Environmental Loads in the North Sea – The missing piece in the MAH jigsaw?

David Sanderson, Director, MMI Engineering, The Brew House, Wilderspool Park, Warrington, WA4 6HL; dsanderson@mmiengineering.com

Iain Manclark, S&OR Upstream Structural & Civil Engineering TA (Eastern Hemisphere), BP c/o WGPSN Building, Wellheads Industrial Estate, Wellheads Place, Dyce, Aberdeen

The OSC regulations call for the identification and management of all major accident hazards. Since their introduction, methods for the quantification of hazards arising from hydrocarbons have been developed and refined. A great deal of effort has also been (quite rightly) spent on improving the effectiveness of measures in place to manage hydrocarbon hazards such that risks are ALARP. For non-hydrocarbon hazards, methods for quantifying risks associated with helicopter travel and ship collision are also relatively well developed. The way in which the risks associated with platform collapse due to environmental loads, however, is anomalous.

Many QRA use the information in Spouge's guidance on QRA for the frequency of collapse of structures. However, in this author's experience the frequency of structural collapse for structures in the North Sea is highly variable. A majority of structures have such large design safety margins that Spouge is quite conservative but others have smaller safety margins that result in predicted probabilities of collapse greater than 1 in 10,000 years.

This paper examines work performed to predict the frequency of fixed jacket structure failures for a variety of structural types in order to examine to what extent the Spouge assumption is conservative for North Sea jackets. It goes on to present a method by which specific major structural elements may be identified as Safety Critical Elements (as per the OSC regulations) and concludes by presenting a framework within which the SCEs can be managed.

Keywords : QRA, PFEER, Major Hazards, Structural Reliability, Ageing Structures

Introduction

The guidance to the 2005 OSC regulations [1] states that *"safety-critical elements" means such parts of an installation and such of its plant (including computer programmes), or any part thereof – (a) the failure of which could cause or contribute substantially to; or (b) a purpose of which is to prevent, or limit the effect of, a major accident*. Guidance to the 2015 Regulations [2] extends the guidance in that it modifies the term major accident to include those incidents which may result in major environmental impact. In practice, in the following all reference to SCEs would equally apply to SECEs apart from the discussions on ALARP which are confined to life safety consequences.

The management of ageing assets in the UKCS is a key issue for operators and the regulator and has resulted in various initiatives such as the HSE's KP programmes and industry body initiatives which has resulted in various guidance on the subject of life extension. Much of this guidance relates to the management of ageing issues with regards to safety critical elements. Much attention has been given to the management of ageing systems such as fire and gas detection, ESD and blowdown systems. Topsides structures also feature prominently in industry guidance. In the author's opinion, the management of the supporting structure has not received the attention it merits.

Why is this?

In a study performed for the HSE, the author reviewed a number of offshore safety cases held by HSE. The outcome from the study is confidential and is not citable, but its purpose was to risk-rank the platforms in the UKCS with regards to the risk due to structural collapse. Whilst it is not possible to cite the details of the study, it was found that the vast majority of Offshore Safety Cases did not report platform-specific data with regards to the risk of structural collapse. In a large number of cases, the QRA report used a figure of $1x10^{-5}$ per annum as the risk of platform collapse due to extreme environmental events [3]. In many cases, this figure was quoted despite the fact that the organisation knew that the risk of structural collapse was actually much less than this. In summary, the study identified a disconnection between the work that goes into assessing the risk of structural collapse and the Quantitative Risk Assessment. In the vast majority of cases, assuming that the platform failure rate is $1x10^{-5}$ per annum is conservative, but there existed a significant number for which it was not.

From the failure to consider the risk of structural collapse within the same goal-setting framework as is done for hydrocarbon and transport hazards follows the inevitable failure to ensure that the risks of structural collapse have been managed to levels that are ALARP. Further, advances in drilling and production technology have led to platforms being increasingly demanded operate beyond their original design life. An important failure mechanism for fixed offshore installations is fatigue failure of individual structural elements which weakens the structure and therefore increases the risk of structural collapse. As structures go beyond design life, the uncertainty of the condition of the platform increases and our confidence in our calculations of the risk of structural collapse (should it have been determined) decreases.

The increasing uncertainty of the risk of platform collapse is addressed in HSE Information Sheet 4/2009 [4] which states that *"It is important that assessment for life extension takes account of new technology developments in structural assessment, particularly in system strength, … Areas of particular progress include the understanding of system performance following single and multiple member failure, the effects on fatigue life due to load redistribution and structural reliability analysis for the determination of inspection plans and evaluation of system reliability."* What this means is that operators should take cognisance of their increasing uncertainty and perform deeper assessments to account for a greater possibility of failures due to fatigue and consider what the effect those might have. However, as has already been stated, the fact that the risk of structural collapse is not generally dealt with in the ALARP framework means that these considerations have not generally been adopted by industry.

The Risk of Structural Collapse

The risk of structural collapse can be estimated using structural reliability techniques; see for example [5]. Figure 1 shows a probability density distribution for load (S) and a probability density distribution for resistance / strength (R). The risk of structural collapse is calculated as the convolution of two distributions. Simply put, the more the two distributions overlap, the greater the probability of failure. Good design involving the incorporation of factors of safety results in the resistance distribution being well-separated from the load distribution with correspondingly low probabilities of collapse. In the author's experience, structural reliability techniques for UKCS structures often result in very high reliability predictions (reliability is the reciprocal of annual frequency of failure).

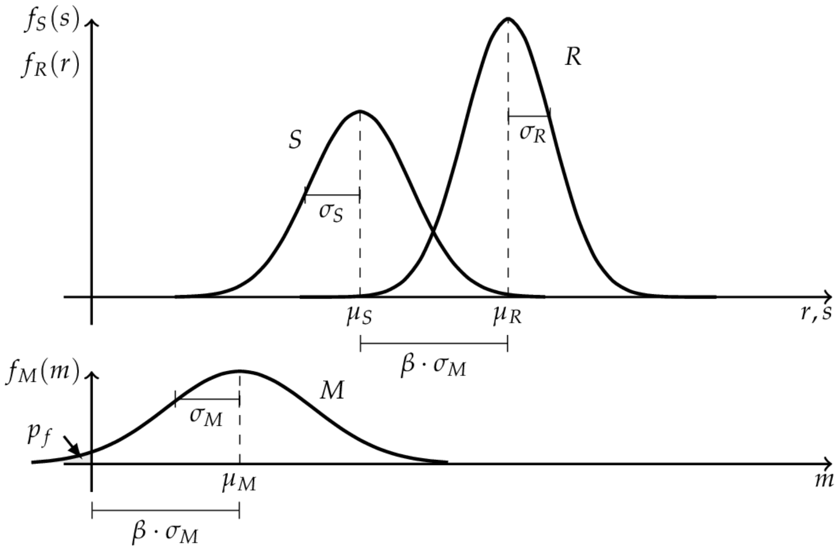


Figure 1 – Probability Density Distributions of Load (S) and Resistance (R)

If we consider the possibility that a structure may have a member failure due to fatigue (or indeed any other failure mechanism) then the result of that is to reduce the strength or resistance of the structure as illustrated in Figure 2. Many older structures were designed with high levels of structural redundancy. Such structures have multiple load paths and are therefore quite resilient to damage. The loss of any single member is very unlikely to lead to a large loss of structural strength. This is illustrated in Figure 2. Conversely, more modern structures (especially those designed during the CRINE era) are 'leaner' and often have lower redundancy.

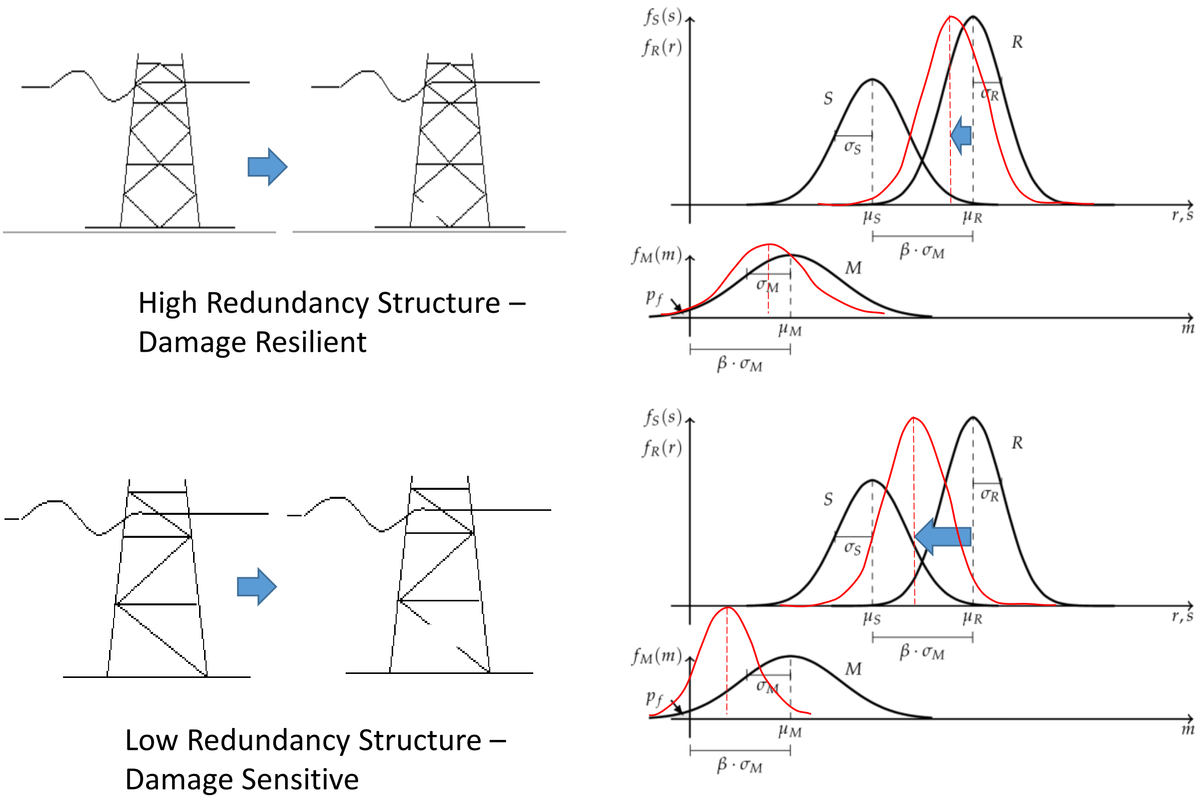


Figure 2 – Effect of Structural Member Failure on Global Structural Strength and Probability of Failure

The recommendations of HSE Info Sheet 4/2009 is that operators consider the possibility that one or more members have failed and that in making that consideration, they can still assure the integrity of the structure and thereby the safety of occupants of that structure. Such an exercise may require an understanding of the likelihood of members failing and the effect of failed members on structural strength.

The calculation of the reliability of a platform then becomes a matter of understanding the likelihood of the platform being in a given condition (undamaged or a specific damaged state, where damage is defined as the member being completely severed) and the probability of the platform failing given that it is in such a condition. This is expressed by the following equation:-

$$P_f = \sum_{j=0}^{j=N!} P^{j}_{storm} P_j(t) \qquad (1)$$

In Equation (1), P_f is the annual probability of structural failure / collapse due to environmental loads. P^{j}_{storm} is the probability of a storm that will cause collapse of the structure when it is in the j'th condition. $Pj(t)$ is the time varying probability that the platform is in the j'th condition, where a 'condition' describes the amount of damage within the structure. Theoretically, there are $N!$ possible damaged states, but it is impracticable to consider all of them. In the current work, some conditions where up to 4 members were considered to have failed was included.

Probability of Storms

Every platform has an associated MetOcean study which uses meteorological and oceanographic data to estimate the likelihood of extreme weather events. Work performed by Shell in the 1990s [6,7] mapped across wave heights to structural loads and produced a Long Term Load Distribution (LTLD). The LTLD relates extreme environmental loads to their return period and hence probability of occurrence. Once the LTLD is known for a given geographic region, then to estimate the probability of collapse simple means mapping the strength of the structure onto the LTLD. This is shown in Figure 3. On the left hand side of Figure 3 is a schematic of the 'pushover' curves which show the maximum strength of the structure. There is a family of curves with each dotted line representing a different damaged state. In reality there are hundreds of such curves. The strengths are mapped across to the LTLD which is shown in the right hand side of Figure 3.

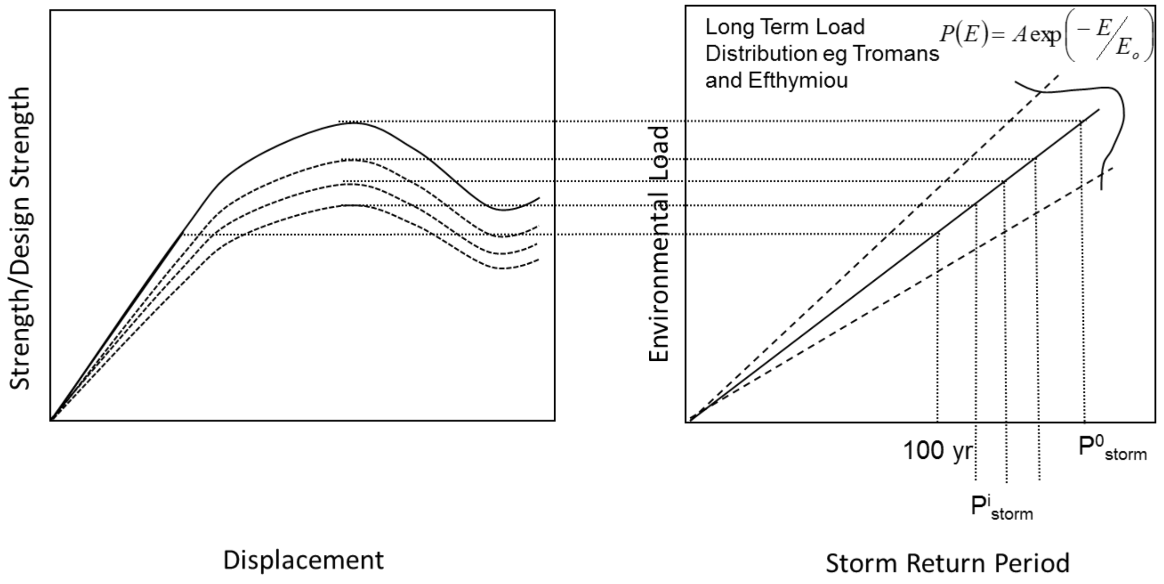


Figure 3 Mapping of Ultimate Strengths to Long Term Load Distribution to Predict Probability of Platform Collapse

Probability of Members Failing

Perhaps one of the main reasons that the recommendations made in HSE Info Sheet 4/2009 cited above are not yet widely followed, is that the anecdotal evidence seems to suggest that the frequency of member failure is low. A previous JIP by EQE International (now ABS Consulting) conducted in 1999 / 2000 highlighted the fact that, at that time, there was a limited number of member failures and those that were found were as a result of initial large, ‘rogue’ defects. The historical data was recorded as a number of failures per platform year, which would have been more helpful had it been recorded as failures per member year.

Probabilistic fracture mechanics models have also been developed but seem to over predict the rate of member failure. One issue is that probabilistic fracture mechanics models do not deal very well with the time to initiation which, whilst not being a random process, certainly manifests itself as one given the paucity of failure data. It would be a very valuable exercise to conduct another industry survey of recorded member failures in order to construct a database of failures similar to that which QRA practitioners use to predict the frequency of hydrocarbon releases.

In the current work, it was assumed that the probability of failure was related to the amount of fatigue life that had been ‘consumed’ for a given member. This approach is problematic in that if 100% of the life was consumed, then the member would be assumed to have failed. The approach was therefore adapted with the forward looking assumption that at each inspection interval, it was discovered that no members had failed, resulting in a Bayesian type updating of the original assumption relating probability of failure to fatigue life. The way this was done (for expediency’s sake) was to assume that if it was predicted that there was a probability of failure >80% for at least one member (and assuming an inspection revealed that none had failed) then the fatigue life was stretched such that that probability became 20%. It is acknowledge that this approach may seem somewhat arbitrary, but given the shortcomings in the precursor fracture mechanics calculations, and the lack of resources available to revisit the same calculations, the approach seemed reasonable.

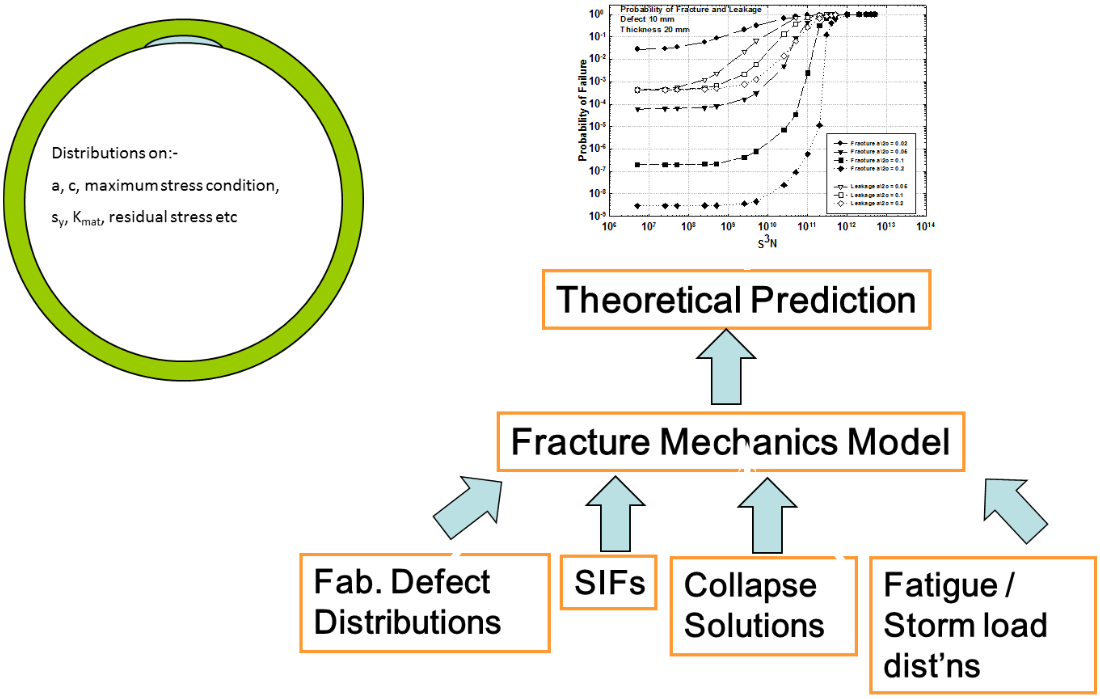


Figure 4 – Typical Approach for Theoretical Fracture Mechanics Prediction of Member Failure

An Assessment of Two Different Platforms

An assessment as described above was carried out for two platforms with very different characteristics from an asset integrity point of view. The first platform, Platform A had relatively high safety factors on structural strength, but relatively low fatigue lives. Conversely, Platform B had lower safety factors on structural strength but very high fatigue lives. The question posed was how would through-life reliability profiles look for the two different platforms?

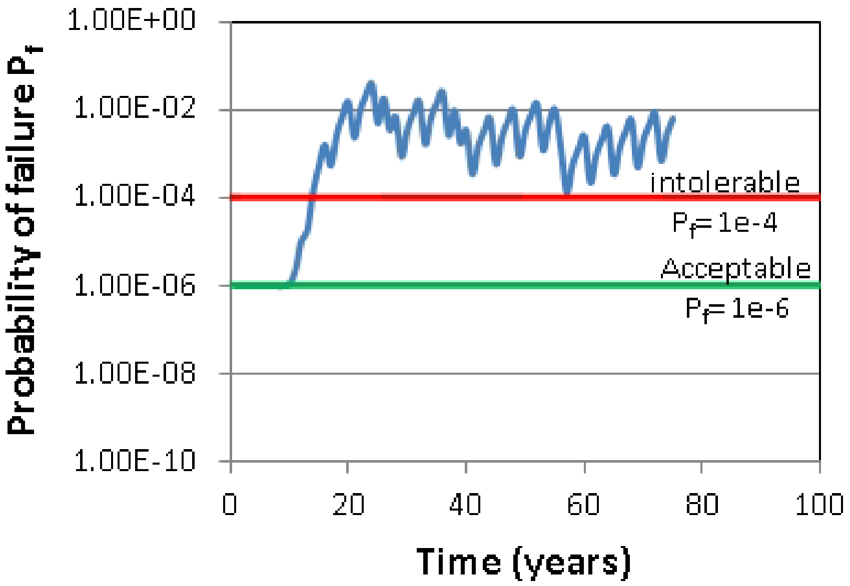


Figure 5 – Results of Assessment for Platform A – High Strength, Low Fatigue Lives

Figure 5 shows the results of probability of failure assuming four-yearly inspection. The effect of ageing, is that beyond design life, between the inspections, the probability of having several failed members becomes significant quite quickly. The probability of the platform being severely weakened due to multiple member failure is therefore high resulting in failure probabilities as high as one in one hundred years. Also plotted are the company thresholds for individual risk tolerability.

These results are highly dependent on the fracture mechanics models which are probably over predicting the failure rate of individual members. Notwithstanding that, it is clear that having an understanding of the possibility of multiple member failure is important. Also worth noting is that if this platform was to be operated beyond the design life, it would not be sufficient to quote a generic structural failure rate of 1×10^{-5} per annum in the QRA.

The results of the assessment for Platform B are shown in Figure 6.

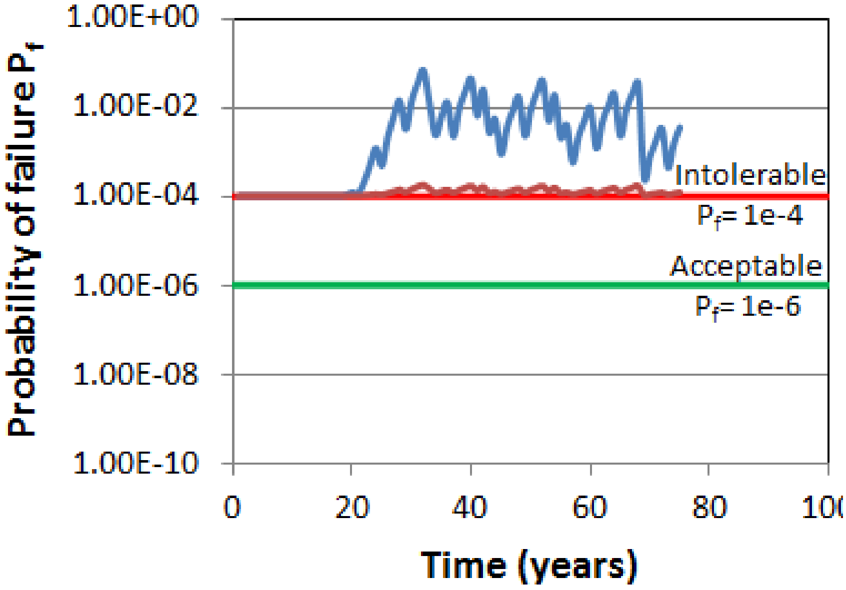


Figure 6 Results of Assessment for Platform B – Low Strength, High Fatigue Lives

The results show again that beyond design life, the probability of the structure being in a weakened condition between inspections is sufficient and the structure is sensitive to that damage. The result is that high collapse probabilities are predicted beyond design life. Once again, it would be inappropriate to cite a generic failure rate of 1×10^{-5} per annum for this platform.

Are Individual Structural Members Safety Critical?

The preceding examples demonstrate that the failure of some structural members could cause or contribute to a major accident. The structure itself is generally designated as a safety critical element, but is it possible to designate individual members or component parts of a structure as being safety critical in order that they receive the greater share of attention that SCE designation is intended to necessitate?

In the previous examples, we included thousands of analyses of the structure in weakened states. Just as is the case in a QRA, the overall likelihood of failure is a summation over all those possible conditions. In the field, however, if a member were to actually fail between inspections then the structure would actually be in that weakened condition. The risk associated with platform collapse would actually have increased. Moreover, is that the platform would continue in that condition until the next inspection identified that damage. This is shown schematically in Figure 7.

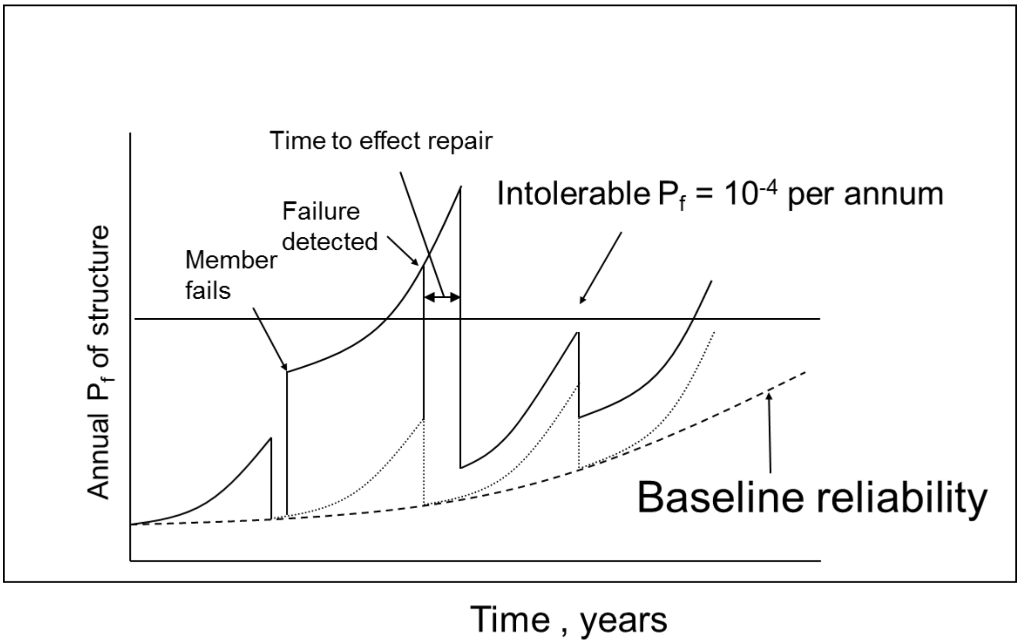


Figure 7 – Schematic of the probability of collapse of a structure if a structural member actually fails.

In Figure 7, we see that if an important member fails then the structure is weakened so that its probability of failure immediately increases dramatically. This increases with time as the uncertainty of the remainder of the structure increases, but the important point to note is that the risk may increase, sometimes quite significantly, and that the operator is unaware of this condition until the next inspection by which time the platform may have been subjected to several severe winter storms.

If the risk increases significantly, can we argue that we have managed risks to levels that are ALARP? Or as an analogue, would it be sufficient to monitor periodically for hydrocarbon leaks? Would both situations not lead to an unacceptable situation in which we are faced with *dangerous* and *undetected* situations?

Structural Monitoring

Structural monitoring for fixed offshore platforms can be relatively easily achieved. The principle is simple; accelerometers are placed on the topsides structure and the natural response frequencies of the first and second order sway and torsional modes are recorded. Any change in modal response can be used to indicate the presence of damage and sometimes identify where the damage is. Such a system enables the structure to be repaired as quickly as possible and would also inform as to the likely increase in the levels of risk exposure.

In the work reported above, we tested the hypothesis that if the structure is in a damaged condition that reduces the strength with an associated, significant increase in risk, then structural health monitoring will be able to detect it. We assumed that a structural monitoring system is capable of detecting changes in frequency of greater than 0.5% [8] and that for a given storm direction, the intolerable limit on strength reduction (in terms of its effect on risk and the company's individual risk tolerability criterion) was 0.46. We then plotted, for every case, what the reduction in strength and change in natural frequencies were. These are plotted below in Figure 8.

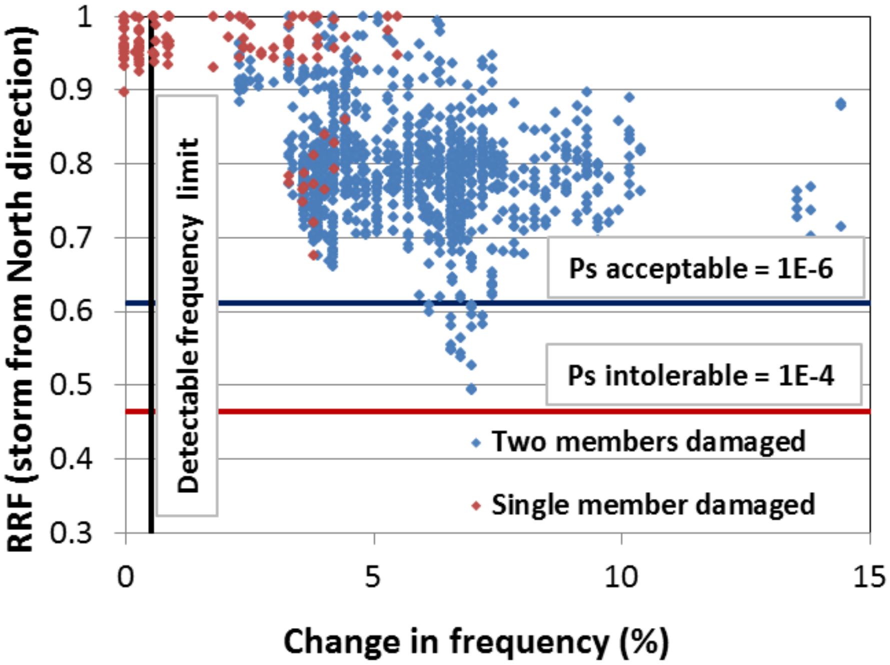


Figure 8 – Strength Reduction (RRF) and Change in frequency for all damaged cases for one storm direction (Platform A)

What Figure 8 (and others like it not shown herein) shows is that for thousands of analyses all of them that resulted in a significant increase in risk *were* detectable. Figure 8 shows that for this platform (A), for all single members failed, the risk of platform collapse is still in the acceptable region. The overall risk of platform collapse in the calculation was from multiple member failure due to low fatigue lives.

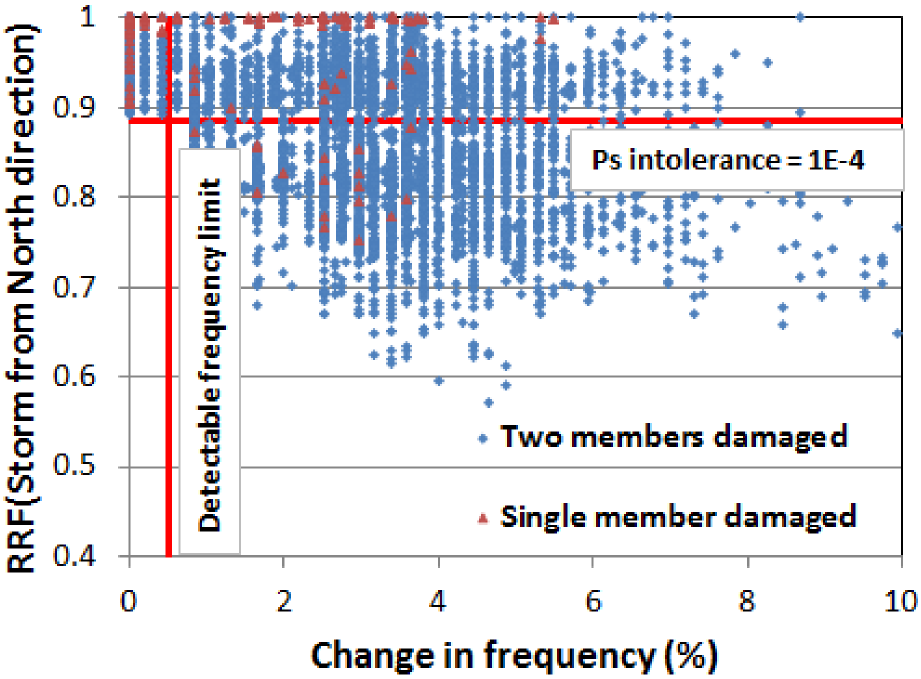


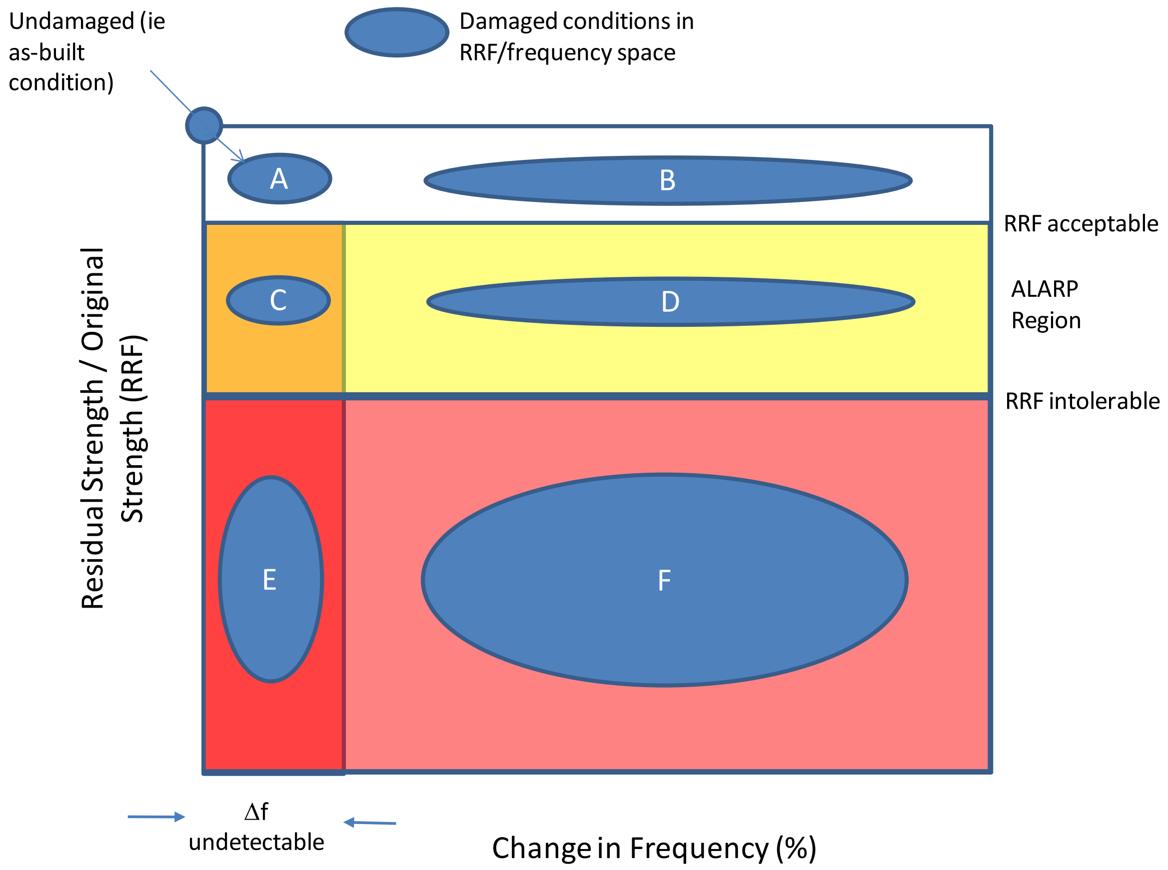
Figure 9 – Strength Reduction (RRF) and Change in frequency for all damaged cases for one storm direction (Platform B).

Figure 9 shows a similar plot for Platform B (low strength, high fatigue lives). One can immediately see from this plot that for most single members that fail, the risk of platform collapse is increased to intolerable levels. Whilst this platform is unusual in how low its strength is, it is far from unique.

In such a case, the risk to personnel would be intolerable. Can we claim to have managed these risks to ALARP if we have credible scenarios which remain undetected for several years?

Figure 10 shows the same ordinates of Figures 8 and 9 broken into regions.

An undamaged platform is at its original design strength and original frequency. The starting point for any platform is therefore the top left hand side. If a structural member is damaged, the strength will reduce and the frequency will increase. Each structural member damaged will map onto a point somewhere in one of the six regions marked A-F. These regions are described in more detail below.



- Region A. Member failure results in an undetectable change in frequency. The increase in risk is not significant (risk is still broadly acceptable)
- Region B. Member failure results in a detectable change in frequency. The increase in risk is not significant (risk is still broadly acceptable)
- Region C. Member failure results in an undetectable change in frequency. The increase in risk is significant (risk now falls within ALARP region)
- Region D. Member failure results in a detectable change in frequency. The increase in risk is significant (risk now falls within ALARP region)
- Region E. Member failure results in an undetectable change in frequency. The increase in risk is very significant (risk now falls within intolerable region)
- Region F. Member failure results in an detectable change in frequency. The increase in risk is very significant (risk now falls within intolerable region)

In several studies involving tens of thousands of damaged conditions, for various platform configurations MMI has never mapped a point into Regions C or E. Many points have been mapped into regions D and F.

What does this mean? Mapping a point into Regions D and F means that the failure of single structural elements will increase the risk of personnel to the ALARP region (Region D) or the intolerable region (Region F). Given this, and despite the fact that structural monitoring is being used more, it is somewhat surprising that structural health monitoring is still not commonly employed in the UKCS. If such a circumstance were possible for process safety related risks, the author would expect the situation to be treated very differently.

It is argued that if a fixed platform maps into regions D or F then we may only claim that risks have been reduced to ALARP if Structural Monitoring is in place. We would argue that members whose failure maps into those regions should be viewed as Safety Critical Elements. It could be more strongly argued that if points map into Region F, it is a legal requirement to install structural monitoring and adopt an adverse weather working policy including de-manning prior to extreme weather

Conclusions

- Previous work showed that the link between structural integrity analysis and the QRA is not consistent and, in general, of a poor standard in UK offshore safety cases.
- Advanced techniques are available for predicting the probability of structural collapse.
- As platforms go beyond design life, the uncertainty in their condition between inspection intervals increases.
- Techniques for predicting the likelihood of member failure need improving: Both theoretical models and industry data.
- If structural members fail, the actual risk exposure of personnel increases.
- A framework has been presented which would enable the designation of certain structural members as safety critical.
- It has been shown that for data derived to date, there would be no dangerous, undetected situations if a structural monitoring system were installed.

References

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