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Assessment of statistical parameter uncertainty in the reliability analysis of jacket platforms

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ABSTRACT

Statistical uncertainty is undoubtedly introduced in the estimation of parameters usually involved in the physical or probabilistic models employed for reliability analysis. Provided that such models parameters are uncertain, the probability of failure and the reliability index become uncertain variables as well. In this work, a general formulation is introduced to account for parameter uncertainties in the reliability analysis of jacket platforms under storm conditions. A point estimates method based on the Rosenblatt transformation is used to compute the statistics of the failure probability and the reliability index. It has the advantage that the estimating points and weights are readily defined. The effect of considering parameter uncertainties in the probability distribution of maximum wave height and the environmental load model was assessed. The relative influence of the different sources of parameter uncertainty and the implications of neglecting it were examined. Credible bounds of failure probability and coefficients of variation of the reliability index were evaluated as means of charactering uncertainty in their estimation. A decision problem regarding optimal probabilities of failure for structural design using a risk model is also analyzed, showing that depending on the coefficient of variation of the failure probability greater safety margins may be required.

1. Introduction

The reliability assessment of jacket platforms under storm conditions involves probabilistic and physical models of environmental loading and structural resistance. Some of the parameters in these models are estimated by means of statistical inference using possibly recorded, numerical, and experimental or field-test data on metocean conditions, loading and structural capacity. The uncertainty in the parameter estimates that results from such statistical process is regarded as parameter uncertainty. When accounting for parameter uncertainty, the probability of failure and the reliability index are functions of the uncertain models parameters and, hence, become random variables as well. It is therefore of interest to characterize the statistics of the failure probability and the reliability index. The so-called predictive failure probability, defined as the mean value of the probability of failure, is considered to be a measure that takes into account parameter uncertainty (Der Kiureghian, 2008). Credible intervals may also be a tool to characterize the uncertainty in the estimation of the failure probability.

Quantifying the uncertainty involved in the estimation of reliability improves risk informed decision making, for instance regarding optimal and acceptable reliabilities for design and reassessment, code-calibration, as well as optimal inspection planning and maintenance prioritization. It would be possible to assess to which extent such uncertainty could be reduced as a consequence of gathering additional information, provided that increasing statistical data and observations should reduce parameter uncertainty. Furthermore, the impact of reducing parameter uncertainty on safety measures could be compared, within the framework of a cost-benefit analysis, against the investment to gather more information. For instance, the economic benefits resulting from designing for lower safety margins, extending inspection intervals, and reducing the number of critical components to be inspected, as a consequence of reducing the uncertainty in the estimation of the failure probability, should at least be balanced by the cost of getting more information to characterize the parameters of the models for environmental loading demands and structural performance. Proper treatment of parameter uncertainty is also relevant for system reliability analysis. Parameter uncertainty in the load and capacity distributions of system components can introduce statistical dependence and have significant influence on the estimates of the system probability of failure. Der Kiureghian and Ditlevsen (2009) have shown that as the sample size of observations decreases and parameter uncertainty becomes larger, the

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estimates of predictive failure probability can increase quite significantly. Such an effect depends on the redundancy of the system and can reach several orders of magnitude for highly redundant systems.

Structural reliability formulations and applications for design criteria and risk-based inspection planning of jacket platforms have been developed in previous works (see e.g. Ayala, 2001; Bai et al., 2015; Ersdal, 2005; Faber et al., 2000; Frieze et al., 1997; Heredia-Zavoni et al., 2008; Heredia-Zavoni et al., 2004; Madsen et al., 1989; Manuel et al., 1998; Mathisen et al., 2004; Montes-Iturrizaga et al., 2009; Onoufriou and Forbes, 2001; Sigurdsson et al., 1994). These studies have advanced procedures to deal with: (1) the probabilistic modeling of environmental loads; (2) the probabilistic characterization of structural capacity; (3) the stochastic modeling of damage and deterioration; (4) approaches for system analysis; and (5) time-dependency and directional effects, among other topics. A comparative study conducted by Zhang et al. (2010) analyzed the features of some statistical models for the uncertainty in the parameters of a steel corrosion model and applied it to the reliability analysis of a fixed jacket platform. Efforts to assess the effect of parameter uncertainty have been made mainly for reliability analysis of offshore applications other than jacket platforms. Formulations considering uncertainties in the probability distributions of mooring loads and suction-caisson capacity for the reliability analysis of floating production systems have been developed recently (Rendón-Conde and Heredia-Zavoni, 2014, 2016). These studies have shown that significant differences may be found between the predictive and the mean reliability indices, and that the predictive failure probability is more sensitive to statistical uncertainties in the loading distribution. The effect of parameter uncertainties on the reliability of mooring lines for floating structures under extreme sea-states has been analyzed by Rendón-Conde and Heredia-Zavoni (2015). Their case study for catenary and taut-leg mooring lines of FPSO systems indicated that the predictive failure probability was much more sensitive to the statistical uncertainty in the probability distribution of loading than to that in the distribution of line resistance. Significant differences were also found between the predictive and the mean reliability index.

In this work, we study the effect of parameter uncertainty on the predictive failure probability and the statistics of the reliability index of jacket platforms. Environmental loading due to storm conditions is considered since the ultimate limit state, which addresses the structural capacity to withstand extreme environmental loads, is, understandably, a most relevant limit state for the design of reliable facilities in areas exposed to tropical cyclones. A general reliability formulation is presented first to account for uncertain parameters in the probabilistic and physical models of environmental loading and structural resistance of jackets. The probability of failure and the reliability index are expressed as random functions of the uncertain modeling parameters. The point estimates method used for the computation of the statistics of the reliability index and the failure probability is described next. An application example is then given considering parameter uncertainty in the wave height probability distribution and the load model. Results are thoroughly examined and discussed. A decision problem to select target probabilities of failure for design using a risk model is also analyzed. Main findings and concluding remarks are summarized at the end.

2. Reliability formulation

Consider a fixed jacket structure subjected to loads from extreme sea states due to hurricane or storm conditions, as schematically depicted in Fig. 1. The limit state function for the ultimate capacity of the jacket structure can be written in terms of the base shear resistance at collapse, , and the base shear from environmental loads during extreme sea-states, $s(\boldsymbol{x})$, as follows,

$$g(r, s) = r - s(\boldsymbol{x}) \tag{1}$$

where $\boldsymbol{x}$ is a vector of environmental variables, such as wave height, current velocity, and wind speed, etc. Let $\hat{f}(\boldsymbol{x}|\Theta_f)$ denote the selected

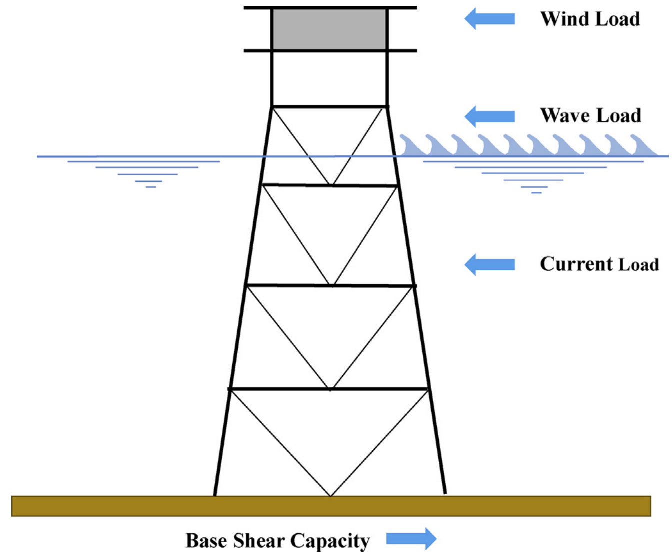

Fig. 1. Schematic depiction of jacket structure subjected to environmental loads.

model for the probability density function of $\boldsymbol{x}$ and Θ_f the set of distribution parameters to be estimated from statistical data. Let $\hat{s}(\boldsymbol{x}|\Theta_s) + E$ be an idealized model for $(\boldsymbol{x})$, in which $\hat{s}(\boldsymbol{x}|\Theta_s)$ is a deterministic model with Θ_s denoting its parameters and E is the model error or residual. The model parameters and the residual are estimated by statistical inference using for instance data from numerical response analyses. From the limit state function, the probability of failure for a given value of $\boldsymbol{x}$ is $P_{\boldsymbol{x}} = F_R(\hat{s}(\boldsymbol{x}|\Theta_s)|\Theta_R)$, where $F_R(r|\Theta_R)$ is the probability distribution of the resistance R, and Θ_R the distribution parameters. Considering the parameterized models $\hat{f}(\boldsymbol{x}|\Theta_f)$, $\hat{s}(\boldsymbol{x}|\Theta_s)$, $F_R(r|\Theta_R)$, and the statistical model for the residual E, $\hat{f}_{\mathrm{E}}(\varepsilon|\boldsymbol{\Theta}_{\mathbf{e}})$, with parameters $\boldsymbol{\Theta}_{\mathbf{e}}$ independent from $\boldsymbol{\Theta}_{\mathbf{s}}$, $\boldsymbol{\Theta}_{\mathbf{f}}$ and Θ_R, the failure probability is then given by

$$P(\Theta) = \int_{\varepsilon}\int_{\boldsymbol{x}} F_R[\hat{s}(\boldsymbol{x}|\Theta_s)|\Theta_R]\hat{f}_{\mathbf{X}}(\boldsymbol{x}|\boldsymbol{\Theta}_{\mathbf{f}})\hat{f}_{\mathrm{E}}(\varepsilon|\boldsymbol{\Theta}_{\mathbf{e}})d\boldsymbol{x}d\varepsilon \tag{2}$$

Eq. (2) indicates that the failure probability is a function of the set of uncertain model parameters $\boldsymbol{\Theta} = (\boldsymbol{\Theta}_{\mathbf{s}}, \Theta_R, \boldsymbol{\Theta}_{\mathbf{f}}, \boldsymbol{\Theta}_{\mathbf{e}})$, and thus, $P = P(\boldsymbol{\Theta})$ is also a random variable representing the uncertain failure probability. The uncertain reliability index, $\beta(\boldsymbol{\Theta})$, is equal to

$$\beta(\boldsymbol{\Theta}) = \Phi^{-1}(1 - P(\boldsymbol{\Theta})) \tag{3}$$

where $\Phi(\cdot)$ is the standard normal distribution function. A measure of reliability that accounts for parameter uncertainty is the so-called predictive failure probability, $\widetilde{P}$, which is defined as the expected value of $P(\boldsymbol{\Theta})$ over the outcome of uncertain model parameters $\boldsymbol{\Theta}$ (Der Kiureghian, 2008). Using Eq. (2), this can be written as,

$$\widetilde{P} = \int_{\theta} P(\boldsymbol{\Theta})f_{\boldsymbol{\Theta}}(\theta)d\theta \tag{4}$$

where $f_{\boldsymbol{\Theta}}(\theta)$ is the joint density function of $\boldsymbol{\Theta}$**.** The corresponding predictive reliability index can be obtained from

$$\widetilde{\beta} = \Phi^{-1}(1 - \widetilde{P}) \tag{5}$$

The predictive failure probability in Eq. (4) can be computed using an auxiliary limit-state function (Wen and Chen, 1987),

$$\widetilde{g}(\theta, u) = u + \beta(\theta) \tag{6}$$

where u is a sample value of an independent standard normal variable U and $\beta(\theta)$ is the reliability index for $\boldsymbol{\Theta} = \theta$ in Eq. (6). Let μ_β and σ_β^2 be the mean and variance of $\beta(\boldsymbol{\Theta})$. Since in Eq. (6), $\mu_{\widetilde{g}} = \mu_\beta$, and $\sigma_{\widetilde{g}} = \sqrt{1 + \sigma_\beta^2}$, an approximate estimate for the predictive reliability