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Conditional reliability of bulk carriers damaged by ship collisions

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ABSTRACT

Time-variant reliability analysis of a bulk carrier in damage conditions, after a collision event, is performed by Monte Carlo simulation. Two different collision models are applied, the former based on the deterministic format actually embodied in the Harmonized Common Structural Rules for Oil Tankers and Bulk Carriers, the latter based on a probabilistic format, derived by the recently developed GOALDS database statistics for collision and grounding events. A modified incremental-iterative method is applied, to account for instantaneous neutral axis rotation, due to asymmetrically damaged cross-sections, as for collision events. Time-variant residual strength statistical properties are preliminarily determined by Monte Carlo simulation, up to 25-year ship lifetime, accounting for corrosion wastages of all structural members contributing to hull girder strength, welding residual stresses and material properties randomness. Finally, time-variant reliability analysis is performed, to investigate the incidence of the applied collision damage models on hull girder annual failure probabilities in sagging and hogging conditions. Reliability analysis is performed for the Capesize single side bulk carrier, benchmarked in the 2012 ISSC report and assumed as reference ship in current analysis. Obtained results are fully investigated and discussed.

1. Introduction

Probability-based structural design was started at the end of the 1940s by Ref. [1]; who suggested to apply statistical distributions of design parameters when establishing safety factors for engineering structures. Early efforts, performed in the subsequent decades, were mainly devoted to develop reliability analysis methods for risk assessment, in terms of failure probability [2,3], while the first attempts of applying probability-based techniques to ship structural design were undertaken at the beginning of the 1970s by Refs. [4,5] and [6]. The earliest applications of reliability analysis to ship structures were carried out by applying the Mean Value First-Order Second-Moment Method (MFOSM) or the First-Order Reliability Method (FORM), while more advanced techniques, such as Second-Order Reliability Analysis (SORM) or adaptive Monte Carlo simulations, were applied after the 1990s. In all cases reliability analysis was devoted to estimate the hull girder failure probability in intact conditions, accounting for uncertainties in estimating (i) the ultimate bending capacity, due to corrosion wastage of all structural members contributing to hull girder strength and (ii) the still water and extreme vertical wave bending moments, based on long term statistics.

All mentioned efforts were mainly devoted to hull girder reliability analysis in intact conditions, as in traditional engineering practice the role of hull girder residual strength, after collision or grounding occurrences, was not explicitly defined till the Ship Structure Committee Symposium in 1984 addressed the role of design inspections and redundancy in marine structures reliability and

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highlighted the incidence of residual strength on safety and reliability of marine structures [7]. In the following years characteristic damage typologies, based on review of ship casualty records and available analytical methods for assessing both local and global residual strength, were investigated [8], in order to evaluate the structural redundancy, identify the desired local and global safety levels and develop new inspection, maintenance and repair criteria in a more rational and cost effective approach [8]. Hence, in the same years the first guidelines for assessing the hull girder residual strength of oil tankers [9] and bulk carriers [10] were developed by the American Bureau of Shipping; moreover the need for a more reliable hull girder capacity assessment, after collision or grounding events, became particularly stressed after the Prestige's accident occurred in 2002. In this respect, in the last two decades several advances have been made to improve present scantling requirements and define more refined reliability analysis procedures in damage conditions, as shown by the new Rules and Guidelines provided by Det Norske Veritas [11] and IACS (2015[a]) among others.

Furthermore, in the last two decades many appreciable advances have been carried out by several researchers. From this point of view, the hull girder residual strength after collision events was investigated by Ref. [12]; who determined relevant statistical properties, in terms of mean values and variation coefficients. Subsequently, the relationship between risk analysis and structural reliability was investigated by Ref. [13] who focused on the limit state function after collision and grounding events and applied Monte Carlo simulation to evaluate the hull girder failure probability. The residual strength of double hull tankers was also investigated by Refs. [14] and [15]; who studied the impact of damage size and location on hull girder residual capacity and relevant reliability index [16]. presented a probabilistic framework for ship performance assessment under sudden damages, accounting for different operational conditions and progressive deterioration, due to corrosion. Finally, [17] [18]; investigated the time-variant statistical properties of bulk carrier residual strength, after collision and grounding events, accounting for corrosion wastage of all structural members contributing to hull girder capacity, based on different correlation models among all random variables and investigating relevant impact on reliability analysis, performed by FORM, SORM and adaptive Monte Carlo simulation.

In the same years several efforts have been also undertaken to provide more refined structural models, capable of correctly estimating the hull girder residual strength capacity in sagging and hogging conditions. In this respect, a modified incremental-iterative method was proposed by Ref. [19]; to account for a given biaxial curvature ratio, in terms of secant modulus corresponding to the bending moment-curvature slope [20]. derived several interaction curves for different loading conditions, combining both vertical and horizontal bending moments [21]. provided two convergence criteria, to find translational and rotational locations of neutral axis plane, based on contemporarily satisfying both force and moment equilibrium criteria. The progressive collapse method was also applied by Refs. [22] and [23]; who derived an explicit expression of the instantaneous neutral axis rotation, as a function of the hull girder cross section biaxial curvature, finding that the obtained hull girder residual strength is lower than the relevant one, derived by constraining the rotation, as commonly assumed in the classical incremental-iterative method [24]. Finally [17], proposed a varied-form of the classical incremental-iterative method, including a new loop in the existing procedure [24], in order to satisfy the horizontal bending moment equilibrium equation, in case of asymmetrically damaged cross-sections, as for collision or grounding events.

All previously discussed efforts were mainly devoted to evaluate the hull girder residual strength capacity, as well as its statistical properties and reliability, based on several deterministic collision and grounding scenarios provided by Rules, in terms of damage penetration depth and height, based on statistical analysis of grounding and collision statistics. In this respect, in the last two decades several attempts have been undertaken to investigate the statistics of collision and grounding events, as confirmed by the EU-funded HARDER and GOALDS projects, launched in 2000 and 2009 respectively, with the main aim of developing improved databases for collision and grounding statistics and derive relevant probability distributions, in terms of damage size and location. Based on actual state of art, some concerns arise with reference to the application of Rule deterministic damage scenarios and relevant impact on hull girder residual strength statistical properties and reliability, after collision or grounding events. In this respect, the paper focuses on the incidence of collision damage statistical properties on bulk carrier reliability, by means of a comparative analysis between deterministic collision damage scenarios provided by Rules [24] and probabilistic models derived by GOALDS database statistics for oil tankers and bulk carriers [25]. Hence, the main purpose of the paper is to compare CSR-H deterministic and GOALDS probabilistic models for collision events, accounting in the latter case for randomness due to damage penetration depth/height and investigating the incidence on time-variant hull girder failure probability, conditional on the occurrence of a collision event. Hence, three main aspects are fully discussed and investigated:

(i) Time-variant hull girder residual strength mean values and variation coefficients are determined by Monte Carlo simulation. Both deterministic and probabilistic collision damage models are applied, accounting for uncertainties due to corrosion wastage of all structural elements contributing to hull girder strength, welding residual stresses and material properties randomness.
(ii) The incidence of collision model on sagging/hogging probability distributions of hull girder residual strength is investigated, as this outcome is a basic issue to perform reliability analysis.
(iii) Time-variant hull girder sagging/hogging failure probabilities are determined by Monte Carlo simulation, to investigate the differences between the IACS deterministic collision model [24] and the probabilistic format derived by GOALDS database statistics [25].

In this respect, it must be pointed out that in IACS (2015[b]) background document a statistical distribution of damage height is applied and reduction in bending moment capacity is given as a function of damage size. Nevertheless, rule residual strength check criterion [24] is based on deterministic damage scenarios, mainly derived by the [11] CSA-2 criterion, that may lead to the same failure probability level as that one based on probabilistic damage penetration depths and heights, following a collision event.