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Influence of structural deterioration over time on the optimal time interval for inspection and maintenance of structures

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ABSTRACT

The influence of the time variation of the structural demand and/or of the structural capacity on the optimal time interval (based on a cost–benefit analysis) for inspection and maintenance of offshore structures is analyzed. Reliability is expressed in terms of the expected number of failures over a time interval by means of closed-form mathematical expressions which consider the structural degradation. The mathematical expressions are incorporated into the cost optimization formulation. Three scenarios are considered: (1) structural demand (for a given intensity) varies in time, while structural capacity remains constant, (2) structural capacity deteriorates over a time interval, while structural demand remains constant, (3) both structural capacity and structural demand vary simultaneously over time. The optimal time interval for inspection and maintenance corresponds to the lowest cost of inspection, repair and failure. The cost optimization is applied to an offshore jacket platform. The damage condition is given by the fatigue crack size at critical joints. It is shown that in order to estimate the optimal time interval for inspection and maintenance of the structure, it is necessary to take into account the variation in time of both its structural capacity and its structural demand (case 3); if one of them were ignored, the optimal time interval could be overestimated.

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1. Introduction

Structures are subjected to loads that can lead to degradation of the structural mechanical properties as time goes by, which leads to the decreasing of the structural capacity while the structural demand increases. As a consequence, the structural reliability is modified; therefore, it is convenient to develop tools oriented to evaluate the structural reliability considering that the structural capacity and/or the structural demand change(s) over time. After the structural reliability is known, an optimization analysis can be applied in order to find the optimal time interval for inspection and maintenance of the structure. The results of the optimization analysis will depend on the hypothesis made about the variation in time of the structural capacity and of the structural demand.

To establish an optimization model, Forsell [1] formulated the problem by minimizing the total cost. The problem has been studied by using probability-based methods [2]. Later, reliability formulations were introduced into probability-based design codes [3–8] and optimal design criteria were developed on the basis of probability concepts [9–13]. During the last fifteen years several authors have applied the concept of time-dependent reliability index to optimize the life cycle of deteriorating structures without structural maintenance [14–16], as well as with structural maintenance [16]. Later, maintenance programs for existing structures using the concept of multiobjective optimization were developed considering different optimization objectives: i.e., (a) minimizing the maintenance cost and maximizing the load-carrying capacity and durability [17], (b) minimizing the cost and maximizing the structural performance [18], (c) minimizing the maximum condition index, maximizing the minimum safety index, and minimizing the present value of cumulative maintenance cost [19–21], and (d) minimizing the maximum probability of failure, maximizing the minimum redundancy index, and minimizing the life-cycle cost [22]. A criterion to find optimal time intervals for maintenance based on multiobjective optimization which considers confidence factors obtained by means of closed-form expressions, damage index and the expected cumulative total cost of structures with degrading structural properties, has been developed [23]. Recently a generalized probabilistic framework for optimum inspection and maintenance planning that maximizes the expected service life and minimizes the total life-cycle cost has been formulated [24].

For the particular case of offshore structures, the degradation of structural properties is mainly due to fatigue phenomena caused by waves continuously acting on the structures. The mechanical deterioration caused by fatigue is reflected by cracking of the tubular joints, giving place to a decrease of the resistance capacity of the structural system, and as a consequence, an increase in its

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structural demand (for a given maximum wave height). The idea behind inspecting an offshore structural system is to detect the presence and growth of size cracks, in order to perform the necessary repairs and maintenance to the structure later on. Several authors have developed inspections and maintenance plans for offshore structures: (a) based on risk and reliability of welded connections subject to fatigue [25–27]; (b) using methodologies that take into account fatigue sensitivity analyses in steel joints [28]; (c) implementing simplified approaches and using practical design parameters such as fatigue design factors [29] and/or reserve strength ratios [30]; (d) considering the damage caused by fatigue, buckling and dents on structural elements [31]; and (e) using Bayesian techniques [32].

The main objective of the present study is to analyze the influence of the time variation of the structural demand and/or of the structural capacity on the optimal time interval (based on a cost–benefit analysis) for inspection and maintenance of offshore structures. Three scenarios are considered: (1) structural demand (for a given intensity) varies in time, while structural capacity remains constant, (2) structural capacity deteriorates over a time interval, while structural demand remains constant, (3) both structural capacity and structural demand vary simultaneously over time.

The optimal interval for inspection and maintenance corresponds here to the lowest total cost associated with inspection, repair and failure, considering risk and reliability of the structure.

The difference between the present study and those mentioned above is that in this paper reliability is expressed in terms of the expected number of failures over a time interval by means of simplified closed-form mathematical expressions that take into account the structural deterioration over time. None of the methods above has solved the problem by means of this simplified approach. The mathematical expressions are then incorporated into the cost optimization formulation. Besides, it is demonstrated that for estimating the optimal interval of inspection and maintenance of a deteriorating structure, the variation in time of both structural capacity and structural demand (for a given maximum wave height) must be taken into account (case 3), otherwise the optimal time interval could be overestimated.

2. Expected total present value of the cost function over a time interval

The expected total cost function is defined as the summation of the total expected cost, $\overline{C}$, of inspection (I), repair (R), and failure (F) at the end of a time interval $[0, \Delta t)$ as follows:

$$\overline{C}_{Total}(0,\Delta t) = \overline{C}_I(0,\Delta t) + \overline{C}_R(0,\Delta t) + \overline{C}_F(0,\Delta t) \tag{1}$$

where $\overline{C}_I(0,\Delta t)$, $\overline{C}_R(0,\Delta t)$ and $\overline{C}_F(0,\Delta t)$ are the present value of the expected cost of inspection, repair and failure, respectively. The optimal interval corresponds to the lowest cost over the design life of the structure. The present value of the expected cost $\overline{C}_I(0,\Delta t)$, $\overline{C}_R(0,\Delta t)$ and $\overline{C}_F(0,\Delta t)$ considering the structural deterioration over a time interval, is defined in Sections 2.1–2.4, respectively.

2.1. Quality of inspection (q)

The inspection quality is related to the probability of detecting a crack of a given size. That probability depends on the crack size, the inspection method and the inspection team. The reliability with respect to the probability of detecting a crack is defined by the probability of detection (PoD) curve which is identical to the distribution function of the smallest detectable crack size [33]. PoD curves for different inspections techniques (i.e. magnetic particle inspection [MPI], Eddy current, alternate current methods [ACFM and ACPD] and ultrasonic techniques) has been compiled by Visser [34]. Also, PoD curves for MPI and Eddy current techniques can be obtained from the DNV guidelines [35]. PoD curves can be represented by a logistics, exponential and lognormal models. In the present study a PoD curve which is represented by the following exponential model is used [36,37]:

$$\mathrm{PoD}(x) = 1 - \exp\left(\frac{x - a_{\min}}{\lambda}\right), \quad a > a_{\min} \tag{2}$$

The inspection quality is given by the parameter λ which is the mean size above $a_{\min}$ (equal to 2 mm, [37]) of the smallest detectable size. In the optimization analysis of the present study the following auxiliary measure of inspection quality is introduced:

$$q = 1/\lambda \tag{3}$$

$q = 0$ refers to no inspection, $q = \infty$ is related to a perfect quality inspection, while $q \approx 0.2$–0.3 can be related to visual inspection.

2.2. Present value of the expected cost of inspection

If a crack size is detected (given by Eq. (3)), the present value of the expected cost of inspection during the time interval $[0, \Delta t)$ can be obtained as:

$$\overline{C}_I(0,\Delta t) = \int_0^{\Delta t} C_I(\tau|q) \cdot p_S[d(\tau)] \cdot e^{-\gamma\cdot\tau} d\tau \tag{4}$$

where $C_I(\tau|q)$ is the cost of inspecting the structure in the instant τ, for a given inspection quality q, it is considered that the structure with cumulative damage d has survived up to the instant τ with a probability of $p_S[d(\tau)]$; and $e^{-\gamma\cdot\tau}$ is a factor that converts the cost to its present value, given a discount rate γ.

Considering that the inspection of the structure will be done if a crack is detected at the end of the interval $[0, \Delta t)$, and assuming that the structure survives up to the end of Δt, Eq. (4) is simplified as:

$$\overline{C}_I(\Delta t) = C_{I|q,\Delta t} \cdot e^{-\gamma(\Delta t)} \cdot p_S[d(\Delta t)] \tag{5}$$

where $C_{I|q,\Delta t}$ is the inspection cost at the end of $[0, \Delta t)$ for a given inspection quality q, $e^{-\gamma(\Delta t)}$ is the present value cost factor. Eq. (5) considers that the structure with cumulative damage d has survived up to the end of Δt with a probability of $p_S[d(\Delta\tau)]$.

On the other hand, if it is assumed that the occurrence of the structural failure corresponds to a non-homogeneous Poisson process, then:

$$p_S[d(\Delta t)] = e^{-\int_0^{\Delta t} \overline{\nu}_F(\tau)d\tau} = e^{-\overline{\eta}_F(0,\Delta t)} \tag{6}$$

where $\overline{\nu}_F(\tau)$ represents the expected annual structural failure rate at instant, τ; $\overline{\eta}_F(0,\Delta t)$ is the expected number of failures at the end of a time interval Δt, $\overline{\eta}_F(0,\Delta t)$ is defined with more detail in the next section. Finally, the present value of the expected inspection cost, for a given inspection quality, at the end of the interval $[0, \Delta t)$ is:

$$\overline{C}_I(0,\Delta t) = C_{I|q,\Delta t} \cdot e^{-\gamma(\Delta t) - \overline{\eta}_F(0,\Delta t)} \tag{7}$$

2.3. Present value of the expected cost of repair

Following an inspection, a decision must be made regarding if a crack is detected. The repair decision will depend on the inspection quality q [38]. If a crack is not detected, repair actions will not be performed, in the case that a cracked is detected at the end of a time interval of interest, the present value of the expected cost of repair within the time interval $[0, \Delta t)$ is given by the following equation:

$$\overline{C}_R(0,\Delta t) = \int_0^{\Delta t} \sum_{j=1}^{n} C_{rj}[d(\tau)|q] \cdot p_{R_j}[d(\tau)|S] \cdot p_S[d(\tau)] \cdot e^{-\gamma\cdot\tau} d\tau \tag{8}$$

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