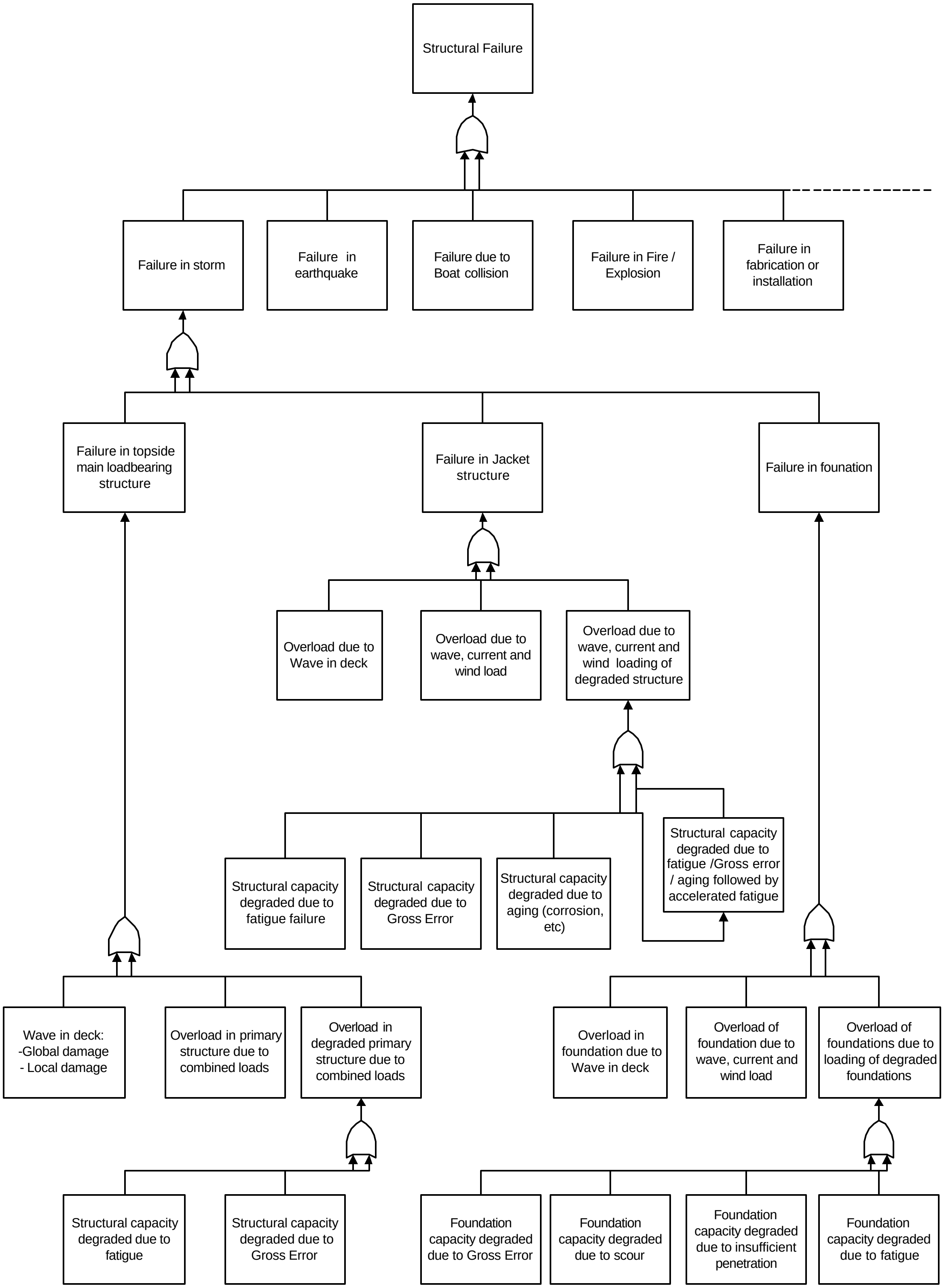

Figure 2: Fault tree / event chart for structural failure of fixed offshore structures in storm

Table 2 Examples of safety measures according to Haddon's strategies

	Strategies related to the energy source (Strategy 1-5)	Strategies related to barriers (Strategy 6-7)	Strategies related to the target / vulnerable target (Strategy 8-10)	Maintenance of barriers. Contributing factors and root causes.
Wave in deck	Reduce wave, current and wind environment.	Air-gap with sufficient safety margin. Evacuate personnel ahead of storm. Restrict people from exposed areas. Restrict people from exposed installations. Wave breaking walls around platform. Local wave breaking walls on topside.	Evacuation equipment that can be used under large tilt. Progressing total collapse should allow time for evacuation.	Monitor subsidence, and jack the platforms if needed.
Wave, current and wind overload	Reduce wave, current and wind environment.	Evacuate personnel ahead of storm. Restrict people from exposed installations. Global and local load capacity with safety margin. Reserve strength and ductility. Wave breaking walls around platform.	Evacuation equipment that can be used under large tilt. Progressing total collapse should allow time for evacuation.	Reduce wave loading: -reduced number of conductors etc. - remove marine growth
Fatigue failure followed by wave, current and wind overload	Reduce wave, current and wind environment.	Fatigue capacity with safety margin. Residual strength. Evacuate personnel ahead of storm. Restrict people from exposed installations. Wave breaking walls around platform.	Evacuation equipment that can be used under large tilt. Progressing total collapse should allow time for evacuation.	Reduce wave loading: - reduced number of conductors etc. - remove marine growth Inspection of structure, maintenance and repair when fatigue cracks are found.
Fatigue failure followed accelerated fatigue followed by wave, current and wind overload	Reduce wave, current and wind environment.	Fatigue capacity with safety margin. Residual strength and residual fatigue capacity. Evacuate personnel ahead of storm. Restrict people from exposed installations Wave breaking walls around platform.	Evacuation equipment that can be used under large tilt. Progressing total collapse should allow time for evacuation.	Reduce wave loading: - reduced number of conductors etc. - remove marine growth Inspection of structure, maintenance and repair when fatigue cracks are found.
Design, fabrication or installation error followed by wave, current and wind overload	Reduce wave, current and wind environment.	Fatigue capacity and load capacity with safety margin. Reserve strength and Residual strength. Evacuate personnel ahead of storm. Wave breaking walls around platform.	Evacuation equipment that can be used under large tilt. Progressing total collapse should allow time for evacuation.	Experience transfer. Updated regulations and standards. First year inspection. Quality assurance. Verification in design and fabrication. Qualifications of personnel. Model scale and full scale tests. Inherent safety.
Aging followed by wave, current and wind overload	Reduce wave, current and wind environment.	Fatigue capacity and load capacity with safety margin. Residual strength. Evacuate personnel ahead of storm. Wave breaking walls around platform.	Evacuation equipment that can be used under large tilt. Progressing total collapse should allow time for evacuation.	Corrosion protection (e.g. anodes, painting, coating) Material selection. Inspection and maintenance. Repair of anodes and paint. Grinding.