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Incidence of residual stresses and steel properties variability on corroded bulk carrier reliability

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ABSTRACT

Time-variant sagging/hogging hull girder bending capacity of a corroded bulk carrier is determined by Monte Carlo simulation, in terms of mean values, variation coefficients and probability density functions; the incidence of welding residual stresses and steel mechanical properties is purposely investigated. Time-variant hull girder reliability is characterized, for both sagging and hogging conditions, by the annual failure probability and is determined by Second-Order Reliability Method. Sensitivity coefficients of all random variables at discrete points in time are also determined. Four different scenarios are considered and analysed, in order to separately and jointly investigate the incidence of welding residual stresses and material properties variability on hull girder capacity and annual failure probability and compare individual results with the reference case, which is relative to no welding stresses and material properties nominal values. The Capesize single side bulk-carrier, benchmarked in the last ISSC Report, is assumed as test case. Finally, obtained results of time-variant hull girder statistical properties and annual failure probabilities are discussed.

1. Introduction

Reliability analysis of ship structures has been carried out since the 1970s, to develop new and more rational hull girder longitudinal strength check criteria. In this respect, Mansour (1974) determined the reliability indexes of several oil tankers and bulk carriers by the Mean Value First-Order Second-Moment Method, accounting for uncertainties associated with random variables and quantifying relevant variation coefficients. Faulkner and Sadden (1979) analysed the reliability index methods, comparing the safety indexes of five candidate vessels, assumed as case studies, with the ones of similarly sized merchant ships, designed in accordance with Rules and found some shortcomings of current design practices. Hence, ship structural reliability analysis has become a popular research topic since the 1980s and more advanced techniques, such as the First-Order Reliability Method, were applied to estimate the time-variant hull girder failure probability. In this respect, Mansour et al. (1984) performed reliability analyses of several ships, deriving the variance of all random variables by first-order Taylor series expansion method. Subsequently, Guedes Soares (1989) determined the time-variant hull girder reliability index, resulting from degrading effects due to corrosion, at discrete points during the ship lifetime, carrying out some example calculations for an oil tanker. Ostergaard (1992) performed the reliability analysis of a containership, determining relevant hull girder statistical properties by sagging/hogging mean values and variation coefficients, deriving the still water and vertical wave bending moments by hydrodynamic analyses and met-ocean statistical data, including long term statistics. Subsequently, at the end of the 1990s, more refined reliability analyses, mainly based on Monte Carlo simulation or Second-Order Reliability Method, were applied by Mansour et al. (1996) to a Floating Product and Storage vessel and by Paik et al. (1998a) to an oil tanker and a bulk carrier. In the same years Wirsching et al. (1997) investigated the time-variant reliability of a corroded oil tanker, with the aim of providing information to ship designers and owners about corrosion margins and steel replacement, during the entire ship lifetime. Hence, the growing interest in investigating the incidence of corrosion and fatigue on the risk assessment of aging ships extended the research field to time-dependent models, accounting for corrosion growth and fatigue cracks (Akpan et al., 2002; Sun and Bai, 2003). Subsequently, Vhanmane and Bhattacharya (2011) investigated the incidence of material properties randomness and fabrication related imperfections, due to initial deflections and welding residual stresses, on hull girder ultimate strength capacity. In the same years, new methods to reduce uncertainties in the performance assessment of ship structures were developed too, updating the wave-induced load effects by Bayesian methods with data acquired from structural health monitoring (Zhu and

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Frangopol, 2013) or focusing on fast integration techniques, to estimate long-term vertical wave bending moments (Zayed et al., 2013). Subsequently, the incidence of correlation among corrosion wastages of structural members contributing to hull girder strength has been investigated for intact (Campanile et al., 2014) and damage conditions (Campanile et al., 2015a) by Taylor series expansion method and Monte Carlo simulation, to determine the ultimate and residual hull girder bending capacities. Finally, Campanile et al. (2015b) focused on the incidence of correlation among corrosion wastages on reliability analysis of a corroded bulk carrier in intact condition, finding that the hull girder capacity sensitivity coefficient plays a fundamental role in the evaluation of annual failure probability.

Following all previous efforts, since the 1990s Classification Societies have developed several Rules and Guidelines for a more reliable evaluation of hull girder loads and scantlings. In this respect, structural reliability analysis revealed a suitable tool for calibration of Rule formulas, which require a consistent safety level, providing the so-called "design point" that, in turn, furnishes the most likely values of all random variables at failure and represents a guidance to define the characteristic values and partial safety factors of design formulas, by means of a comparative analysis with target reliability levels, assessed from historical experience and existing designs (Hørte et al., 2007). This rational approach was applied as a tool for code calibration within the Joint Tanker and Bulk Carrier Projects, started as a combined effort among American Bureau of Shipping, Lloyd's Register and Det Norske Veritas, with the aim of developing harmonized rules, subsequently embodied by the International Association of Classification Societies (IACS) that developed the first Common Structural Rules for Oil Tankers (IACS, 2006a) and Bulk Carriers (IACS, 2006b), actually joined within the Harmonized Common Structural Rules (IACS, 2014a).

Anyway, although the aim of structural reliability analysis is to provide models as far as close to realistic situations, some conservative simplifications have been undertaken to make the analysis feasible (IACS, 2014b). In this respect, statistical properties of hull girder ultimate bending capacity have been assessed by the so-called "net-scantling approach", assuming the ultimate strength follows the lognormal distribution with 5% coefficient of variation (IACS, 2014b). Hence, provided that uncertainties in structural load models and calculations significantly influence the attained failure probability level, the paper focuses on a more reliable estimation of hull girder statistical properties, to investigate the incidence of combined randomnesses due to corrosion wastage, welding residual stresses and material properties on failure probability level. Particularly, time variant hull girder statistical properties of a corroded bulk carrier are preliminarily determined by Monte Carlo simulation (Campanile et al., 2014, 2015a), applying the corrosion wastage model proposed by Paik et al. (1998a), to separately and jointly investigate the incidence of welding residual stresses and material properties randomness on hull girder statistical properties. Subsequently, time-variant annual failure probabilities are determined for sagging and hogging conditions, up to 25-year ship lifetime, by the Second-Order Reliability Method. Before performing actual analysis, the reference case of a corroded bulk-carrier, with no welding residual stresses and deterministic nominal values for material mechanical properties is analysed. Subsequently, three main subjects are fully investigated and discussed:

(i) Incidence of welding residual stresses on time-variant corroded hull girder bending capacity and annual failure probability is investigated, assuming the nominal values for yield strength and Young modulus of all elements contributing to hull girder strength. Welding residual stresses are determined modifying the element stress-strain curve by Crisfield (1975) formulation, mainly based on the Dwight and Moxham (1969) tension block parameter that, in turn, is assumed to follow the normal distribution, according to Chryssanthopoulos (1998).

(ii) Incidence of material properties randomness on time-variant corroded hull girder bending capacity and annual failure probability is investigated, with no residual stresses. Statistical properties of yield strength and Young modulus are determined according to DNV (1992) guidelines.

(iii) Incidence of combined welding residual stresses and material properties on hull girder bending capacity and relevant failure probability is investigated.

In all cases time-variant sensitivity analysis of all random variables is performed, to investigate the incidence of hull girder bending capacity on annual failure probability. Finally, actual results are compared with the reference case, having no welding residual stresses and deterministic nominal values for material mechanical properties. The Capesize single side bulk-carrier, reported in the last ISSC benchmark study (Paik et al., 2012), is assumed as reference. Both Monte Carlo simulation and Second-Order Reliability Analysis are carried out by two dedicated programmes developed in Matlab (MathWorks, 2014).

2. IACS ultimate strength check criteria

Hull girder ultimate strength is probably the most critical failure mode for oil tankers and bulk carriers, as far as the traditional design criterion, based on hull girder section modulus, cannot capture the "real" hull girder capacity and may produce some scatter in safety level between different designs (Hørte et al., 2007). In this respect, structural reliability analysis has been widely carried out by IACS as a tool for code calibration, to determine both hull girder loads and relevant safety factors. Particularly, several test ships were analysed during the development of Common Structural Rules, to provide some deterministic rule requirements consistent and practical to use (IACS, 2006c). In this respect, within the partial safety factor calibration process, the characteristic ultimate bending capacity has been determined by the single step method, provided that some comparative studies, carried out during the IACS harmonization process, showed that it provides results similar to the incremental-iterative approach (IACS, 2006c).

The physical model, applied by IACS for hull girder capacity evaluation, accounts for uncertainties due to yield strength only that is modelled by the lognormal distribution, derived by relevant characteristic value representing the 5% lower fractile, with 8% and 6% variation coefficients for mild (Fjeld, 1978) and high-tensile (Hart et al., 1985) steels, respectively. Besides, geometrical dimensions are regarded as deterministic values and the "net-scantling approach" is applied, disregarding time-variant corrosion wastage. Hence, model uncertainty factor on ultimate capacity is introduced to account for differences among the single step method, the non-linear FE analysis results and real life (IACS, 2006c), finding it has a bias of 1.05, with a standard deviation of 0.10. Finally, calibration of partial safety factors has been carried out for different target probability levels, based on existing structures and comprised between 10^{-4} and 10^{-3}.

With reference to the IACS reliability analysis procedure, it is important to point out that obtained results provide nominal values of failure probabilities that, in turn, are very sensitive to both applied reliability models, uncertainty factors and loading conditions that, in turn, refer in all cases to the North Atlantic ones, disregarding any benefits of route changing due to bad weather conditions (IACS, 2006c). Furthermore, as the probability of failure, based on the "net-scantling approach", is about 10 times higher than the gross one (IACS, 2006c), a more reliable evaluation of hull girder statistical properties needs to be undertaken, in order to provide a more reliable format to assess relevant statistical properties, accounting for other uncertainty sources, disregarded by previous reliability analyses. In this respect, it seems that combined randomness due to time-variant corrosion wastage, welding residual stresses and material properties may be taken