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Reliability based optimization of inspection and maintenance schedules for offshore jacket structures subject to marine corrosion

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Abstract: Offshore structures are subject to different types of marine corrosion leading to fatigue which may ultimately result in a collapse of the entire structure. In reality, these catastrophic failures rarely occur due to the application of protective coatings and regular inspection and maintenance. However, these inspections are time intensive and costly, which is why an optimized schedule is desired. This work proposes a reliability based optimization of the inspection intervals using the survival signature. The survival signature is a novel tool for the reliability analysis of systems and networks. Jacket structures are built from three basic components: legs, bracings, and chords. This allows for an easy translation of the physical structure into a system based model as required by the survival signature. Components are grouped in types by corrosion zones (submerged, splash, atmospheric). Using the survival signature, the reliability of the jacket structure is computed by Monte Carlo simulation. Based on the system reliability the inspection and (if required) maintenance schedules are optimized, significantly reducing effort and cost. The main advantage of the proposed technique over traditional methods stems from the separation of structural and probabilistic information in the survival signature. This allows to efficiently analyze the same structure in varying locations where different strengths of marine corrosion can occur.

Keywords: reliability, survival signature, optimization, simulation, corrosion.

1. Introduction

Offshore jacket structures have wide applications in areas such as the production of oil, gas or wind energy. These structures operate in a marine environment and are therefore subject to complex degradation effects such as corrosion which can, when ignored, lead to catastrophic failures. In reality, these failures rarely occur due to the application of protective coatings and other corrosion prevention systems (LaQue 1975). However, even after application of protective measures, structures must be regularly inspected and maintained as these protections only last for a limited time. Performing inpection and maintenance is a costly and time consuming task, which is why optimizing the schedules can result in large cost reductions while keeping the risk of structural collapse low.

This paper expands on a method presented by Regenhardt et al. (2018) where the survival signature (Coolen and Coolen-Maturi 2012) was applied to compute the reliability of an offshore jacket platform. Since jacket stuctures are built from welding together components such as legs and bracings, they can be easily transformed into a system representation as required by the survival signature. In this work, the survival signature is computed by performing a full pushover analysis of the structure, where the previous study was based on deducing the survival signature from a simplified fault tree representation of the system. Though initially higher in computational effort, the resulting accuracy in the survival signature pays off during the reliability analysis. In addition, the resulting system reliability is used to optimize inspection and maintenance schedules of the structure based on costs and reliability constraints.

The paper is structured as follows. First, the concept and theory of the survival signature is presented. The next, section briefly introduces the different corrosion zones applied in this work. In the following section the survival signature is applied to compute the reliability of a simple jacket structure. Section 5 presents the optimization of the inspection and maintenance cycles, followed by concluding remarks and perspectives into future research.

2. Survival Signature

The survival signature (Coolen and Coolen-Maturi 2012) is a tool for the quantification of system and network reliability based on the system signature (Samaniego 2007).

Consider a system with m components. The state vector is defined as $\underline{x} = (x_1, \ldots, x_m)$, where $x_i = 1$ and $x_i = 0$ indicate if a component is in a working or in a failed state. As such, the state vector represents the state of the individual components. The state of the full system is obtained by evaluating the structure function $\varphi(\underline{x})$ for the state vector. The structure function yields 1 if the system is working or 0 if the system has failed. The structure function is defined based on the problem at hand as the definition of a working system changes with the type of analysis. Calculating the survival signature for l out of m components working is then defined as the following combinatorial problem:

$$\Phi(l) = \binom{m}{l}^{-1} \sum_{\underline{x} \in S_l} \varphi(\underline{x}). \tag{1}$$

The survival signature is easily extended to systems with multiple component types. Consider a system with K component types, m_k components per type $k\,(k = 1, \ldots, K)$ and l_k out of m_k components per type in a working state, the survival signature becomes

$$\Phi(l_1, \ldots, l_K) = \left[\prod_{k=1}^{K} \binom{m_k}{l_k}^{-1} \right] \times \sum_{\underline{x} \in S_{l_1,\ldots,l_K}} \varphi(\underline{x}). \tag{2}$$

Efficient computation of the survival signature is not a trivial task. Most complex systems are built from a large number of components and component types such that a full evaluation of all combinations is infeasable. A new approach attempting to reduce the high computational demand of the survival signature by eliminating trivial (known) parts and then approximating the remaining entries using Monte Carlo simulation can be found in Behrensdorf et al. 2019.

2.1. Survival Function

Based on the survival signature, the survival function is defined as

$$P(T_s > t) = \sum_{l_1=0}^{m_1} \ldots \sum_{l_k=0}^{m_k} \Phi(l_1, \ldots, l_K) P\left(\bigcap_{k=1}^{K} \{C_t^k = l_k\} \right). \tag{3}$$

This function gives the probability that a system is still working at time t, in other words the reliability of the system. The equation clearly shows the separation of structural information (survival signature on the left) and probabilistic information about component failures (right). This is beneficial as it allows to analyse the system once ahead of the reliability analysis instead of having to re-evaluate the structure every step of the way as with traditional techniques such as fault tree analysis.

Additionally, this makes it possible to efficiently run multiple failure scenarios against a system. In the context of offshore structures, the same design might be operated on different coast subject to vastly different strengths of corrosion. By nature of the survival signature, the structure must only be evaluated once in order to analyse all types of different scenarios.

If the failure time distribution of the components of type k are independent and have a known CDF $F_k(t)$, the survival function can be evaluated analytically by using

$$P\left(\bigcap_{k=1}^{K} \{C_t^k = l_k\} \right) = \prod_{k=1}^{K} \left(\binom{m_k}{m_l} [F_k(t)]^{m_k - l_k} [1 - F_k(t)]^{l_k} \right) \tag{4}$$

In more complex cases one must resort to simulation techniques. For examples of simulation methods using the survival signature see Patelli et al. 2017 or Behrensdorf et al. 2019.

3. Corrosion

This section introduces the different marine corrosion zones applied in this work. Corrosion of steel structures in seawater is typically divided into five zones with varying intensities:

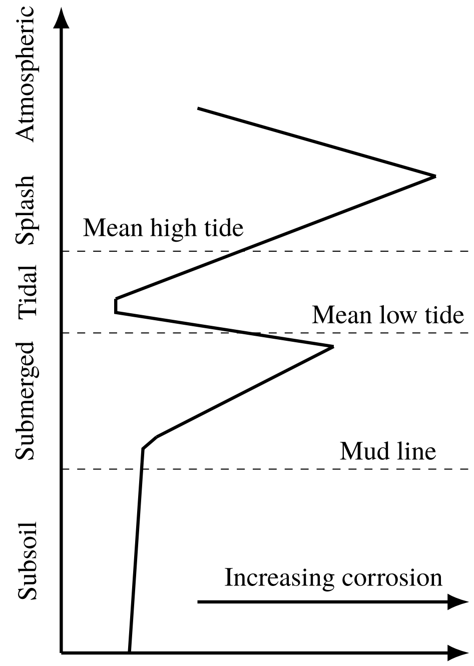

Figure 1. Relative thickness loss in different corrosion zones.

1. Atmospheric zone
2. Splash zone
3. Tidal zone
4. Submerged zone
5. Subsoil

A qualitative representation of the corrosion effect in these zones is illustrated in Fig. 1. For simplicity reasons, this work only consideres three zones: the submerged zone, the tidal/splash zone and the atmospheric corrosion zone, although inclusion of additional zones is trivial.

Typical corrosion rates for the zones are displayed in Tab.1 (Melchers 1999).

Table 1. Typical marine corrosion rates.

Zone	Corrosion rate (mm year^{-1})
Submerged	0.08
Tidal/splash	0.10–0.25
Atmospheric	0.05–0.10

4. Numerical example

The structure considered in this work is an offshore jacket platform as displayed in Fig. 2. For simplicity a 2-dimensional model is used. Note that the techniques presented here directly translate to the 3-dimensional case.

The structure is 68.58 m high, 21.76 m wide at seabed level and 8 m wide at the top. It is designed to carry a top load of 1250 t. The foundation at seabed level is considered as fixed support. All structural components, i.e. legs, chords, and bracings, all share the same material parameters with

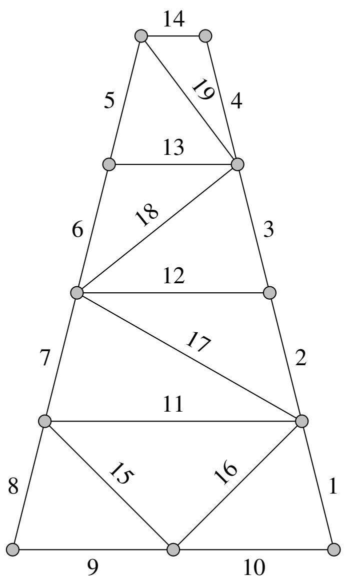

Figure 2. Structure of the jacket with labeled components.

Table 2. Component types for the jacket structure shown in Fig. 2.

Type	Components	Zone
1	1, 2, 7, 8, 11, 12, 15, 16, 17	Submerged
2	3, 6, 18, 13	Tidal/splash
3	4, 5, 19	Atmospheric

$E = 205\,\text{GPa}$, $\nu = 0.3$ and $\rho = 7850\,\text{kg}\,\text{m}^{-3}$. This structure is taken from Punurai et al. (2018). The platform is affected by marine corrosion. The first and second level from the bottom are assumed to be fully submerged at all times while the third level is in the tidal/splash zone. The top most level is considered to be under atmospheric corrosion only. Corresponding to this, the components are separated into three types as displayed in Tab. 2.

4.1. Computation of the survival signature

In order to compute the survival signature, the structure function has to be defined. In this work, we evaluate the structure using a displacement controlled static pushover analysis. The analysis is performed in OpenSees (McKenna et al. 2009). Starting from an initial displacement of 0 m, the displacement is increased by 0.001 m at each step until the structure collapses and the base shear forces are recorded. Figure 3 shows a typical pushover curve.

A structural failure occurs when the maximum base sheer resulting from the pushover analysis exceeds the design capacity of 180 000 kN.

This pushover analysis is performed for every combination of working/failed components in the survival signature. For computational efficiency, we assume that the structure immediately collapses if any part of the legs (one or more of the components 1, 2, 3, 4, 5, 6, 7, 8) has failed.

4.2. Reliability analysis

Before the inspection and maintenance schedule can be optimized, the reliability of the system is required. To begin with, failure times are generated for each component. Failure times for components of the same type are drawn from the same distributions. The assumed distributions for the different component types are shown in Tab. 3. As this study serves as a proof of concept to show how the survival signature can be applied to structural probals, the failures are modelled by simple log-normal distributions.

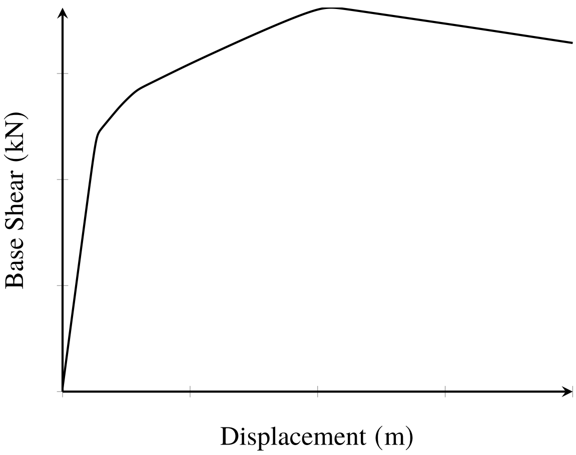

Figure 3. Typical pushover curve showing base shear over lateral displacements

Table 3. Parameters.

Component type	Distribution
1	$LN(\mu = 3.5,\ \sigma = 0.125)$
2	$LN(\mu = 3,\ \sigma = 0.225)$
3	$LN(\mu = 3.55,\ \sigma = 0.15)$

Note, that the chosen distributions are loosely based on the corrosion rates shown in Tab. 1 and are not a representation of a real world process. In a more extensive study, the corrosion should be modelled by accurate models, preferebly using data (Melchers 1999; Qin and Cui 2003).

The survival function (see Eq. 3) is computed using Algorithm 2 as presented in Patelli et al. (2017) yielding the reliability of the jacket structure as seen in Fig.4. Without inspection and maintenance the reliability of the structure reaches zero after approximately 30 years.

5. Reliability-based inspection and maintenance schedule optimization

Inspection and maintenance is performed at regular intervals t_i in this study. The quality of inspection and repair is denoted by q_1, q_2 and q_3 for the respective component types. Thus, the vector of design variables is $x = [t_i, q_1, q_2, q_3]$.

During inspection components are repaired/replaced only if the following equation evaluates as true

$$\frac{t_m}{t_f} >= 0.5 + (1 - q) \cdot 0.4, \tag{5}$$

where t_m is the time of maintenance, t_f is the component failure time and q is the inspection quality level. A quality of $q = 0$ means that component failures are only detected if the component life has exceeded 90 % of it's expected life. Conversely, with a quality of $q = 1$, maintenance will be performed after 50 % of the component's life.

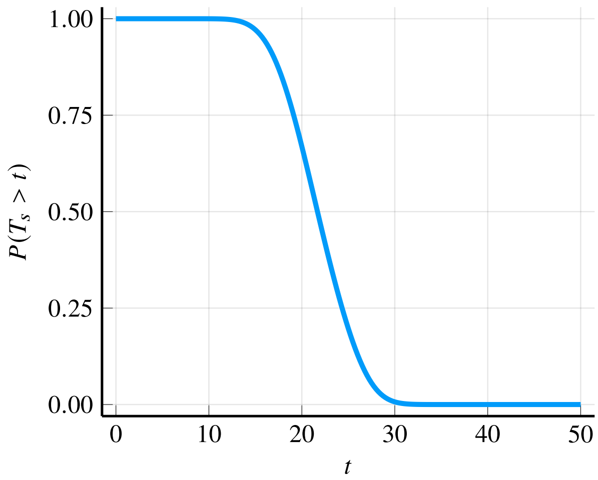

Figure 4. Reliability of the offshore jacket structure without inspection or maintenance.

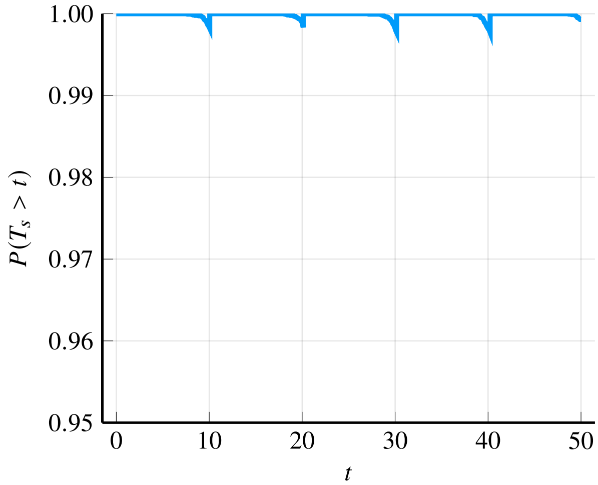

Figure 5. Reliability of the offshore jacket structure with optimized maintenance intervals.

The cost of inspection increases with the quality as defined by

$$C_m(x) = \begin{cases} c_{m_1} \exp(q_1), & \text{for } i = 1 \\ c_{m_2} \exp(q_2), & \text{for } i = 2 \\ c_{m_3} \exp(q_3), & \text{for } i = 3 \end{cases} \tag{6}$$

where c_{m1}, c_{m2} and c_{m3} are coefficients weighting the contribution of a single component of the respective type to the total inspection and maintenance costs. This way, the costs increase exponentially with the quality of the inspection.

The total costs associated with inspection, maintenance and failure are defined as

$$C(x) = C_m(x) + C_f(x) \tag{7}$$

where the cost of failure $C_f(x)$ is based on the minimum of the reliability over the time of operation times a constant defined as

$$C_f(x) = (1 - \min(P(t, x))) \cdot c_f. \tag{8}$$

Recurring costs of operation as well as the initial acquisition costs are neglected in this work as they are independent of the maintenance schedule.

In the next the design variables are optimized in order to minimize costs subject to constraints on the reliability of the system. As such the optimization problem can be defined as

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & C(x) \\ \text{subject to} \quad & 0 \leq x_1 \leq 50, \\ & 0.8 \leq \min(P(t, x)) \leq 1.0. \end{aligned} \tag{9}$$

In other words, find the maintenance interval and inspection quality associated with the lowest cost over a period of operation of 50 years where the system reliability never drops below 0.8.

Since this is a constrained optimization problem, *Constrained Optimization By Linear Approximation* (COBYLA) (Powell 1994) is used to find a solution. As a gradient free optimization algorithm it suited for this problem, as the complexity of the underlying model prevents efficient computation of gradients. The implementation used is included in the Nlopt library (Johnson 2020) whiche includes slight modifications of Powell's original algorithm. Specifically, the Nlopt interface for Julia (Bezanson et al. 2017) is used. Note, that this is only one of several applicable algorithms.

Solving the problem using an initial maintenace interval of $t_m^0 = 15$ years and initial inspection quality levels $q = [1.0, 1.0, 1.0]$ based on cost factors $c_m = [1500, 1000, 500]$ and a cost of failure $c_f = 500000$ results in an optimal interval of 10.055 years and inspection quality levels of $q = [0.703, 0.999, 0.982]$.

The reliability only slightly dips below 1.0 in the months before the next inspection. As expected, the lowest quality of inspection is applied to component type 1 (submerged) due to the associated higher cost. At the same time, because components in the tidal/splash zone have the highest corrosion rate, the best level of quality is applied to the inspection. The reliability over the whole operational period is presented in Fig. 5.

6. Conclusion

This study presented a new approach to the optimization of corrosion inspection and maintenance intervals for offshore jacket structures based on the survival signature. The survival signature captures the structural properties of the system and is computed based on a static pushover analysis. This works exceptionally well due to the component based nature of the jacket structure. Using the survival signature, the reliability of the system is calculated and used as a constraint in an optimization to find the optimal intervals. The separation of structural and probabilistic information of the survival signature has powerful implications on the application as it allows to optimize one structure for use in varying locations with vastly different environmental properties without having to reevaluate the structural properties. This way, a globally operating company could efficiently optimize maintenace schedules for the same model of a jacket for different locations without needing repeated numerically demanding structural analyses.

In the future, closer attention must be paid to the modeling of the corrosive behaviour and additional failure mechanics. Since the goal of this work is to prove the applicability of the methodologies developed in network/system analysis to the structural problems, the modelling of the failures is kept relatively simple. Additionally, the application of global optimization algorithms should be investigated in order to avoid ending up in a local minimum.

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References

Behrensdorf, J., Broggi, M., and Beer, M. (Sept. 2019). "Reliability Analysis of Networks Interconnected With Copulas". In: *ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg* 5.4. ISSN: 2332-9017. DOI: 10.1115/1.4044043.

Bezanson, J. et al. (2017). "Julia: A fresh approach to numerical computing". In: *SIAM review* 59.1, pp. 65–98. DOI: 10.1137/141000671.

Coolen, F. P. A. and Coolen-Maturi, T. (2012). "Generalizing the signature to systems with multiple types of components". In: *Complex Systems and Dependability*. Ed. by W. Zamojski et al. Berlin: Springer, pp. 115–130.

Johnson, S. G. (2020). *The NLopt nonlinear-optimization package*. URL: https://github.com/stevengj/nlopt.

LaQue, F. L. (1975). *Marine corrosion: causes and prevention*. John Wiley and Sons, Inc., New York.

McKenna, F., Scott, M. H., and Fenves, G. L. (2009). "Nonlinear finite-element analysis software architecture using object composition". In: *Journal of Computing in Civil Engineering* 24.1, pp. 95–107.

Melchers, R. E. (1999). "Corrosion uncertainty modelling for steel structures". In: *Journal of Constructional Steel Research* 52.1, pp. 3–19.

Patelli, E. et al. (2017). "Simulation methods for system reliability using the survival signature". In: *Reliability Engineering & System Safety* 167, pp. 327–337.

Powell, M. J. (1994). "A direct search optimization method that models the objective and constraint functions by linear interpolation". In: *Advances in optimization and numerical analysis*. Springer, pp. 51–67.

Punurai, W. et al. (2018). "Adaptive meta-heuristic to predict dent depth damage in the fixed offshore structures". In: *Safety and Reliability–Safe Societies in a Changing World*. CRC Press, pp. 1143–1149.

Qin, S. and Cui, W. (2003). "Effect of corrosion models on the time-dependent reliability of steel plated elements". In: *Marine Structures* 16.1, pp. 15–34.

Regenhardt, T.-E. et al. (2018). "A Novel Application of System Survival Signature in Reliability Assessment of Offshore Structures". In: *International Conference on Intelligent Computing & Optimization*. Springer, pp. 11–20.

Samaniego, F. J. (2007). *System signatures and their applications in engineering reliability*. Vol. 110. International Series in Operations Research & Management Science. Springer US.