Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 11 (2013) 296 – 300

www.elsevier.com/locate/procedia

2nd International Through-life Engineering Services Conference

Risk Based Maintenance for Offshore Wind Structures

Feargal Brennan*

[a]School of Engineering, Cranfield University, Bedfordshire, MK43 0AL, UK

* Corresponding author. Tel.: +44 (0)1234 758249; *E-mail address: f.brennan@cranfield.ac.uk*

Abstract

Offshore wind is increasingly becoming the driver for Britain's wind power. Statistics released by the European Wind Energy Association (EWEA) this year confirm that the UK is consolidating its position as the world leader in the offshore wind sector, with 2.95 GW installed, or 59% of the EU total of the installed 5GW, compared to 921MW for Denmark, 249MW for the Netherlands and 380MW for Belgium. The emerging offshore wind sector is however unlike the Oil & Gas industry in that structures are unmanned, fabricated in much larger volumes and the commercial reality is that the sector has to proactively take measures to further reduce CAPEX and OPEX. Support structures need to be structurally optimised and to avail of contemporary and emerging methodologies in life-cycle structural integrity design and assessment. This paper focuses on methodologies to optimise life-cycle costs using probabilistic risk based design, inspection and maintenance approaches for offshore wind support structures.

Selection and peer-review under responsibility of the International Scientific Committee of the "2nd International Through-life Engineering Services Conference" and the Programme Chair – Ashutosh Tiwari

Keywords: risk; wind power; maintenance; life-cycle cost; optimised design

1. Introduction

This paper describes the use of inspection reliability information in fitness-for-service and criticality assessments for offshore structures. Assessments of components that have never been inspected should assume a defect distribution from manufacturing quality assurance reports taking into account any propagation of damage that might have occurred. By understanding how to incorporate Probability of Detection (POD) and Probability of Sizing (POS) information with associated confidence measures into damage modelling, operators can appreciate the benefit of conducting inspections and the resulting implications for quantitative risk assessments particularly where no defects are found.

The paper illustrates the use of POD and confidence levels for predicting remaining life due to corrosion and fatigue and also how to incorporate sizing statistical performance characteristics of the inspection system into remaining life assessments. In addition, the paper addresses the emerging trend towards monitoring with inspection and how operators and designers can benefit from future trends in structural health monitoring.

Nomenclature

ICON	Inter Calibration of Offshore NDT
NDT	Non Destructive Testing
POD	Probability of Detection
POS	Probability of Sizing
RBI	Risk Based Inspection
ROC	Reliability Operating Characteristics

2. Inspection Reliability

Inspection, NDT and monitoring equipment and procedures can result in data having varying degrees of accuracy. Certain NDT methods for example are very well suited to surface breaking defects but may be ineffective to inspect for sub-surface flaws. Equally, different systems may

2212-8271 © 2013 The Authors. Published by Elsevier B.V. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the International Scientific Committee of the "2nd International Through-life Engineering Services Conference" and the Programme Chair – Ashutosh Tiwari
doi:10.1016/j.procir.2013.07.021

be more accurate in detecting and measuring defects of a particular size and orientation compared to others. In order to assess the best method to use for a given application it has become standard practice to conduct inspection reliability trials so that performance between one technique and another can be compared.

The Offshore Industry has been aware of the need for an understanding of the performance of the overall NDT systems used in fatigue crack detection and sizing for some time. A large number of offshore structures consist of steel welded tubular joints, the greater part of which are underwater. About 15 years ago preparations were therefore made for a series of major underwater inspection trials through the ICON project [3].

ICON was approved for support by the EC through the THERMIE programme (DG XV11) and received industrial sponsorship from AGIP, British Gas, BP, Comite d' Etudes Petrolieres Marines, Elf Aquitaine, Elf UK Ltd, Health and Safety Executive, Saipem and Shell UK Exploration and Production. Additional support was also received for Offshore Trials from Shell and Elf. ICON has been able to satisfy most of these needs and demonstrated that adequate equipment is available for all the tasks considered and in most cases there is a choice.

Robustness of procedures and sensitivity to operator was investigated through testing in three onshore centres and two offshore sites. The mix of sites and operators and the use of repeat tests on certain parts of the library (called overlap POD) allowed the production of capability and reliability POD curves (the best and worst combined performances) and the combined POD/False Call graphs showing what is termed Reliability Operating Characteristics (ROCs). Crack sizing (POS) was also demonstrated to be possible in both laboratory trials and offshore sea trials.

2.1. Probability of Detection (POD)

For inspection performance trials, it is normal to have a large number of both cracked and uncracked components which are sectioned after the trials had been completed to establish the true crack size. Even for small samples this is an expensive exercise but the manufacture of genuine fatigue cracks in large tubular welded joints is extremely costly. For this reason it was necessary to implement the concept of a library of tubular welded joints.

The library, containing joints with well characterised cracks, could be maintained for a series of trials without the need for destructive sectioning. The setting up of the library and the trials procedures necessary for obtaining probability of detection (POD) information with a certain confidence level are described below.

It is not possible to consider assessing the performance of NDT systems on all cracks that might exist (the population). Instead a sample must be chosen which is representative of the population and of sufficient size to give a desirable confidence level in the result. All types of inspection will have an uncertainty regarding whether they will be successful. The measure of this uncertainty comes from blind trials on the sample and is often expressed as a Probability of Detection (POD) associated with a certain confidence level (C). The blind trials would be on a series of groups of representative defective specimens, of size N, and the simple experimental measure of POD would be the number of successful inspections (S) divided by the number of attempts (N), i.e. the individual values of measured POD (P) are the quotient S/N.

P is related to the lower bound true population value of POD (p) with a certain confidence level and has been given for example by Packman et al [4] as follows.

$$C = 1 - P^N \qquad (1)$$

Using equation (1) it can be found that for a confidence level of 95% and a lower bound population POD of 90% 29 defects would be needed in each group and 100% success in detection (P = 100%).

It would be possible to use a smaller number of specimens but in this case either the confidence level or the lower bound estimate of the population POD would have to be less. Take for example groups of specimens which are only five in number. If all five were successfully found, giving a measured POD of 100%, one could only have a 95% confidence of a population POD of about 50%. Fig. 1 below shows POD results from a trial conducted on three inspection techniques for offshore tubular joints.

The use of a 90/95% POD in structural integrity calculations will be illustrated later in this paper.

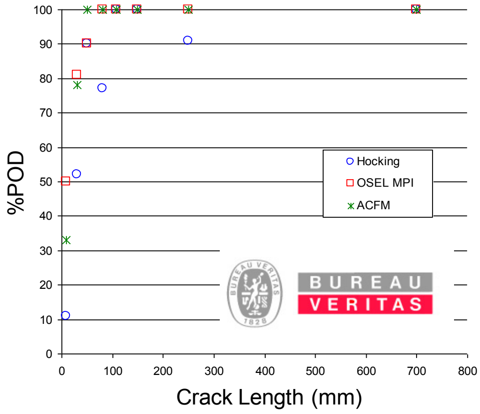

Fig. 1. Experimental POD Class B1 ICON Tubular Library

The use of a 90/95% POD in structural integrity calculations will be illustrated later in this paper.

2.2. Probability of Sizing (POS)

Inspection generally involves two distinct elements: 1) the ability to detect, and 2), the ability to size. POS is a measure of a particular inspection method's ability to accurately quantify the dimensions of a flaw or defect. It is less well known than POD but often just as important for damage assessment. Fig. 2 shows an example of a POS distribution.

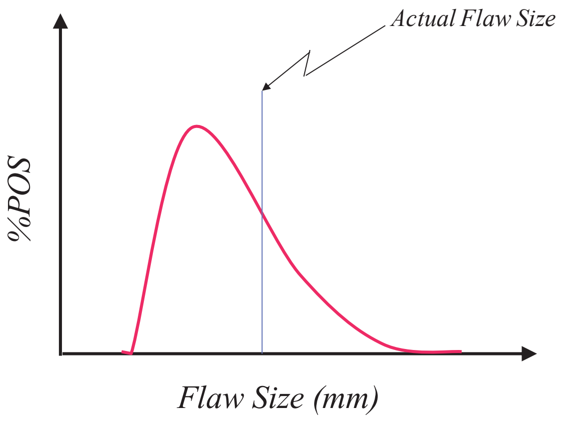

Fig. 2. POS Distribution

This is again obtained by performing blind inspection trials on a range of representative defects. Fig. 2 shows a distribution of measurements using one inspection method on a range of cracks having the same dimension. It shows that the method is inclined to under predict the actual flaw size and only over predicts the size in a minority of tests. This is useful information for the structural integrity engineer so that provision can be made in damage predictions knowing that the inspection method used is likely to be unconservative. Again this will be illustrated later in this paper.

3. Criticality & Defect Assessment

Reliability (or Risk) Based Inspection (RBI) is only applicable to components that have some damage tolerance, components that are designed for a finite life with little redundancy (e.g. electronic components, some valves, helicopter rotor blades etc.,) will use Risk Centered Maintenance (RCM) rather than RBI.

There is no such thing as a generic RBI strategy for all components and installations, strategy is dependent on Probability of Failure, Consequence of Failure, Damage Tolerance, Inspectability (including inspection reliability), Maintenance and Repair capability and strategy.

Ship and offshore structure are in general defect tolerant and are also generally quite repairable. This leads to a requirement to be able to assess the criticality of flaws and defects that might be detected after a period in service. In order to assess whether or not a flaw is critical the structural integrity engineer needs to understand the ability of the structure to resist further damage and the critical amount of damage that the structure can sustain before remedial action is required. BS7910 [1] and API 579 [2] were developed for welded steel piping and pressure vessels but are often used for defect assessment of flaws in ships and offshore structures. They use fracture mechanics based damage models that require detailed local stress analysis and knowledge of material fatigue and fracture parameters. The starting point is however an estimate of the size of the flaw. Those familiar with linear elastic fracture mechanics calculations will be aware that relatively small errors in initial flaw size can have very large consequences on the prediction of remaining life. Therefore, it is important that there should be a proper understanding of the degree of confidence in the inspection results. This is where the inspection reliability information becomes important. The following sections illustrate the use of inspection reliability information for three different scenarios.

4. Application of POD Data to Reliability Based Analysis for the Prediction of Corrosion

Presented below is a proposed approach for the inclusion of Probability of Detection (POD) data into Reliability Analysis for Corrosion Inspection Scheduling of offshore pipelines. This approach considers the defect growth with an assumed ‘as manufactured’ defect distribution as a starting point before any inspection has taken place. Determination of the as-manufactured defect distribution ties in with Quality Control procedures implemented by the manufacturers.

In the case of offshore corrosion, the defect growth rate will be defined by the corrosion model applied; in the example illustrated in Fig. 3 a constant corrosion rate is assumed. The aim is to use the ‘as manufactured’ defect distribution as a starting point for the analysis, which will be subsequently updated as actual inspection data becomes available. Fig. 3 below illustrates the ‘as manufactured’ defect distribution, defect growth pattern and the critical defect size, which in pipeline corrosion will be a percentage of through wall thickness of the pipe.

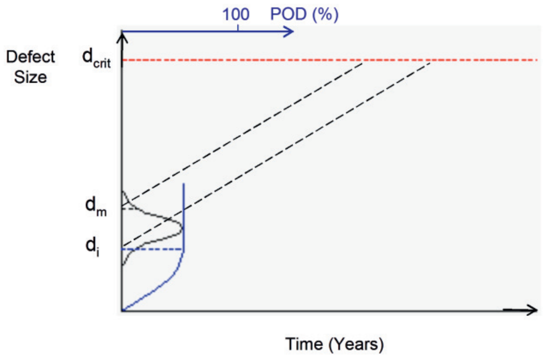

Fig. 3. Corrosion Prediction using POD

By taking an upper limit value from the as manufactured defect distribution (d_m) a limit state function can be applied based on reduction of wall thickness over time:

$$g(z) = K \text{ x } W \text{ x } T - d_m - r_d \text{ x } t \qquad (2)$$

Where:

K is the proportion of allowable wall thickness reduction

WT is the pipe wall thickness;

d_m is the initial defect size based on ‘as manufactured’ defect distribution;

r_d is the radial corrosion rate based corrosion models;

t is the projected time.

The level of uncertainty associated with the initial condition of the pipeline is likely to be relatively high due to the lack of in-service information. This level of uncertainty will continue to increase with time in service. Carrying out inspection of the site can reduce this uncertainty and resulting conservatism in the analysis. The inspection outcome can be detection of a defect, non-detection, or a false call.

In the case of a defect detection, the analysis is updated by applying a new initial defect size based on the results. The accuracy of sizing and probability of false detection should be considered at this stage.

In the event of non-detection, it is assumed the largest defect that could have just escaped inspection is present, i.e. the 90/95% defect size. In this way inspection will always result in a distribution to replace the as-manufactured defect distribution but will also reduce the uncertainty of the defect distribution.

The POD curve provides information on the likelihood of detecting defects of a particular size. When the POD analysis is carried out using the binomial method, defects are 'binned' into groups relating to a particular range of defect sizes, based on sample size. This enables a level of confidence to be associated with the results as outlined by Packman et al. [4], which can also be translated to a confidence level for the updated initial defect size.

Fig. 3 illustrates the concept of updating the initial defect size based on the POD results for the event of a 'non-detection' following an inspection. To illustrate the idea, the POD curve is shown superimposed on the defect growth curve. The updated initial defect size is related to the most likely minimum defect size that can be expected to be found by an inspection technique with a specified level of confidence (d_i).

5. POD in Fracture Mechanics Based Life Predictions

The table below shows the results of a POD trial for a particular inspection method for the detection of weld toe defects in Offshore Tubular joints. It can be seen that from the trial that 36% of flaws in the range 0 – 1 mm were detected, 76% in the range 1 – 2 mm and so on. A superficial use of such data might claim that the inspection method will detect flaws of a depth 2 – 3 mm 95% of the time however, this would be to misuse the statistical information. Remembering that a trial only represents a sample of the potential population and confidence in the trial results is dependent on the number of samples in the trial assuming of course the inspection procedure, flaws and component geometry and material are representative of the entire population.

In order to have a 95% confidence in a 90% POD value the number of samples required for the trial is:

$$N = \frac{\log(1-C)}{\log(P)} = \frac{\log(1-0.95)}{\log 0.9} = 28.4 \tag{3}$$

= 29 Specimens

This means that it is not possible to claim a 95% POD from a 2 – 3 mm flaw size with a high degree of confidence. The proper treatment of the POD trial information illustrated in Table 1 is to group the 2 - 3 and 3 - 5 mm range specimens together giving 29 defective specimens having a POD value of greater than 90%. i.e. the smallest crack having a 90/95% POD is 5mm.

Table 1. Example POD Trial Data

Defect Depth Range (mm)	0-1	1-2	2-3	3-5	5-7
No. of Defects	199	42	20	9	10
No. detected	72	32	19	0	10
% POD	36	76	95	100	100

This is a very important principle and more often than not one that is either not properly understood or ignored particularly by the manufacturers of inspection equipment.

Another important consideration is what to do if after an inspection no cracks are found? In this case it should be assumed that for remaining life prediction purposes that the maximum flaw that would have escaped a 90/95% POD is present in the structural detail i.e. the minimum 90/95% POD flaw size. In Table 1 above this is a 5mm deep flaw.

6. POD in Fracture Mechanics Based Life Predictions

As discussed earlier, inspection involves two distinct tasks: detection and sizing. Probability of Sizing (POS) is a measure of the ability to accurately measure a crack or flaw geometry and is very important in defect assessment calculations. Certain inspection methods characteristically undersize (under estimate size) particular defects or conversely may have a tendency to oversize (over estimate size). The extent to which this might happen should be understood when considering the use of inspection information into damage models. For example Fig 4 below shows a remaining fatigue life prediction based on an inspection result.

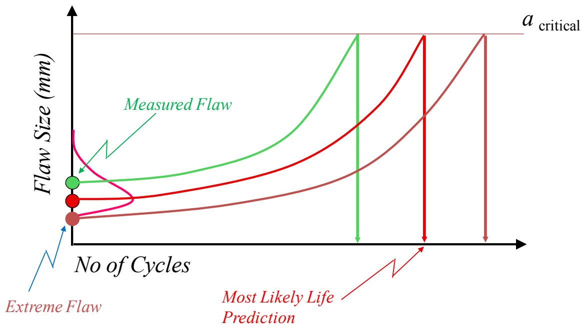

Fig. 4. Crack Propagation Prediction using POS

Firstly considering the as measured flaw, the crack is predicted to grow with number of cycles until it reaches a critical value determined by an appropriate failure criterion. However if the POS distribution for the inspection method is superposed onto the graph it is clear that the measured value is likely to be an overestimate of the actual flaw size. This then means that the number of cycles to failure will be greater and that there is a lower probability that the life could be greater or less than predicted. Knowing the actual POS allows a quantitative estimate of the probability that a certain life will be achieved.

7. Discussion

Inspection can be a costly process but it is a false economy not to properly understand the reliability of the inspection method and the implications of any inspection result. There are also significant cost benefits from conducting inspections with good POD and POS characteristics as these can then be used with appropriate damage models to plan further inspection intervals in a cost effective way. This is particularly important with the rising population of aging structures and installations that are increasingly being used beyond their original design life.

An emerging trend is the increased use of integrity Monitoring. As yet there are no equivalent measures of performance for displacement, stress, strain and even crack monitoring systems. POD and POS cannot be used in their current forms for such systems as inspection observations from a permanently deployed system is not statistically independent. This is a topic that needs further development in order to reap the full advantage of monitoring techniques.

8. Conclusions

POD should be used within fracture mechanics based criticality or defect assessments following inspection irrespective of whether or not a defect is found. It is imperative that a POD with a known confidence level is used and that the confidence level in the POD estimate is always reported. Levels of uncertainty should be calculated and reported quantitatively rather than the presentation of qualitative and often subjective assessments of reliability.

Inspection reliability information and its implementation need not be complicated

References

[1] BS 7910:2005, “Guide to methods for assessing the acceptability of flaws in metallic structures”, British Standards Institution, 2005.
[2] API 579-1 / ASME FFS-1, “Fitness-For-Service”, Second Edition, American Petroleum Institute, June 2007.
[3] Dover, W. D., Brennan, F. P. Karé, R. F and Stacey, A., “Inspection reliability for offshore structures”, proceedings of 22nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2003) 8-13 June 2003, Cancun, Mexico.
[4] Packman, P.F. et al, Metals Handbook, American Society for Metals 8th Edition Vol 11, pp 414-426.
[5] Sharp, J. V., Kam, J. and Birkinshaw, M., “Review of Criteria for inspection and Maintenance of North Sea Structures”, 1993 OMAE, Volume II, Safety and Reliability, ASME 1993.