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Incidence of load combination methods on time-variant oil tanker reliability in intact conditions

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ABSTRACT

Reliability analysis of an oil tanker in intact conditions is performed to investigate the incidence of load combination methods on hull girder sagging/hogging time-variant failure probability. Particularly, Turkstra rule, Ferry Borges and Castanheta method and Poisson square wave model are applied to evaluate the statistical distribution of bending moment, with reference to both one voyage and 1-year period. Statistical properties of time-variant ultimate strength are determined by Monte Carlo simulation, up to 25-year ship lifetime; bending capacity is determined by means of a modified incremental-iterative method, to account for corrosion wastage of structural members contributing to hull girder strength, welding residual stresses and material properties randomness. After determining the still water load combination factors, based on statistical properties of still water, wave and total vertical bending moments, with reference to 1-year time interval, reliability analysis is performed by Monte Carlo simulation, based on limit state formulations relative to different load combination methods. Finally, the VLCC double hull oil tanker, benchmarked in the 2012 ISSC report, is assumed as a reference ship and obtained results are fully discussed.

1. Introduction

Structural reliability analysis was started at the end of the 1940s by Freudenthal (1947), who suggested that statistical distributions of load factors should be taken into account for a more rational design of engineering structures, based on safety and serviceability levels. Following the first attempts in developing probability-based formats for ship structural design, carried out by Mansour, (1972a, 1972b) and Mansour and Faulkner (1972), the earliest applications of reliability analysis to ship structural design mainly focused on global safety and serviceability levels of ship structures under vertical bending moments (Stiansen et al., 1979; Mansour et al., 1984). In this respect, the main difficulty in estimating the hull girder failure probability was encountered when combining still water and wave vertical loads, as they are characterized by different time variability and relevant maxima do not occur simultaneously, so that the maximum of the combined process may be smaller than the sum of individual load maxima (Teixeira et al., 2013). Furthermore, when structures are subjected to the combined action of two or more stochastic load processes, reliability analysis becomes a time-variant problem, that reduces to a time-invariant one if external Ioads are resembled by relevant extreme values, with reference to a given time interval, based on load-combination analysis (Huang and Moan, 2008). From this point of view, several load combination methods of vertical still water and wave bending moments have been applied to ship structural design in the last decades (Guedes Soares, 1992; Wang and Moan, 1996; Huang and Moan, 2008; Teixeira et al., 2013), with reference to both deterministic methods, such as peak coincidence, root of sum of squares (Goodman et al., 1955) and Turkstra (1970) rules, and stochastic techniques, such as Ferry Borges and Castanheta (1971), load coincidence (Wen, 1977) and point-crossing (Larrabee, 1981) methods.

In the same years, the other main source of uncertainties, mainly related to hull girder ultimate bending capacity, has been widely investigated to derive probabilistic values of hull girder strength, in terms of nominal mean values, coefficients of variation and distribution types (SSC, 1996). In this respect, Wirsching et al. (1997) focused on time-variant reliability of an oil tanker experiencing structural degradation, due to corrosion wastage. Sun and Bai (2003) carried out the reliability assessment of a Floating Production, Storage and Offloading (FPSO) vessel by a modified Smith method, accounting for corrosion growth and crack propagation by Paris-Erdogan equation. Zhu and Frangopol (2013) presented a new approach to reduce uncertainties in the performance assessment of ship structures, updating the wave-induced load effects by Bayesian methods with data acquired from

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structural health monitoring and comparing time-variant reliability indexes before and after the improvement process. Zayed et al. (2013) applied fast integration techniques to estimate the long-term vertical wave bending moment, with reference to a time-variant reliability analysis. Finally, Campanile et al. (2014, 2015) investigated the statistical properties of time-variant ultimate and residual strength of a bulk carrier, accounting for structural degradation and neutral axis rotation, in case of asymmetrically damaged cross-sections. They also investigated the incidence of different reliability analysis techniques, namely First, Second-Order Reliability Analysis and Importance Sampling simulation, on time-variant hull girder failure probability in pure bending intact and damage conditions (Campanile et al., 2016a). Finally, real-time reliability of ship structures recently became a popular topic. In this respect, Decò and Frangopol (2013, 2015) investigated the optimal mission-oriented routing of ships and developed a risk-informed approach for ship structures, assessing the risk levels by reliability analysis of hull girder amidships cross-section and accounting for corrosion wastage, different damage levels and plasticity propagation.

Hence, following the improvements in the assessment of hull girder failure probability with reference to the statistical analysis of vertical bending moments and hull girder capacity, the International Association of Classification Societies (IACS) developed the new ultimate hull girder strength check criterion for oil tankers (IACS, 2006), actually embodied in the Harmonized Common Structural Rules for Oil Tankers and Bulk Carriers (IACS, 2015a), calibrating partial safety factors by structural reliability analysis. Particularly, reliability analysis was based on Turkstra (1970) rule and the characteristic value of still water bending moment (SWBM), with reference to one voyage, was combined with the extreme vertical wave bending moment (VWBM) one, with 1-year return period, for which a Gumbel type distribution has been applied. Besides, the ultimate bending capacity has been determined by the single-step method, based on the net scantling approach, disregarding time-variant corrosion wastage and accounting for model uncertainties due to material properties randomness, by means of an uncertainty factor, following the normal distribution with 1.05 mean value and 0.1 standard deviation, to reflect differences between the single-step method and more advanced techniques, such as non-linear FE analysis. Similarly, model uncertainty factors for still water and wave vertical bending moments were derived to account for differences between sagging and hogging conditions and nonlinearities due to large amplitude motions in harsh weather conditions. Hence, following the outcomes stressed within the calibration process of partial safety factors for ultimate strength check criterion of oil tankers, the same format, mainly based on deterministic Turkstra (1970) rule, has been recently applied in the calibration process of the residual strength check criterion for oil tankers and bulk carriers, after collision or grounding events. In this respect, the structural reliability analysis model for intact condition has been partly modified to account for lower exposure times to wave loads and milder weather conditions in coastal areas, where collision and grounding events generally occur, with respect to 25-year time interval and North Atlantic climate adopted for intact condition.

Anyway, following the outcomes stressed by Wen (1977), Naess (1989, 1999) and Turkstra (1970) rule may furnish quite unconservative results and underestimate the structural failure probability, if the combined random load processes have the same order of magnitude, as for vertical still water and wave bending moments. Furthermore, Teixeira et al. (2005) performed the reliability analysis of an oil tanker by different wave load formulations, concluding that failure probabilities change significantly with the applied format, so that relevant choice becomes a matter of standardisation in order to allow different ship structures to be consistently compared each other. Hence, based on actual state of art, some concerns arise with reference to the evaluation of hull girder stochastic properties and the application of load combination methods to reliability analysis. In this respect, the paper provides a comprehensive format to investigate the statistical properties of time-variant hull girder strength and focuses on the incidence of load combination methods on sagging/hogging failure probabilities of a double hull oil tanker in intact condition. Stochastic modelling of extreme still water and wave vertical bending moments, as well as the basics of the modified ultimate strength method to account for corrosion wastage, welding residual stresses and material properties randomness are preliminarily discussed. Subsequently, three main aspects are fully investigated:

(a) Hull girder ultimate strength is assessed by Monte Carlo simulation, accounting for corrosion wastages of structural elements contributing to hull girder strength, welding residual stresses and material properties randomness.
(b) Sagging/hogging failure probability is investigated by Monte Carlo simulation, based on two different limit state formulations, the former mainly derived by the IACS format with reference to deterministic Turkstra (1970) rule, the latter accounting for stochastic load combination among vertical still water and wave bending moments.
(c) A comparative analysis among deterministic Turkstra (1970) rule and load combination methods, based on Ferry Borges and Castanheta (1971) and Poisson square wave (Larrabee and Cornell, 1981) models for still water loads, is performed to investigate the incidence of extreme value statistics on the attained failure probability level.

Finally, the double hull VLCC oil tanker, analysed for the first time in the ISSC (2000) report and subsequently benchmarked in the ISSC (2012) study, is assumed as a test case for reliability analysis, carried out by a dedicated programme developed in Matlab (MathWorks, 2014).

2. Stochastic modelling of longitudinal bending moments

2.1. One voyage still water bending moment distribution

The first systematic study on the stochastic properties of SWBM was performed by Guedes Soares and Moan (1988), who carried out a statistical analysis on a data set consisting of about 2000 voyages of 100 ships from 39 ship-owners, to establish the variability of still water loads during normal operations of oceangoing ships. They concluded that the SWBM follows the normal distribution, with mean and standard deviation mainly depending on ship types and loading conditions that, in turn, were kept constant during each voyage, assuming the probabilistic model at departure as representative of any random point in time, till arrival in port (Teixeira et al., 2013). This hypothesis revealed to be adequate in many cases, namely ballast and partial/ballast load conditions for double and single hull oil tankers respectively, even if Guedes Soares and Dogliani (2000) found that SWBM of double-hull oil tankers in partial or full load conditions could significantly vary during each voyage and recommended, for practical applications, to take relevant mean and standard deviation equal to the average values between departure and arrival conditions.

Furthermore, if the SWBM is regarded as a random variable, it may exceed the maximum value reported in the loading manual that should not obviously be surpassed, which implies that relevant distribution should be truncated to avoid unrealistic sagging/hogging bending moments (Teixeira et al., 2013). Anyway, Huang and Moan (2008) concluded that the truncation of SWBM distribution has negligible effects on oil tankers.

In this respect, in actual analysis the one voyage SWBM is assumed to follow the normal distribution, with mean and standard deviation equal to 70% and 20% of the maximum bending moment reported in the loading manual, with reference to both full load and ballast load conditions, corresponding to sagging and hogging bending moments