11th World Congress on Structural and Multidisciplinary Optimisation
07th -12th, June 2015, Sydney Australia

Data based materials numerical modelling for FPSO safety and reliability optimization

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Abstract
Adequate modelling of material behaviour is required for the optimal operation and structural-environmental system safety and reliability of complex structural-mechanical systems. Herein floating production storage and offloading (FPSO) vessels are considered. These are used for offshore oil and gas exploration and exploitation activities. Critical components are the mooring lines, usually 8-12 per vessel. Typically they consist of a wire (or non-metallic) rope (some 100mm diam.) with steel chains at the upper (FPSO) end and on the seafloor. They are meant to keep an FPSO 'on-station' within close limits. Failure may result in rupture of oil production pipelines (risers) with possibly extreme environmental effects and high costs to operators and to industry. Recently the industry has funded ground-breaking research to improve understanding of the fatigue, wear and corrosion particularly of the upper chains. The present paper outlines the new mathematical-probabilistic models developed for prediction of chain corrosion and pitting, using data collected by the industry world-wide and in a set of major field research projects in Australia. Both forms of corrosion are functions of seawater temperature and local seawater pollution. The unique full-scale experimental work for the wear of full-scale chain links is outlined together with the on-going development of numerical models that will ultimately include associated finite element modelling. The outcomes provide much improved basic knowledge, and numerical and probabilistic modelling to permit improved optimisation of FPSO operations and overall risk management.

Keywords: Materials, safety, reliability, modelling, optimization.

1. Introduction

Floating Production Storage and Offloading (FPSO) vessels increasingly are being used for oil and gas related operations offshore and in particular in deeper waters, currently up to 3 km deep. The FPSOs are moored on-station using a set of mooring lines consisting, for various operational conditions, at the upper end of chain, then wire or non-metallic rope and, at the base more chain (Fig. 1). The reliability of this system is crucial as failure can incur rupture of risers and subsequent environmental and other damage [1]. Field inspection of the system is difficult, costly and generally unreliable owing to the harsh operational conditions prevalent in most operational areas. Early design and operational protocols were based on cold-water North Sea experience. This is reflected in most current requirements defined by Classification Societies [1]. These offer design guidance usually in terms of expected life in years, mainly for uniform corrosion loss, with a nominal allowance for wear, but offer little guidance about the separate effects of corrosion and wear and of the influences of climatic, environmental and operational conditions. As oil and gas exploration and exploitation increasingly has moved to warmer waters in tropical climates, such as in West Africa and the Timor Sea it has become evident, including from field observations, that improved material characterization is required for robust prediction of likely safe life and thus of optimal operational protocols including timely mooring replacement. This paper gives an overview of recent efforts in that direction, using field full-scale laboratory observations over extended time periods and built on analytical tools for corrosion and wear.

2. Optimal structural reliability

The lifetime reliability of any system can be represented by the development with time of the stochastic loading *Q(t)* acting on the system and the (deteriorating, monotonically decreasing) random variable capacity *R(t)* of the system (Fig. 2). For known time dependency of *R(t)* and with *Q(t)* also known from local climatic information, the probability of failure at any time *t* as given by [2]:

$$p_f\,|t = \iint_{D_f} f_Q(x).f_R(x)\,dx \tag{1}$$

where $f_Q(x)|t$ is the (conditional) probability density function for the load Q and similarly for R at t. As conventional, D_f represents the failure domain defined by the performance function (or Limit State function) $G(\mathbf{X}) = G(R,Q) = R\text{-}Q < 0$. Each mooring line composed of a chain of many links and also of wire rope is a classic 'series' system – one for which failure of any one (or more) components means failure of the overall system. It is therefore sufficient to consider only the simplest problem given by Eq. 1, without entering into 'systems' reliability considerations [2]. For the collection of mooring lines industry practice will not tolerate failure of more than one and thus the corresponding probability of a second mooring line failure given that one has occurred need not, to a first approximation, be considered.

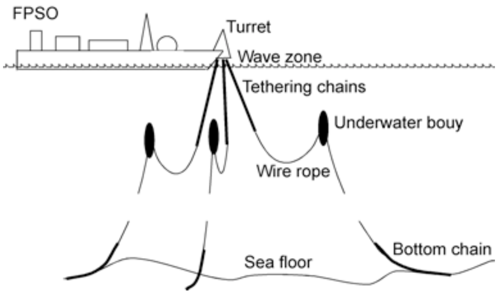

Figure 1: Schematic view of FPSO mooring system [3].

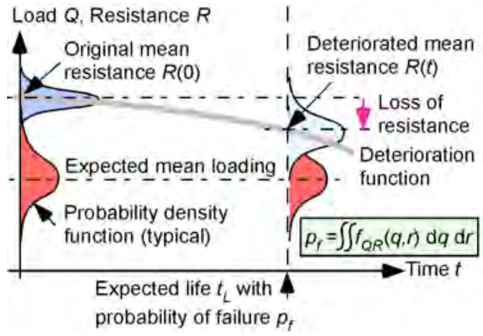

Figure 2: Development of structural deterioration with time, and the probability density functions for capacity and loading [3].

For an individual mooring line subject to corrosion the limit state function *G( )* is a function of time:

$$G(\mathbf{X},t) = R(t) - Q(t) < 0 = [A - a_p(t)] - Q(t) < 0 = [A - K(c(t))] - Q(t) < 0 \qquad (2)$$

where A is the cross-sectional area of the chain link or rope and a_p the area loss of the cross-section caused by corrosion *c(t)* and *K( )* is the functional relationship between $a_p(t)$ and *c(t)*. It is clear that *c(t)* is crucial to estimating the probability of failure at any time *t*.

Although it is common in the engineering literature to assume a constant 'corrosion rate' there is now much evidence that this is a misleading concept. The functional form for *c(t)* is highly nonlinear, particularly in the earlier years of exposure, as shown in Fig. 3 for general corrosion loss as a function of exposure time [4]. The parameters that describe this form have been determined for clean coastal seawaters as a function mainly of water temperature but also other parameters and, more recently, also for the influence of water pollution. The main effect of water pollution is on microbiologically influenced corrosion (MIC) resulting from the involvement of bacteria on the corrosion processes [5]. For long-term corrosion the effect is shown schematically in Fig. 3. It is clear that the assumption of a corrosion rate, that is a linear function passing through the origin, is a very poor approximation for the actual development of corrosion with time and hence for optimization decisions based on it. The determination of the actual corrosion behavior at a particular operational offshore site is therefore critical to making optimal reliability-based decisions.

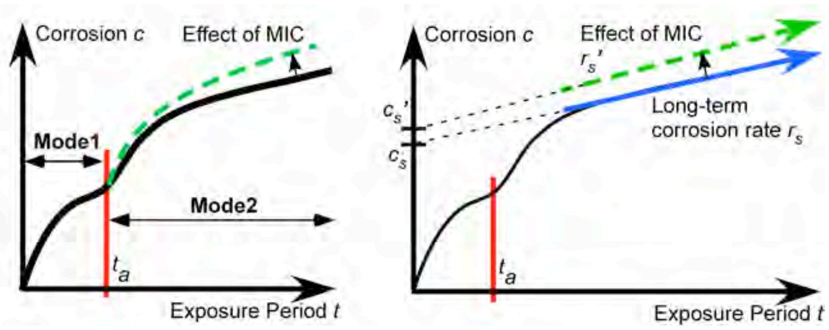

Figure 3: Typical bi-modal loss function for immersion corrosion in temperate waters, showing (some) model parameters and also idealized long-term trend and the effect of MIC [4, 5].

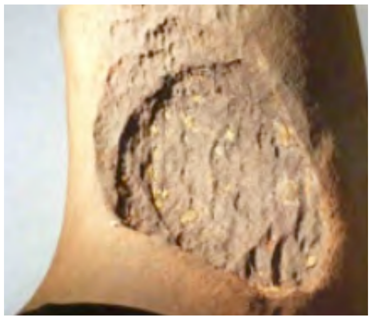

Figure 4: Field recovered chain links (76mm diam.) after surface cleaning showing highly varied local corrosion.

3. Field observations of mooring chain corrosion

Field experience in some geographical operational areas had shown that in some cases the mooring chains were found, during routine inspection, to show corrosion more severe than expected based on early, mainly North Sea, experience. In particular, in some cases of severe pitting corrosion were observed on mooring chain, with deep, elliptical pits of very considerable size on some chain links in the near-submerged splash zone (Fig. 4). It was thought this could be caused by higher water temperatures. As a result, a joint industry project (SCORCH: seawater corrosion of rope and chain) was established to investigate the corrosion rates of mooring chains (and wire rope) in tropical waters. This was an unprecedented cooperative effort between most of the leading oil and gas producers (the so-called 'majors'), contractors and materials suppliers.

The SCORCH JIP developed a data-base of worldwide corrosion measurements from in-service and retired mooring chain and wire rope from 18 FPSOs for chain and 13 FPSOs for wire rope from warm waters off South-East Asia, West Africa, the Gulf of Mexico, Brazil and the North West Shelf of Australia (Fig. 5) [6, 7]. Sample chain links taken from many of the chains recovered from industry operations were subjected to photogrammetric measurement, from which computer 3D images of chain links were constructed (Fig. 6). This allowed computer meshing, statistical analysis of the corroded surface and relatively simple estimation of maximum pit depth and also of pit size [7].

Figure 5: Locations of controlled tests or literature/in-kind data sites (★) and operational field data sites (★) [7].

Figure 6: Computer model of chain link constructed from photogrammetric data [7].

As shown in Figs. 4 and 6, the most severe corrosion was found, repeatedly, to be pitting corrosion, for example some 10-15 mm in depth and often 100-200mm or more in size after 7-8 years seawater exposure. In most cases the most severe corrosion occurred in the region around and just below the still water level. Such severe pitting was not observed in all cases. Where severe pitting corrosion was observed there was also evidence of black corrosion deposits within the pitted areas and strong hydrogen sulphide and other odours. Taken together, this suggests, but does not prove, the involvement of microbiologically influenced corrosion [8]. To investigate this possibility, water quality analyses were undertaken in the immediate vicinity of the chains showing severe pitting. This showed a high degree of correlation with the concentration of dissolved inorganic nitrogen (DIN) in the seawater and that has been strongly linked with MIC of steel in seawater [5]. This allowed estimation of the increase in long-term corrosion (cf. Fig. 3). It is noted that normal, natural, unpolluted ocean seawater has negligible DIN. Usually elevated DIN can be attributed to anthropological or industrial pollution, including that from oil drilling and recovery operations [9].

The observation that the most critical corrosion for chain links is that of pitting, permits simplification of the limit state function (Eq. 2) to represent the probability of the deepest pit $y(t)$ penetrating a given distance (d) into the chain link (or a wire rope):

$$p_f = P[G(\mathbf{X}) < 0] = P[d - y(t) < 0] \tag{3}$$

As visually evident from Fig. 6 and as also noted below, there is much variability in the maximum pit depth observed relative to all the other parameters involved, and this suggests that in addition to conventional reliability analysis the results also can be represented through application of Extreme Value theory. This is described in the next section.

For optimization, the key issue is the determination of the maximum acceptable probability of failure within an overall expected cost or expected cost-benefit analysis. Eqs. (1-3) provide the tools to determine the relationship between acceptable depth of pit penetration d and the corresponding probability of mooring line (and hence system) failure. This also will involve the probability of failure in axial tension for a given depth of pitting.

4. Site and laboratory corrosion tests

In addition to the examination of actual chains recovered from operations, a large series of controlled field tests was conducted over 3.5 years at selected sites around Australia. This program comprised some 388 chain coupon and chain link tests (and also 373 wire and wire rope tests), designed specifically to investigate the impact of sea temperature, depth, water velocity, oxygenation and steel grade. Also, laboratory tests were conducted to assess the effect of MIC, and the combined effect of corrosion and wear, of full-sized mooring chains. The details have

been described elsewhere [6, 7]. The results showed mainly uniform or general corrosion rather than pitting. The average corrosion rates for uniform corrosion were much lower than those for pitting, consistent with what has been found elsewhere.
These results added rigor to the field test results and confirmed that steel composition, location on a link and at the weld zone did not cause significant variations. The results also confirmed that corrosion of chains showed the bi-modal model characteristic (Fig. 3) and were consistent with the effect of seawater temperature, seawater oxygen content, water particle velocity, splash zone action and tidal zone wetting, all as expected from earlier work [4]. This is important as it indicates that other research results, for various steels, can be applied also for steel chains.

5. Extreme value analysis of corrosion pitting
For estimating the reliability of systems in which one random variable predominates, an extreme value analysis can be both useful and illustrative. There is a long history of applying it to pit depth data [10]. Usually, for pit depth, the so-called Gumbel extreme value distribution for the maximum pit depth measured on multiple areas or samples is used. The usual approach is to plot the pit depth data on a Gumbel plot [11]. It consists of one axis showing the reduced variate *w* that represents the cumulative probability, more formally given by the function $\phi(y_1)$, defining the probability that pit depth $y < y_1$ where y_i is a given value. If the data is truly Gumbel, a straight best-fit line can be constructed through the data. Typical pit depth data (85 pit depths across 25 chain links) are shown on the Gumbel plot in Fig. 7. It is evident immediately that the collected data does not all fit a straight line - only some of it does, as shown. In fact the deepest pits, those of most practical interest, are shown at the upper right and clearly do not fit the linear trend (or indeed any linear trend). This suggests strongly that they are part of a statistical population, with, most likely, a different probability distribution [2]. In turn this implies that the mechanism causing pitting is different in some way, a point noted earlier in a more general context [12]. In the present case it can be shown that this subset is more consistent with the Frechet extreme value distribution, as also found for other cases reported for a variety of exposure conditions [12]. The implication of this observation is that the random variable representation for pit depth *y* in Eq. (3) must be more complex than a simple random variable and must distinguish between deeper pits and shallower pits. This distinction has only recently been recognized [12] and the necessity to do so in reliability analysis has not been proposed previously.

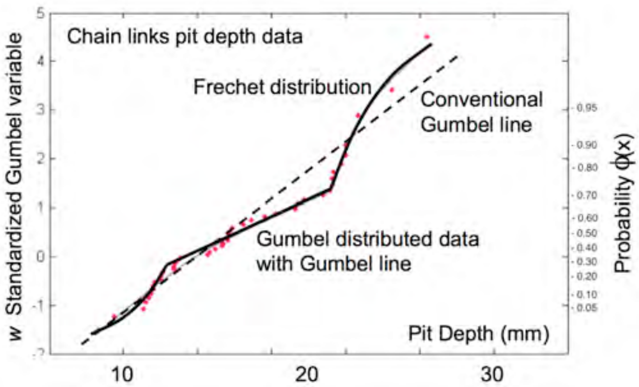

Figure 7: Gumbel extreme value plot showing typical data for pit depth. Data from [6].

6. Wear of mooring chains
Wear of mooring chains can, under certain circumstances, be the primary mechanism of degradation and potentially failure. The current level of codification regarding the analysis of wear on anchor chains is rudimentary [6, 7]. It uses an average annual loss of metal due to both corrosion and wear, without discrimination, and is based on empirical data and engineering experience. There is an extensive body of research for wear as caused by dry sliding and rolling contact [13], confined mainly to 'pin-on-disk' tests, but there is almost no information about the wear of chains in sea water.
It is known that wear can be the result of a number of different processes that can take place by themselves or in combination. Material is removed from the surfaces in contact through a complex combination of local shearing, ploughing, gouging, welding, tearing, and others [14]. Other major subcategories of wear include adhesive, abrasive, corrosive, surface fatigue, and deformation wear, as well as fretting, impact, erosion and cavitation. However, the modes of wear usually recognized for chain links are [6, 7, 15]:

- Adhesive (sliding) wear, in which interlink rotational motion cause wear at the crown of the chain (Fig. 8).
- Abrasive wear, where chain abrasion against objects including the seabed, ship hulls and other mooring components causes wear on the outer body of the chain link.

Figure 8: Adhesive (sliding) wear in the interlink zone.

Figure 9: Wear rig at The University of Newcastle, Australia, showing 5-link chain set under cantilever-applied static axial load and hydraulic oscillatory lateral loading system.

Of the various analytical models for wear, the Archard equation [14] is the best known and widely applied:

$$V = k/H \cdot N \cdot D \tag{4}$$

where V is the volume of material lost, N is the normal force between sliding contacts, D is the sliding distance, H is the hardness of the contacting materials and k is a dimensionless 'wear coefficient.' Laboratory test results show that typically k varies by several *orders* of magnitude [16] even with high metal compatibility and good lubrication conditions. This was found also in the results for wear tests on machined 0.5 inch diam. steel rods sometimes considered relevant to offshore chain wear [15] although these are known to substantially over-estimate wear compared with field observations. The changing topography of the contact surfaces in chains wear is a contributing factor (Fig. 8). In a desire to obtain data more relevant to actual mooring chains several wear tests were conducted as part of the SCORCH-JIP on full-scale stud-less chain links (76 mm nominal diam.) using the wear test rig shown in Fig. 9. It uses a static load for axial tension through a 1:10 ratio lever arm. The central link in the 5-link test specimen is displaced laterally by a hydraulic jack. The upper and lower links are held in place and are restrained from rotation. The angular changes are fixed by the lateral displacement.

Figure 10: Progression of wear on full-scale links as number of wear cycles increases (from left to right).

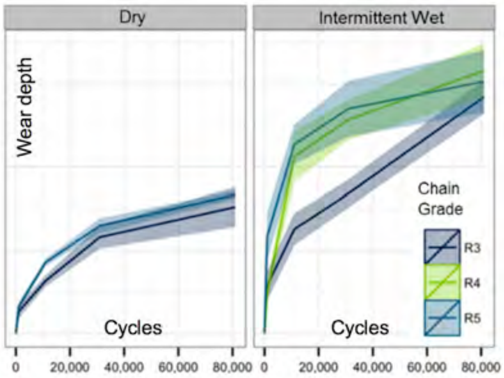

Figure 11: Wear as a function of number of cycles, steel grade and water lubrication [7].

Three grades of chain were tested under two lubrication conditions: dry and intermittent wet (simulating a 'splash zone' effect). Measurements of the interlink diameter at the crown of the chain link were taken at various times during the tests to monitor the progression of wear over time (Fig. 10). The bright metal is the worn contact surface of a chain link. A summary of wear test results is shown in Fig. 11. It is clear that wear is not a linear function of the number of cycles of loading as implied by Eq. 4, but it is consistent with earlier findings for small diameter bars [15]. The changing trend has been attributed to the effects of work hardening, the formation of patches of hard martensite, gradual accumulation of worn particles and the formation of protective films (mostly oxides) on the sliding surfaces [17]. Again, this departure from the usual assumption of linearity could have a major influence on prediction of likely service life and hence on the optimization of the strategies for safety management of FPSOs, particularly those operating in Tropical waters [18]. Similar differences are expected to arise in the wear of chains under other, relevant, conditions, including in the touch-down zone were abrasion from sands and rock could be significant, and in areas such as at the fairleads and in the splash-zone.

7. Optimization

Once improved understanding is reached of the mechanisms of corrosion and wear under the different conditions that may be involved, numerical modeling efforts based on much better theoretical and empirical foundations can commence in earnest, thereby opening up the possibility for robust optimization. For example, for structural optimization, say of chain possibly subject to long-term corrosion, one obvious choice for the objective function is minimization of Eqn. (1) subject to the constraints set by the requirement to meet the limit state function Eqn. (2) or, for the simplified problem, Eqn. (3). The design variables in this case would be terms such as the cross-sectional area A, with given random variables/processes for loading Q. Fundamentally this is an extremely simple optimization problem, however the accuracy with which it is solved depends much on the accurate representation of the applied mechanics 'within' it - in this case the evolution of corrosion with time and the associated uncertainties.

8. Conclusion

For the robust reliability optimisation of the design and the operation of infrastructure facilities it is necessary to have a sound understanding of the factors involved and their inter-relationship to form a sound basis for the development of analytical models. Such models are the essential backbone for robust optimization. It was shown that the processes and hence the models for time dependent corrosion and maximum pit depth are much more complex than conventionally assumed by a simple corrosion rate. Similarly, it was shown that for wear of chains the behaviour is not as simple as predicted by conventional wear models. The results obtained are considered ground-breaking for industry and expected to lead to revisions of design codes and optimal operational practices.

9. Acknowledgements

The authors acknowledge the support of the Australian Research Council and the SCORCH-JIP. The material presented herein is in the public domain and is not part of the privileged information available only to SCORCH-JIP participants. The opinions and analyses presented herein are those of the authors. More details about the SCORCH-JIP are available at *www.amogconsulting.com/dev/index.php/**scorch-jip***

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