



Assessment of characteristic values of the ultimate strength of corroded steel plates with initial imperfections



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ABSTRACT

This paper presents an approach for the assessment of percentiles of the response of any structural system with random properties. Different approaches are first introduced that differ on the level of accuracy of their predictions, which increases with the complexity of the approach adopted. The simpler approaches are built upon the concept “Level of Certainty” (LoC). The essence of the LoC-approach is the use of all input parameters (treated as random variables) with exactly the same Probability of Exceedance (PoE). An alternative and more accurate approach is suggested based on the assessment of the First-Order Second Moment sensitivity values of the random input parameters that are then used to calculate their design values and to predict the percentiles of the response.

The ultimate strength of a corroded steel plate with random initial distortions and random material and geometrical properties predicted by semi-empirical design equations or by means of non-linear Finite Element Analysis (FEA) is adopted as a case study to demonstrate the accuracy of the proposed approach. The percentiles of the ultimate strength of the plates calculated using these simplified approaches are compared with the ones obtained by Monte Carlo simulation.

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1. Introduction

In the last decades several parametric studies have been performed to describe the effect of different parameters on the collapse strength of plates [1]. These, include the effect of initial global imperfections (e.g. [2–5]) and of local distortions [6,7], residual stresses, lateral pressure [8,9], heat loads [10–12] and corrosion (e.g. [13]).

The random characteristics of several parameters that influence the ultimate strength of the plates have motivated many authors to propose probabilistic models for the plate strength, as discussed by Guedes Soares [14] and more recently by Teixeira and Guedes Soares [15]. These models describe the effect of the variability of the parameters and the uncertainty of the models in the assessment of the ultimate strength of the structures and can be used as tools to derive probabilistically based design rules as demonstrated by Guedes Soares [16].

The probabilistic description of the strength of structural elements can be established using different levels of complexity. The simpler approaches are built upon empirically based formulas of the type that are normally used as design requirements. The

other extreme is to use non-linear finite element calculations to determine the ultimate strength of the structural elements.

In what regards the probabilistic techniques, also different levels of complexity can be adopted. The first approaches have used First Order Second Moment (FOSM) and Monte Carlo simulation (MCS) techniques to construct the probabilistic models of the response of the structures.

Later, with the development and the generalized use of numerical Finite Element Analysis (FEA), Response Surface Methods (RSMs) have proved to be an efficient and widely applicable method in reliability and probabilistic assessments of the response of structures [17,18]. The response surface approaches have been adopted by Kmiecik and Guedes Soares [19] for probabilistic modeling of the strength of compressed steel plates and recently extended by Teixeira and Guedes Soares [20] to reliability problems involving random fields of corrosion. Although the approximating function is normally obtained with much less FEAs, when compared with direct use of simulation methods, the polynomial response surface has its limitations in fitting complicated response behaviors, and there is no guarantee that the fitted surface is in fact a sufficiently close fit in all regions of interest.

Within the various approaches to deal with uncertainty [21], an elegant technique for probabilistic representation of response quantities has been proposed by Ghanem and Spanos [22]. The so-called Spectral Stochastic Finite Element Method (SSFEM), has

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shown to be well suited to second-moment analysis of the response of structures involving random fields, being also particularly suited to deal with composite materials [23].

More recently, Teixeira et al. [24] have constructed probabilistic models of the collapse strength of plates with random fields of corrosion using a technique based on the inverse application of the First Order Reliability Method (iFORM). The technique consists in fitting a three-parameter lognormal distribution to three fractiles of the ship longitudinal strength obtained by inverse FORM (iFORM) [25,26].

Although several advanced probabilistic techniques have been developed in the past, there are cases in which simplified approaches to estimate particular characteristic values of the response of any structural system are desirable.

An approximate approach for calculation of response characteristic values has been proposed by Yuen et al. [27] based on the concept “Level of Certainty” (LoC). The essence of the LoC-approach is the usage of all input parameters (treated as random variables) in analytical formulas (used to predict the strength of the structure) with exactly the same Probability of Exceedance (PoE). The assumption is that the obtained result of the calculations will have a PoE very close to the PoE of the input parameters (random variables).

The present paper proposes an alternative and more accurate approach, but still simple, that uses the First Order Second Moment (FOSM) sensitivity values of the random input parameters to identify the contribution of each parameter to the total uncertainty of the response of the structure. The sensitivity factors can be then used to predict the design values of the input variables and the corresponding percentiles of the response using general First-Order Reliability Method (FORM) considerations [28,29].

The suggested approach based on the FOSM-sensitivity factors can be used to predict with a reasonable accuracy particular percentiles of the response of a structural system with a limited number of response evaluations.

The ultimate strength of a corroded steel plate with random initial distortions and random material and geometrical properties predicted by semi-empirical design equations or by means of non-linear Finite Element Analysis (FEA), is adopted as a case study to demonstrate the accuracy of the proposed method.

The characteristic values of the ultimate strength of the plates predicted by the suggested approach are compared with the ones estimated by means of Monte Carlo simulation. It is shown that the proposed method based on the FOSM-sensitivity factors is both accurate and efficient in the assessment of response percentiles.

2. Ultimate strength of steel plates with random properties

The ultimate strength of a corroded steel plate with random initial distortions and random material and geometrical properties predicted by semi-empirical design equations or by means of non-linear FEA, is adopted as response model. The ultimate strength calculations were carried out for simply supported square plates with length (a) and width (b) of 850 mm ($a/b = 1$), and slenderness (b/t) of 47.2 (t of 18.0 mm).

Although consistently presented in the following sections, this simplified response model is used mainly to illustrate the accuracy of the proposed approach for estimation of response fractiles. In fact realistic a/b ratios of plates of bulk carriers typically range from 3 to 6.4, which have been studied by several authors with appropriate models of initial distortions (e.g. [30,31]).

2.1. Stochastic modeling of material and geometrical properties

The stochastic modeling of steel material properties is usually based on lognormal distributions for the yield stress (σ_y) and mod-

ulus of elasticity (E). These models are widely used and accepted as proper models to quantify the uncertainty in these design variables (e.g. [32,33]). The distribution for the yield strength is derived from its design characteristic value ($X_{0.05}$) and coefficient of variation (COV). The yield strength characteristic values are usually defined in design rules as the lower limit of the distribution for which 95% of the specimens will have strength values beyond that limit or minimum value. For the modulus of elasticity the value adopted for design purposes is usually the mean value.

The uncertainties related to the panel geometry are associated with the fabrication process of the steel plates, resulting in variability in the plate panels' thickness t , and with the shipbuilding process that also introduces variability in the geometry of the stiffened panels, which may be more significant for main dimensions as the spacing between longitudinal stiffeners and the spacing between transverse frames. These sources of uncertainty are controlled in practice using quality standards that define the permissible limits to be used in the quality control procedures. Typically, the variability in geometrical parameters is modeled by Normal distributions with the mean value equal to the nominal or design value and the standard deviation defined by a specified coefficient of variation that ranges from 1% to 3% [33].

2.2. Stochastic model of the initial distortions of the plates

The complex shape of initial geometrical distortions of ship plates can be described by a Fourier series given by:

$$w_o = \sum_{i=1}^m \sum_{j=1}^n w_{o,ij} \sin \frac{i\pi x}{a} \sin \frac{j\pi y}{b} \quad (1)$$

where a and b are the plate dimensions, m and n represent the number of components in x - and y -direction, respectively, and $w_{o,ij}$ are the amplitude of the deflection components.

The initial deflection of a rectangular plate panel produced by the fillet welding of stiffeners generally takes a “thin-horse” mode represented by only odd terms in the longitudinal direction [34] or also even terms [35].

In the present study the stochastic model of the amplitude of initial distortion of the plates was defined based on measurements of fabrication distortions of ship plating that were undertaken mainly in Polish shipyards in the process of construction of ships. This data has been used to investigate not only the maximum values of plates' initial deflections but also their deflection geometry suggesting that an adequate description is achieved by using only three terms in the series expansion in the longitudinal direction and only the first mode for the transverse component:

$$w_o = \sum_{i=1}^3 w_{o,i1} \sin i \frac{\pi x}{a} \sin \frac{\pi y}{b} \quad (2)$$

A detailed description of this campaign of systematic measurements together with a description of the measurement technique applied has been presented by Kmiecik et al. [36].

A statistical analysis of the initial distortions of the ship plates shows that the majority of the plates, (around 90%) have shapes of initial distortions with one half wave in the longitudinal and transverse directions. Therefore the present study has represented the initial geometric imperfection shape (w_o) by only one component of the Fourier series, which corresponds to the elastic buckling mode shape of the square plate adopted in this study,

$$w_o = w_{\max} \sin \frac{\pi x}{a} \sin \frac{\pi y}{b} \quad (3)$$

where a , and b are the plate dimensions and $w_{\max}$ is the amplitude of the shape of the initial imperfection.

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