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Comparative analysis among deterministic and stochastic collision damage models for oil tanker and bulk carrier reliability

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Abstract

The incidence of collision damage models on oil tanker and bulk carrier reliability is investigated considering the IACS deterministic model against GOALDS/IMO database statistics for collision events, substantiating the probabilistic model. Statistical properties of hull girder residual strength are determined by Monte Carlo simulation, based on random generation of damage dimensions and a modified form of incremental-iterative method, to account for neutral axis rotation and equilibrium of horizontal bending moment, due to cross-section asymmetry after collision events. Reliability analysis is performed, to investigate the incidence of collision penetration depth and height statistical properties on hull girder sagging/hogging failure probabilities. Besides, the incidence of corrosion on hull girder residual strength and reliability is also discussed, focussing on gross, hull girder net and local net scantlings, respectively. The ISSC double hull oil tanker and single side bulk carrier, assumed as test cases in the ISSC 2012 report, are taken as reference ships.

Keywords: Residual strength; Collision damage models; Oil tanker; Bulk carrier; Reliability analysis

1. Introduction

Hull girder residual strength check, following collision or grounding events, is generally based on Rule damage scenarios, providing penetration depths and heights, as a function of ship main dimensions. The first studies on hull girder resistance against collision were carried out at the beginning of the 1980s by Germanischer Lloyd, within the "Tanker Safety" research programme (Egge and Böckenhauer, 1991), funded by the German ministry of research and technology, and devoted to evaluate the absorbed plastic deformation energy in a ship−ship collision. In 1986 GL Rules included for the first time the additional class notation COLL, followed by a number ranging from 1 to 6 and indicating the ratio of deformation energy absorbed during collision by the vessel to the reference value of a similarly sized non-strengthened single side hull (Egge and Böckenhauer, 1991). Some years later, the American Bureau of Shipping published the first guidelines for the assessment of hull girder residual strength of oil tankers (ABS, 1995a) and bulk carriers (ABS, 1995b), following collision or grounding events, with the main aim of avoiding post-accident hull girder collapses, during towing or rescue operations. In the same year, the International Maritime Organization (IMO) provided the first international standard for the evaluation and approval of alternative methods of design and construction of oil tankers, embodied by MEPC.66(37) and, in a revised form, by MEPC.110(49) Resolution (IMO, 1995; IMO, 2003). The basic philosophy of guidelines consists of comparing the oil outflow performances of an alternative tanker design with reference values of a double-hull ship, complying with Regulation 13(F) of Marpol 73/78. In this respect, as calculation of oil outflow

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performances is mainly based on a stochastic approach, devoted to evaluate probabilities of zero, mean and extreme outflows, guidelines provide damage density distributions of transverse penetration, longitudinal/vertical location and extent of collision and grounding events. Hence, in the last decade, following Prestige's accident occurred in 2002, hull girder residual strength became a very popular topic and new strength checks were provided by Det Norske Veritas (DNV, 2011), that introduced the additional class notation CSA-2 for ships complying with enhanced fatigue and ultimate limit state criteria, including residual strength after collision or grounding events. Finally, the IMO Maritime Safety Committee adopted, at the 87th session in May 2010, the resolution MSC.290(87) that partly emended SOLAS requirements for structure, subdivision and stability of oil tankers and bulk carriers of 150 m in length and above, whose building contract is placed on or after 1st July 2016, making mandatory that ships have to be designed and constructed for a specified design life, to be safe and environmentally friendly in both intact and damage conditions, throughout their life. Hence, construction rules for bulk carriers and oil tankers of Classification Societies acting as IMO Recognized Organizations or National Administrations were checked to verify the conformity with the new goal-based ship construction standards for bulk carriers and oil tankers. In this respect, the International Association of Classification Societies (IACS) delivered the Common Packages 1 and 2, comprising various IACS requirements to support the requests from its member societies and embodied in the “Harmonized Common Structural Rules for Bulk Carriers and Oil Tankers” (IACS, 2015a) a mandatory residual strength check criterion for ships with length equal or greater than 150 m.

At the same time, several efforts have been undertaken to harmonize damage stability regulations among different vessel typologies and investigate the impact of a probabilistic approach on safety levels of existing and new ships. In this respect, two EU-funded projects, namely HARDER and GOALDS, were launched in March 2000 and September 2009, as a consortium of 19 and 18 Organizations from industry and academia in Europe, respectively. The main aim of HARDER project was to collect and analyse collision events occurred from 1944 to 1999, updating the IMO database, initially developed for A.265(VIII) Resolution (IMO, 1973). In this respect, based on the newly developed probability distributions of non-dimensional damage location, length, penetration and vertical extent of collision events, new probabilistic damage stability regulations were developed and embodied in SOLAS 2009 (IMO, 2009). Following the main outcomes of HARDER project, the recently launched one, namely GOALDS, rechecked previous results and extended the probabilistic framework of damage stability regulations to grounding events. Particularly, HARDER casualty statistics were updated, including collision and grounding events from 2000 to 2009, mainly based on Lloyd's Register Fairplay database, increasing the overall number of registered accidents up to 1016 collision and 476 grounding events (IMO, 2012). In this respect, the newly performed statistical analyses not only confirmed the main outcomes of HARDER project, but also provided new data on collision and grounding statistical properties for different vessel typologies, namely passenger and ro−ro ships, containerships, general cargo vessels, oil tankers and bulk carriers.

In the same years, due to the growing interest in evaluating ship response in damage conditions, more refined structural models, capable of accurately predicting hull girder sagging/hogging residual strength, following collision or grounding events, were developed by several researchers (Smith and Pegg, 2003; Özgüç and Barltrop, 2008; Choung et al., 2012; Alie et al., 2012; Kim et al., 2013; Choung et al., 2014; Campanile et al., 2015, among others), with the main aim of providing a structural model, based on classical incremental iterative method, but capable of satisfying the horizontal bending moment equilibrium equation, in case of asymmetrically damaged cross-sections. At the same time, hull girder reliability in damage conditions was investigated, focussing on limit state functions after collision events (Fang and Das, 2005), operational conditions and hull girder deterioration (Saydam and Frangopol, 2013), incidence of welding residual stresses and material properties on hull girder reliability (Campanile et al., 2015, 2016a).

Nevertheless, in all cases statistical properties of hull girder residual strength have been determined on the basis of deterministic Rule damage scenarios, neglecting the incidence of damage variability. In this respect, as some concerns arise when applying deterministic damage scenarios to assess the hull girder residual strength statistical properties and perform reliability analysis in damage conditions, the paper provides a comparative analysis among deterministic and stochastic collision damage models for oil tanker and bulk carrier reliability, following collision events. Particularly, the IACS deterministic model, actually embodied in the “Harmonized Common Structural Rules for Oil Tankers and Bulk Carriers” (IACS, 2015a) is compared with two stochastic collision damage models, the former based on the main outcomes of the recently developed GOALDS statistics (IMO, 2012), the latter derived by MEPC.110(49) Resolution (IMO, 2003). Particularly, the paper focuses on three main aspects:

(i) Statistical properties of hull girder residual strength, based on net scantling approach (IACS, 2015a), are investigated by Monte Carlo simulation, accounting for uncertainties due to material properties and deterministic/random damage dimensions, depending on the applied collision damage model.
(ii) Reliability analysis is performed by Monte Carlo simulation, to investigate the incidence of randomness due to collision penetration depth/height on sagging/hogging failure probabilities.
(iii) The incidence of corrosion on residual strength statistical properties and hull girder reliability, following a collision event, is investigated focussing on three hull girder corrosion wastage conditions, namely gross scantlings, hull girder net scantlings and local net scantlings, respectively.

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The double hull oil tanker and the single side bulk-carrier, benchmarked by the ISSC Ultimate Strength Committee (ISSC, 2012), are assumed as test cases for reliability analysis. All calculations are performed by dedicated programmes developed in Matlab (MathWorks, 2014).

2. Collision damage models

2.1. IACS collision damage model

According to IACS (2015b) reliability model for oil tankers and bulk carriers, hull girder residual strength is based on damage dimensions provided by the "Harmonized Common Structural Rules for Oil Tankers and Bulk Carriers" (IACS, 2015a) for ships with length equal or greater than 150 m. Particularly, IACS (2015a) collision damage model, mainly based on CSA-2 criterion provided by Det Norske Veritas (DNV, 2011), assumes that damaged area involves the strength deck, as reported in Fig. 1, so as failure in sagging is more likely to occur than in hogging condition. In this respect, the ratio of collision penetration height h to moulded depth D is equal to 0.75 and 0.60 for single and double side ships respectively, while the collision penetration depth d to moulded breadth B ratio is equal to 1/16, independently of side shell arrangement.

2.2. GOALDS/IMO collision damage models

The final report of GOALDS project (IMO, 2012) provides, in graphical form, the cumulative distribution functions (Cdf) of collision penetration depth to breadth d/B and height to depth h/D ratios for oil tankers and bulk carriers, that have been resembled by a multilinear approximation and reported in Fig. 2(a) and (b), in black continuous lines, with relevant knuckle points. In this respect, it must be pointed out that, even if penetration depth and height exhibit 5% and 10% exceedance probability levels of one-half moulded breadth and depth respectively, in current analysis maximum d/B and h/D ratios are taken equal to 0.50 and 1.00, in compliance with the main outcomes of GOALDS report, where it is suggested not to overtake those values for practical purposes. The same Figures also reports the cumulative functions of IMO collision damage model (black dashed lines), derived by MEPC.110(49) Resolution (IMO, 2003), providing "Interim Guidelines for Alternative Methods of Design and Construction of Oil Tankers under Regulation 13F(5) of Annex I of Marpol 73/78". Finally, red dash-dot lines refer to damage dimensions provided by IACS (2015a) collision damage model.

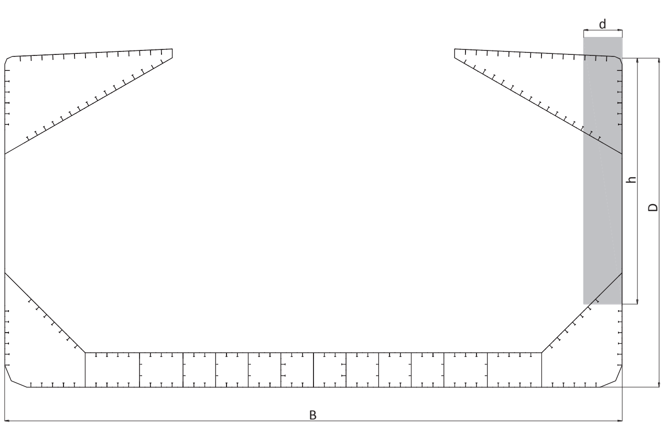

Fig. 1. Collision damage scheme.

Based on cumulative distribution functions reported in Fig. 2, it is gathered that the incidence of collision models on penetration depth and height statistics is noticeable. In this respect, IACS collision penetration depth is characterized by a distribution probability level of about 47% and 80%, if GOALDS or IMO database statistics are applied, respectively. Similarly, IACS collision penetration height for ships with double (single) side shell arrangement leads to distribution probability levels of about 62% (72%) and 80% (87%), based on GOALDS and IMO cumulative distribution functions. Finally, damaged area is assumed in the present analysis to be located in the vertical plane, so as the strength deck is always involved and failure in sagging is likely to occur, in compliance with IACS (2015a) collision damage model.

3. Reliability analysis

3.1. Limit state formulation

The limit state function for hull girder reliability in damage conditions g(x) can be described as Eq. (1) according to IACS (2015a):

$$g(\mathbf{x}) = M_R X_R - (M_{WV} X_{ST\text{-}DAM} X_{NL} + M_{SW} X_{SW} + M_{SW\text{-}DAM}) \tag{1}$$

having denoted by: M_R the hull girder residual strength, after a collision event; M_{WV} the wave bending moment in damage conditions; M_{SW} the still-water bending moment and $M_{SW\text{-}DAM}$ the still-water sagging moment increase, due to flooding of one cargo hold. Besides, X_R is the model uncertainty factor on residual strength capacity, mainly due to differences between the incremental-iterative method and FE analysis; $X_{ST\text{-}DAM}$ and X_{NL} are the vertical wave bending moment uncertainties, due to linear and non-linear response calculations, respectively; X_{SW} accounts for still water bending moment uncertainties, mainly due to loading condition variability among different voyages. In this respect, as gathered from summary of random variables reported in Table 1, all uncertainty factors follow the normal distribution, while the vertical wave bending moment follows the Gumbel law, based on rule values of wave loads, with 3-month exposure time T_E and worldwide environmental conditions, as further discussed in Subsection 3.3. Besides, sagging/hogging still water bending moments are normally distributed, with mean values and standard deviations depending on rule values $M_{SW\text{-}SAG}$ and $M_{SW\text{-}HOG}$ respectively, in absence of more precise data on ship loading conditions. As concerns the sagging moment increase, due to flooding of one cargo hold, it is determined as a fraction of still water bending moment, as detailed in Table 1. Finally,

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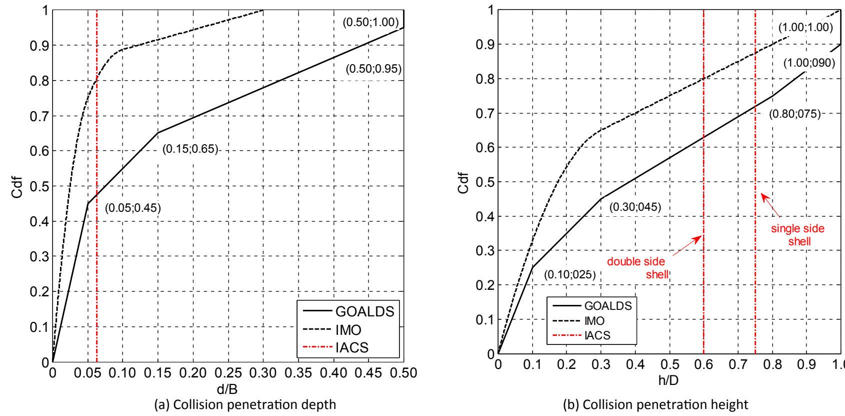

Fig. 2. GOALDS/IMO cumulative distribution functions and IACS values.

Table 1
Summary of random variables.

Description	Item	Distribution	Mean value	Standard deviation
Hull girder residual strength capacity	M_R	Depending on collision damage model	From Monte Carlo simulation	
Model uncertainty factor	X_R	Normal	1.05	0.10
Vertical wave bending moment	M_{WV}	Gumbel	From rule vertical wave bending moment (T_E = 3 months; worldwide)	
Model uncertainty factor	$X_{ST\text{-}DAM}$	Normal	1.00	0.15
Model uncertainty factor	X_{NL}	Normal	1.00	0.10
Still water bending moment	M_{SW}	Normal	$0.45M_{SW\text{-}SAG}/0.65M_{SW\text{-}HOG}$	$0.25M_{SW\text{-}SAG}/0.25M_{SW\text{-}HOG}$
Model uncertainty factor	X_{SW}	Normal	1.00	0.10
Still water bending moment deterministic increase	$M_{SW\text{-}DAM}$	—	0.50 $M_{SW\text{-}SAG}$	—

statistical properties of hull girder residual strength, mainly depending on the applied collision damage model, are directly determined by Monte Carlo simulation, as discussed in Section 5.

3.2. Hull girder residual strength

According to IACS (2015b) reliability model for oil tankers and bulk carriers, hull girder residual strength follows the lognormal distribution with 0.05 coefficient of variation (COV) and mean value based on net scantling approach and Rule values of material yield strength (IACS, 2015a). Furthermore, all elements inside the damaged area, after collision or grounding events, are deleted from the structural model and the Smith method (IACS, 2015a), based on equilibrium of axial forces, is applied, disregarding the equilibrium of the horizontal bending moment, in case of asymmetrically damaged cross-sections, and neglecting the combined effects of vertical shear (Campanile et al., 2010) and non-uniform torsion (Campanile et al., 2009). Really, it is conceivable that hull girder residual strength is generally affected by several sources of uncertainties, during the entire ship lifetime, mainly due to: (i) random corrosion wastage of structural elements (Kim et al., 2014), (ii) welding residual stresses and fatigue (Paik et al., 1998; Paik and Frieze, 2001; Saydam and Frangopol, 2013; Zhu and Frangopol, 2013), (iii) randomness of geometrical (Ivanov, 1986) and material (Vhanmane and Bhattacharya, 2011) properties, (iv) randomness of damage size and location. In this respect, this is the main reason why hull girder ultimate and residual strength variation coefficients are generally affected by a certain variability, as gathered from different values proposed by several researchers in the last two decades: 0.08 (Guedes Soares et al., 1996), 0.10 (Teixeira, 1997; Paik and Frieze, 2001; Fang and Das, 2005), 0.15 (Mansour and Howen, 1994).

In current analysis statistical properties of hull girder residual strength are directly determined by Monte Carlo simulation, accounting for: (i) random material mechanical properties of all structural elements contributing to hull girder residual strength that, in turn, are assumed fully correlated; (ii) deterministic/random collision penetration depths and heights, if IACS or GOALDS/IMO collision damage models are applied. Particularly, material yield strength is assumed to follow the lognormal distribution, with mean value equal to 1.1 times the Rule one (IACS, 2015a), and 0.08/0.06 COVs for mild/high-tensile steels, respectively (Fjeld, 1978; Hart et al., 1985; Hørte et al., 2007; VanDerHorn and Wang, 2011). In this respect, it must be pointed out that yield strength Rule values are equal to about the lower 5% fractile of relevant probability distributions (Hørte et al., 2007) that may be cut, when generating random values of material mechanical properties, so as yield strengths less than Rule values are avoided, in compliance with inspection activities carried out by the Classification Societies. Nevertheless, the lower tail of

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material yield strength probability distributions can be considered on safe side, as carried out by Hørte et al. (2007) who investigated the calibration of hull girder ultimate capacity criterion for double hull tankers, on behalf of Det Norske Veritas, American Bureau of Shipping and Lloyd's Register. Based on previous remarks, the incidence of material yield strength lower 5% fractile has been preliminarily investigated, before performing current reliability analysis. Particularly, it has been verified that percentage differences between hull girder residual strength mean values, with and without the 5% lower fractile of material yield strength, are less than 1%, while COVs and probability distributions remain unchanged. Hence, in compliance with the calibration study performed by Hørte et al. (2007), in current analysis the lower 5% fractile has been considered on safe side, provided that hull girder residual strength are underestimated by about 1%, as materials not complying with minimum Rules values cannot be used, in compliance with class inspection activities.

Furthermore, random generation of collision penetration depths and heights, based on GOALDS and IMO probability functions, is performed assuming that full correlation exists between random variables, to avoid unrealistic damage scenarios, characterized by extremely high penetration depths, coupled with extremely low penetration heights, or vice versa. Finally, the modified incremental-iterative method proposed by Campanile et al. (2015) and mainly based on past efforts by Smith and Pegg (2003), Özgüç and Barltrop (2008), Choung et al. (2012), Alie et al. (2012) among others, is applied, to account for instantaneous neutral axis rotation, due to cross-section asymmetry, as regards the centreline, after collision events. Particularly, based on the section scheme reported in Fig. 3, equilibrium equations of axial forces and horizontal bending moments need to be contemporarily satisfied, for any vertical bending curvature χ:

$$\begin{cases} \sum_{i=1}^{M} \sigma_i(\chi) A_i = 0 \\ \sum_{i=1}^{M} \sigma_i(\chi) y_i A_i = 0 \end{cases} \tag{2}$$

having denoted by M the number of structural elements constituting the hull girder cross-section, by y_i and A_i the transverse coordinate and area of the i-th element, with centre

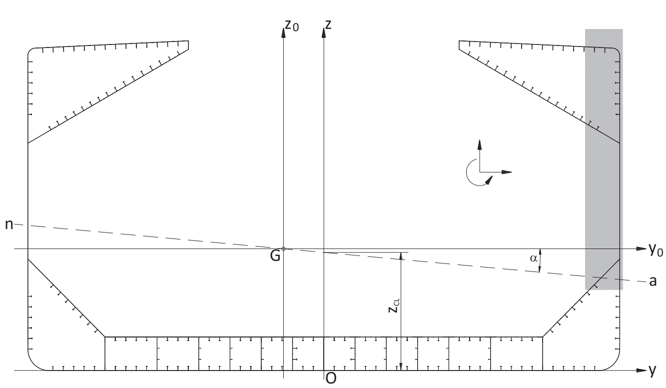

Fig. 3. Global and local reference systems.

of mass $G_i(y_i;z_i)$, as regards the global reference system. Hence, the stress σ_i, due to the imposed curvature χ, is determined assuming that no deformation reversal occurs, when the curvature χ is monotonically increased, and applying the stress—strain curves for hard corners, longitudinal stiffeners and transversely stiffened plate panels provided by IACS (2015a), as a function of the strain ε_i (Campanile et al., 2015):

$$\varepsilon_i(\chi) = [z_i - z_{CL}(\chi) - y_i \tan\alpha(\chi)]\chi \cos\alpha(\chi) \tag{3}$$

having denoted by $z_{CL}(\chi)$ and $\alpha(\chi)$ the instantaneous neutral axis vertical position at centreline and rotation about the horizontal, counter-clockwise positive.

Finally, it must be pointed out that in current analysis possible heelings, due to asymmetric flooding conditions after a collision event, have not been considered, in compliance with the residual strength check provided by CSR-H (IACS, 2015a) and IACS Report on hull girder reliability after damage events (IACS, 2015b). Moreover, the incidence of ship heeling, due to asymmetric flooding conditions, on hull girder residual strength was already investigated by Choung et al. (2014) who determined, for several heeling angles in the range 0°—180°, with 15° step, the damage index, namely the residual to ultimate strength ratio. Based on relevant outcomes, it can be gathered that: (i) maximum hull girder strength percentage reduction occurs at 75° for collision events and that (ii) the dependence of damage index on ship heeling is certainly present, even if moderate, and worthy of being further investigated.

3.3. Vertical wave bending moment

According to IACS (2015b) reliability model, the long-term vertical wave bending moment in damage conditions is determined based on Weibull distribution, while Gumbel law is applied to evaluate the extreme value in n = 1.13E6 load cycles, corresponding to 3-month exposure time T_E, based on a mean wave period of about 7 s (Paik and Frieze, 2001; Hussein and Guedes Soares, 2009):

$$F(x) = \exp\left[-\exp\left(-\frac{x-a}{b}\right)\right] \tag{4}$$

In Eq. (4) a and b are the location and scale parameters of Gumbel law, depending on shape k and scale w parameters of long-term Weibull distribution:

$$a = w[\ln(n)]^{1/k} \tag{5}$$

$$b = \frac{w}{k}[\ln(n)]^{(1-k)/k} \tag{6}$$

The former parameter lies in the range 0.90—1.10 (Wirsching et al., 1997) and is assumed equal to 0.95 in current analysis (Hussein and Guedes Soares, 2009), the latter depends on the exceedance probability level q, assumed equal to 10^{-8}, of worldwide wave bending moment that, in turn, is equal to 80% of the Rule value M_{rule} for North Atlantic sea environment (IACS, 2015b):

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$$q = \exp\left[-\left(\frac{0.8M_{rule}}{w}\right)^{k}\right] \tag{7}$$

It is noticed that the lower value of vertical bending moment, as regards the Rule one, is mainly due to milder climate conditions in coastal areas, where collision events are more likely to occur. Similarly, the return period, equal to 3 months, is lower than the typical value of 1 year, currently applied for reliability analysis in intact conditions, to account for reduced exposure time to environment, before rescue to shore (IACS, 2015b).

3.4. Still water bending moment

Statistical properties of still water bending moment are generally quite difficult to assess, due to different loading conditions in the ship lifetime, as well as for possible flooding of one cargo hold, after collision or grounding events. In this respect, based on IACS (2015b) reliability model, statistics of intact condition are applied, assuming that sagging (hogging) still water bending moment follows the normal distribution, with mean and standard deviation equal to 0.45(0.65) and 0.25 times the maximum value in the loading manual. Besides, a 50% deterministic increase is added to sagging bending moment, to account for possible flooding of one cargo hold.

4. ISSC oil tanker and bulk carrier

The double hull oil tanker and single side bulk carrier, benchmarked for the first time by the ISSC (2000) Special Task Committee VI.2, re-analysed in the ISSC (2012) report and widely investigated in the past by Amlashi and Moan (2008) and Campanile et al. (2014, 2015, 2016a,b) among others, are assumed as test cases for reliability analysis in damage conditions, following a collision event. Ship main dimensions are listed in Table 2, while Fig. 4(a)−(b) report relevant mid-sections, with gross scantlings, frame spacings and materials. Parameters of still water and vertical wave bending moments are reported in Table 3, while statistical properties of hull girder residual strength will be directly investigated by Monte Carlo simulation, accounting for uncertainties due to yield strength of all structural members and random collision penetration depths and heights, if GOALDS or IMO database statistics are applied.

Table 2
ISSC Oil tanker and bulk carrier main dimensions.

Data	ISSC oil tanker	ISSC bulk carrier	Units
Length between perpendiculars	320.0	285.0	m
Rule length	315.0	281.3	m
Moulded breadth	58.0	50.0	m
Moulded depth	30.4	26.7	m
Block coefficient	0.82	0.83	
Gross scantling hull girder ultimate capacity (sag)	22.152	14.708	GNm
Gross scantling hull girder ultimate capacity (hog)	29.089	18.364	GNm

Finally, hull girder bending moment versus curvature diagrams after the IACS like collision event (black continuous lines), are reported in Fig. 5(a) and (b) for the ISSC oil tanker and bulk carrier, respectively. In the same graphs, red dashed and blue dot lines refer to inelastic neutral axis vertical Δz and rotation $\Delta\alpha$ shifts, from relevant elastic neutral axis position (Choung et al., 2012). In both cases, hull girder residual strength is determined by the modified incremental-iterative method, to account for neutral axis rotation, due to cross-section asymmetry after a collision event. Based on current results, neutral axis rotation from relevant elastic neutral axis position ranges from −2 up to 1 deg for the ISSC oil tanker, while it lies from −3 up to 1 deg for the ISSC bulk carrier, in compliance with outcomes stressed by Choung et al. (2012) for a similarly sized double hull oil tanker.

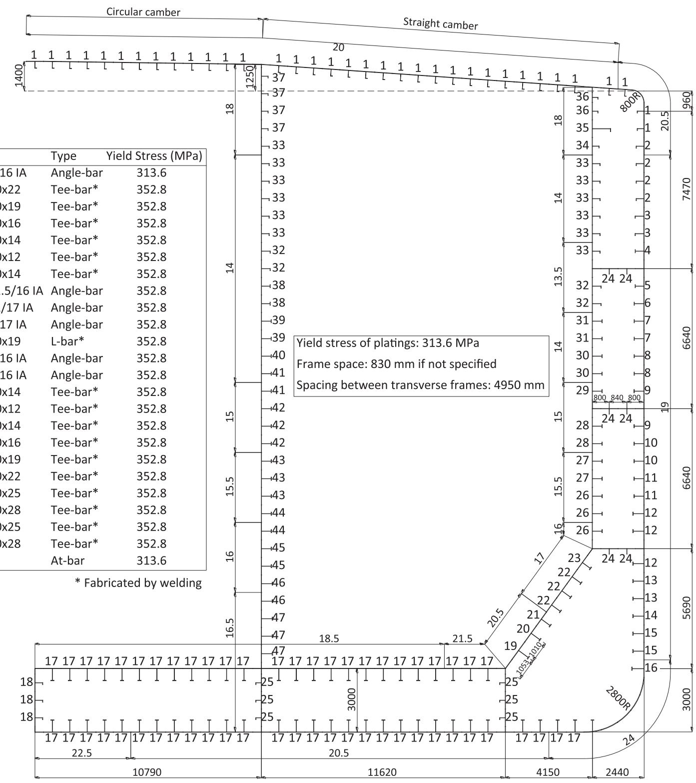
5. Statistical properties of hull girder residual strength

5.1. Residual strength bias

Hull girder residual strength is determined as detailed in Sub-section 3. The double hull oil tanker and single side bulk carrier, benchmarked for the first time by the ISSC (2000) Special Task Committee VI.2, re-analysed in the ISSC (2012) report on hull girder ultimate strength and widely investigated in the past by Amlashi and Moan (2008) and Campanile et al. (2014, 2015, 2016a,b) among others, are assumed as test cases for reliability analysis in damage conditions, following a collision event. In this respect, as yield strength follows the lognormal distribution, with mean value 10% higher than the Rule one, and 0.08/0.06 COVs for mild/high-tensile steels, respectively (Fjeld, 1978; Hart et al., 1985), Monte Carlo simulation is expected to overestimate sagging/hogging residual strength mean values by about 10%, as regards the IACS (2015b) reliability model. Hence, a comparative analysis between IACS (2015b) model and Monte Carlo simulation needs to be preliminarily performed, to investigate the incidence of material yield strength mean values on statistical properties of hull girder residual strength. Based on current results reported in Table 4 with reference to IACS deterministic damage extents, IACS (2015b) reliability model underestimates sagging/hogging residual strength mean values by 7% and 9%, respectively, as regards Monte Carlo simulation, while coefficients of variation are each other comparable. Hence, to consistently evaluate the incidence of damage extent randomness on hull girder residual strength statistical properties, sampled data, obtained by Monte Carlo simulation, need to be divided by 1.07 and 1.09 for sagging and hogging conditions respectively, without varying relevant variation coefficients.

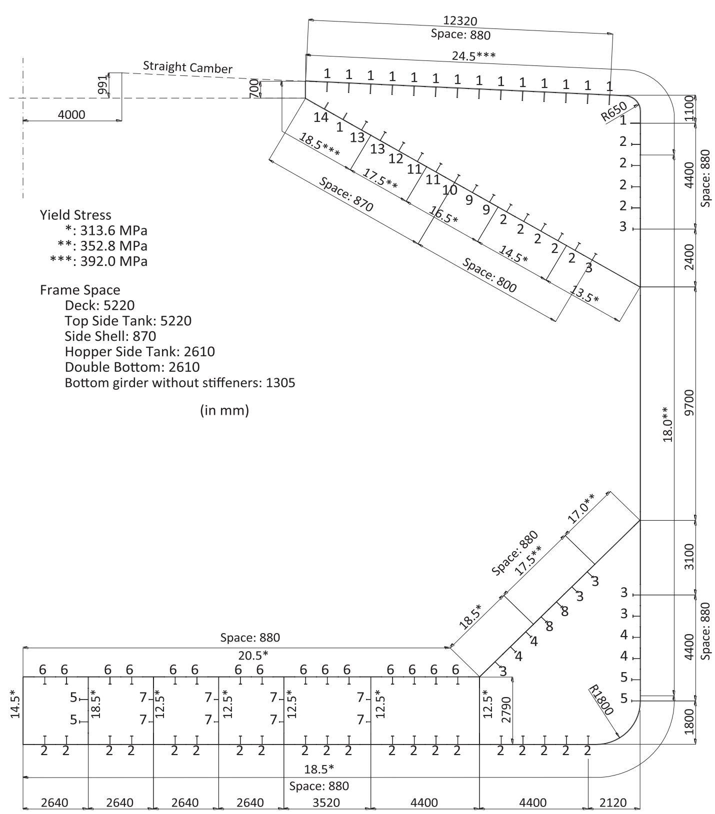
No.	Dimensions	Type	Yield Stress (MPa)	No.	Dimensions	Type	Yield Stress (MPa)
1	300x90x13/17 IA	Angle-bar	313.6	25	250x90x12/16 IA	Angle-bar	313.6
2	350x100x12/17 IA	Angle-bar	313.6	26	450x11+150x22	Tee-bar*	352.8
3	400x100x11.5/17 IA	Angle-bar	313.6	27	450x11+150x19	Tee-bar*	352.8
4	400x11+150x12	Tee-bar*	313.6	28	450x11+150x16	Tee-bar*	352.8
5	400x11+150x14	Tee-bar*	313.6	29	450x11+150x14	Tee-bar*	352.8
6	450x11+150x12	Tee-bar*	313.6	30	450x11+150x12	Tee-bar*	352.8
7	450x11+150x14	Tee-bar*	313.6	31	450x11+150x14	Tee-bar*	352.8
8	450x11+150x16	Tee-bar*	313.6	32	400x100x11.5/16 IA	Angle-bar	352.8
9	450x11+150x19	Tee-bar*	313.6	33	350x100x12/17 IA	Angle-bar	352.8
10	450x11+150x22	Tee-bar*	313.6	34	300x90x13/17 IA	Angle-bar	352.8
11	450x11+150x25	Tee-bar*	313.6	35	850x17+150x19	L-bar*	352.8
12	500x11+150x28	Tee-bar*	313.6	36	250x90x12/16 IA	Angle-bar	352.8
13	500x11+150x30	Tee-bar*	313.6	37	300x90x12/16 IA	Angle-bar	352.8
14	500x11+150x32	Tee-bar*	313.6	38	400x11+150x14	Tee-bar*	352.8
15	500x11+150x34	Tee-bar*	313.6	39	450x11+150x12	Tee-bar*	352.8
16	550x12+150x30	Tee-bar*	313.6	40	450x11+150x14	Tee-bar*	352.8
17	550x12+150x25	Tee-bar*	313.6	41	450x11+150x16	Tee-bar*	352.8
18	350x100x12/17 IA	Angle-bar*	313.6	42	450x11+150x19	Tee-bar*	352.8
19	550x12.5+150x32	Tee-bar*	352.8	43	450x11+150x22	Tee-bar*	352.8
20	500x11.5+150x30	Tee-bar*	352.8	44	450x11+150x25	Tee-bar*	352.8
21	500x11.5+150x28	Tee-bar*	352.8	45	450x11+150x28	Tee-bar*	352.8
22	500x11+150x25	Tee-bar*	352.8	46	500x11+150x25	Tee-bar*	352.8
23	450x11+150x28	Tee-bar*	352.8	47	500x11+150x28	Tee-bar*	352.8
24	250x12.5	At-bar	313.6	48	230x12.5	At-bar	313.6

* Fabricated by welding



(a)ISSC 0il tanker

No.	Dimensions	Type	Yield Stress (MPa)
1	390x27	Flat-bar	392.0
2	333x9+100x16	Tee-bar	352.8
3	283x9+100x14	Tee-bar	352.8
4	283x9+100x18	Tee-bar	352.8
5	333x9+100x17	Tee-bar	352.8
6	283x9+100x16	Tee-bar	352.8
7	183x32.5x9.5	Bulb-bar	235.2
8	283x9+100x17	Tee-bar	352.8
9	333x9+100x18	Tee-bar	352.8
10	333x9+100x19	Tee-bar	352.8
11	383x9+100x17	Tee-bar	352.8
12	383x10+100x18	Tee-bar	352.8
13	283x10+100x21	Tee-bar	352.8
14	300x27	Flat-bar	392.0



(b)ISSC bulk carrier

Figure 4. Section schemes

Fig. 4. Section schemes.

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Table 3
Still water and vertical wave bending moment parameters.

Item	Distribution	Parameter	Units	ISSC oil tanker		ISSC bulk carrier	
				Sag	Hog	Sag	Hog
M_{WV}	Gumbel	Location parameter	GNm	6.169	5.748	4.237	3.970
		Scale parameter	GNm	0.466	0.434	0.320	0.300
M_{SW}	Normal	Mean value	GNm	2.217	4.199	1.523	2.860
		Standard deviation	GNm	1.232	1.615	0.846	1.100
$M_{SW\text{-}DAM}$	—	Deterministic increase	GNm	2.464	—	1.692	—

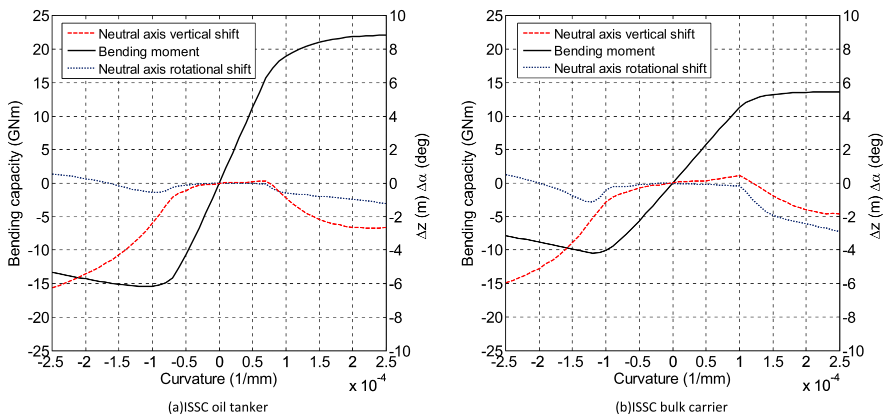

Fig. 5. Moment-curvature diagrams in damage conditions.

Table 4
Comparative analysis between IACS (2015b) format and Monte Carlo simulation.

Test case	IACS (2015b) model				Monte Carlo simulation			
	Mean [GNm]		COV		Mean [GNm]		COV	
	Sag	Hog	Sag	Hog	Sag	Hog	Sag	Hog
ISSC oil Tanker	15.393	22.068	0.050		16.460	23.977	0.040	0.050
ISSC bulk Carrier	10.466	13.623			11.211	14.899	0.043	0.055

5.2. ISSC oil tanker and bulk carrier

Statistical properties of ISSC oil tanker and bulk carrier residual strength are reported in Table 5, while best-fit probability density functions, determined by Maximum Likelihood Estimate techniques (MathWorks, 2014), are plotted in Fig. 6(a)—(f) and 7(a)—(f), respectively, together with sampled data frequency histograms, whose bin size is determined as a function of data set interquartile range (Graham and Cook, 1996).

Table 5
Statistical properties of ISSC oil tanker and bulk carrier residual strength.

Damage model	Parameters	ISSC oil tanker		ISSC bulk carrier	
		Sag	Hog	Sag	Hog
IACS	pdf	Lognormal distribution		Lognormal distribution	
	μ [GNm]	2.732	3.090	2.348	2.614
	σ [GNm]	0.040	0.051	0.043	0.055
GOALDS	pdf	Mixture of two normal distributions		Mixture of two normal distributions	
	μ_1 [GNm]	16.448	22.370	11.003	13.970
	σ_1 [GNm]	1.861	2.108	1.483	1.607
	μ_2 [GNm]	9.846	13.786	6.132	7.384
	σ_2 [GNm]	0.729	1.286	0.426	1.039
	p	0.803	0.800	0.727	0.711
	Δ	4.673	4.916	4.465	4.866
IMO	pdf	Mixture of two normal distributions		Mixture of two normal distributions	
	μ_1 [GNm]	17.645	22.564	11.810	14.500
	σ_1 [GNm]	1.312	2.201	0.878	1.322
	μ_2 [GNm]	14.285	18.874	8.511	9.029
	σ_2 [GNm]	0.948	0.767	1.542	1.366
	p	0.837	0.576	0.871	0.937
	Δ	2.936	2.238	2.631	4.069

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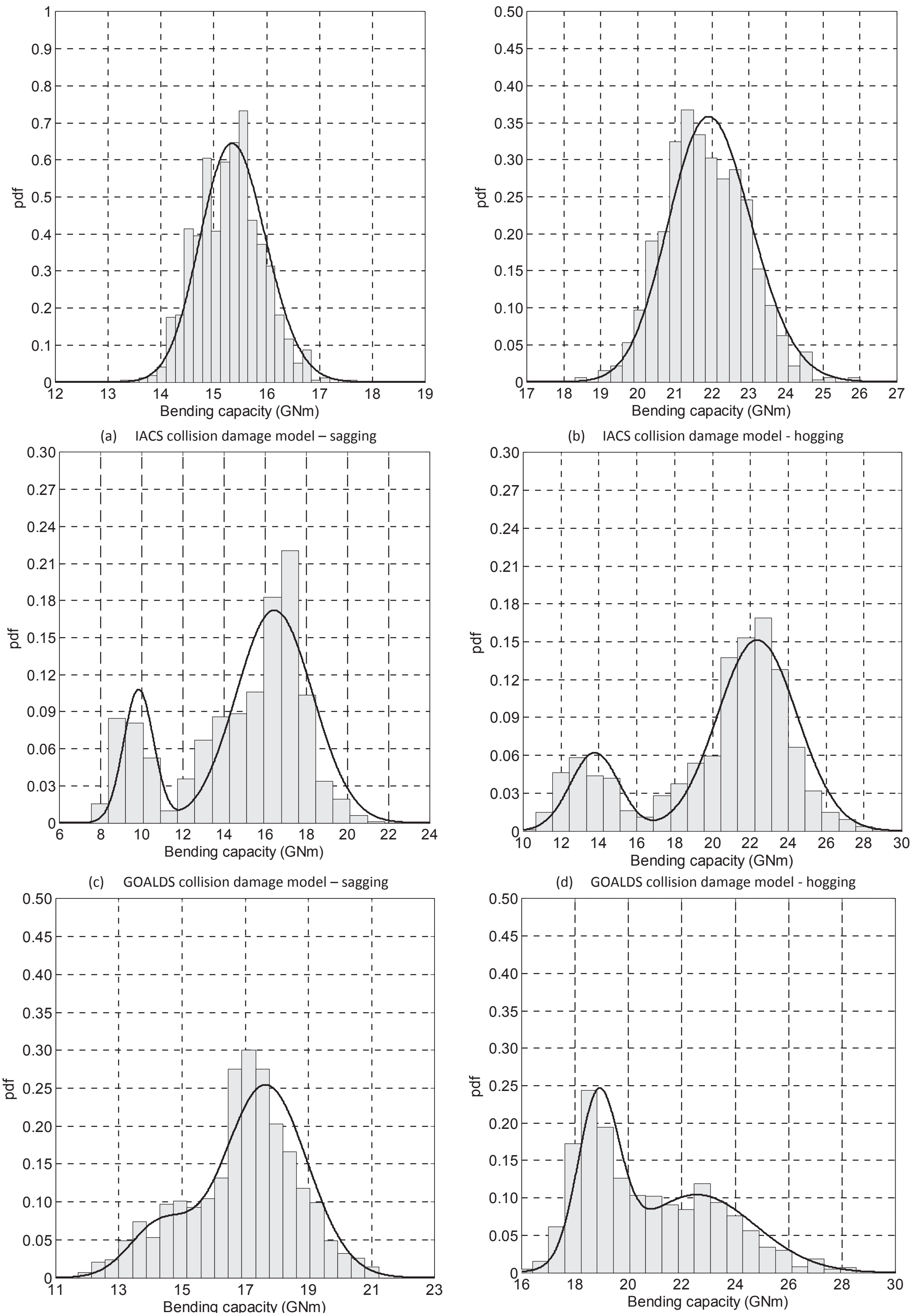

(a) IACS collision damage model – sagging

(b) IACS collision damage model - hogging

(c) GOALDS collision damage model – sagging

(d) GOALDS collision damage model - hogging

(e) IMO collision damage model - sagging

(f) IMO collision damage model - hogging

Fig. 6. Frequency histograms of ISSC oil tanker residual strength.

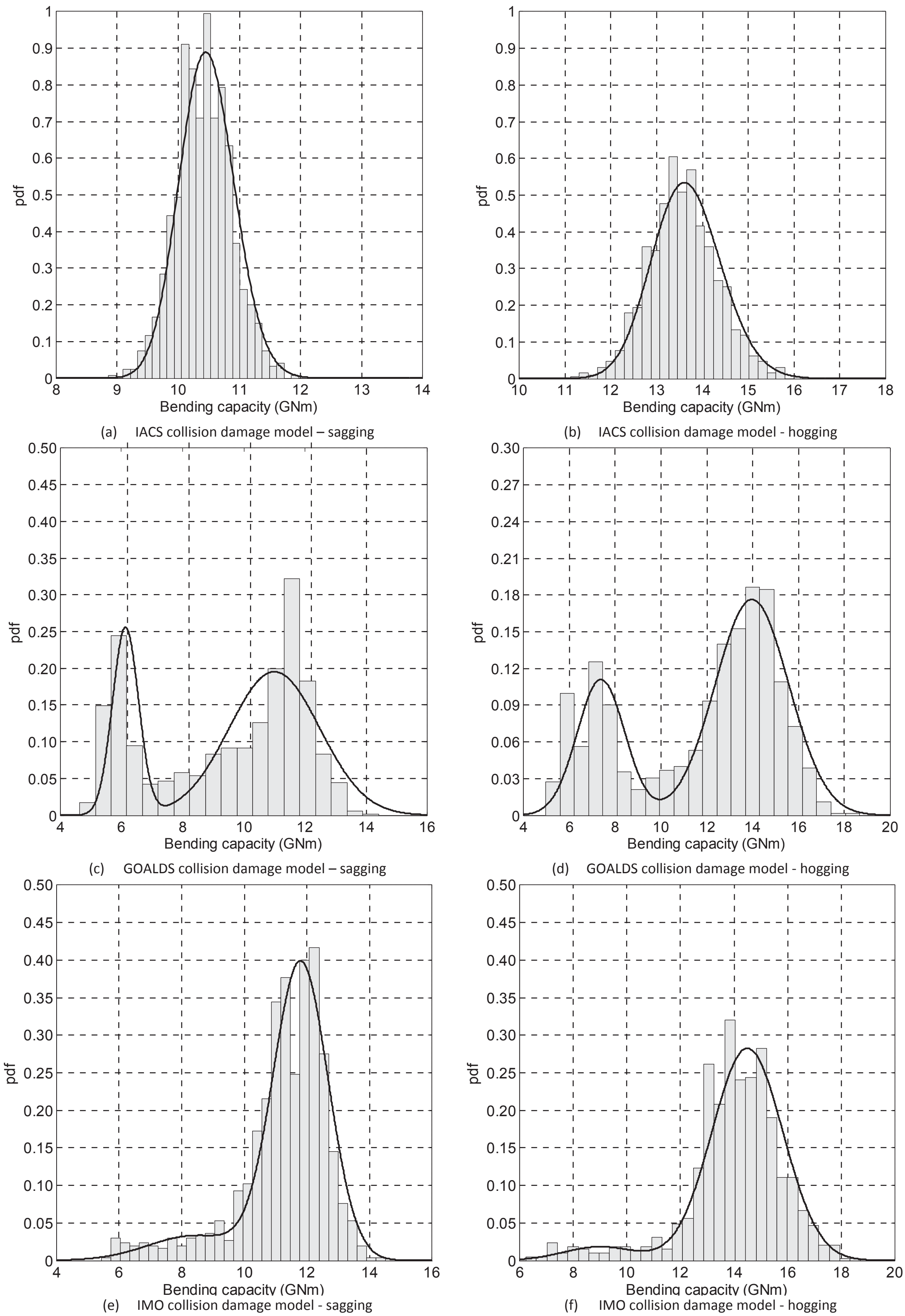

Fig. 7. Frequency histograms of ISSC bulk carrier residual strength.

Based on current results, sagging/hogging residual strength follows the lognormal distribution, with mean value μ and standard deviation σ, if IACS collision damage model is applied. On the contrary, bimodality occurs if random generation of collision penetration depths and heights is based on GOALDS/IMO database statistics, as confirmed by the Ashman et al. (1994) parameter Δ that is always greater than 2, which implies that sampled data don't follow a unimodal distribution. In the examined cases, a mixture of two normal distributions, with mean values μ_1 and μ_2, standard deviations σ_1 and σ_2, mixing parameters p and (1-p) respectively, resembles sagging/hogging residual strength probability functions. Bimodality is mainly due to collision penetration depth and height statistics, provided by GOALDS and IMO databases for oil tankers and bulk carriers and reported in Fig. 2(a) and (b). In this respect, sampled data of ISSC oil tanker residual strength are gathered around two mean values, the former relative to collision scenarios not involving the inner side, the latter relative to more serious damage events, with penetration depths and heights up to half the ship breadth and bottom, respectively. Similar outcomes can be stressed for the ISSC bulk carrier, as also in this case sampled data are gathered around two mean values, corresponding to collision scenarios with penetration depths up to and beyond the hopper tank inner side shell and inner bottom, respectively.

As concerns the GOALDS database statistics, bimodality is very pronounced, as confirmed by the Ashman et al. (1994) parameters of sagging/hogging hull girder residual strength, reported in Table 5 and widely larger than 4. This outcome is mainly due to the statistical properties of GOALDS collision penetration depths and heights, as probabilities of exceedance both inner longitudinal bulkhead and inner bottom are equal to 62% and 20% respectively, which implies that serious damage scenarios, involving the inner side, are quite frequent and substantially affect the statistics of hull girder sagging/hogging residual strength. As concerns the ISSC bulk carrier, probability of collision penetrations exceeding the hopper tanker inner side and double bottom shells are equal to 25% and 20% respectively, so as serious damage scenarios, causing the breaking of the entire hopper tank and double bottom structures, are likely to occur. As concerns the IMO collision damage model, residual strength probability functions are characterized by a slightly less pronounced bimodality compared to GOALDS statistics, as it can be gathered from Figs. 6 and 7 and also by a comparative analysis between the Ashman et al. (1994) parameters that are larger than 2, but in any case consistently lower than GOALDS values. In this case, in fact, probabilities of collision penetration depths and heights exceeding the ISSC oil tanker inner longitudinal bulkhead and inner bottom are equal to about 30% and 7% respectively, which implies that serious damage events are less likely to occur, if compared with GOALDS database statistics. Similar outcomes can be stressed for the ISSC bulk carrier, as probabilities of exceedance the hopper tanker inner side and inner bottom shells, equal to 3% and 7% respectively, are consistently lower than relevant values obtained by GOALDS database statistics.

6. Failure probability following a collision event

6.1. Monte Carlo simulation convergence test

Previous outcomes on hull girder residual strength statistical properties highlight that classical reliability techniques, such as First and Second Order Reliability Methods, cannot be applied to evaluate hull girder sagging/hogging failure probabilities after a collision event, due to the unavailability of normal tail approximation (Sørensen, 2004; Sprinthall, 2011), if bimodality occurs as for GOALDS and IMO database statistics. To overcome this lack, current reliability analysis is performed by Monte Carlo simulation, after carrying out a preliminary convergence test reported in Table 6, to assess the minimum required iteration number N ranging from 10^5 to 10^{10} simulations. Based on IACS (2015b) residual strength statistics, current results highlight that 10^{10} simulations are widely sufficient to achieve convergence of sagging/hogging annual failure probabilities for both ISSC oil tanker and bulk carrier. In this respect, it must be pointed out that failure probabilities are always multiplied by 1.03E-2, to account for probability of collision events, according to IACS (2015b) reliability model. Finally, performed calculations have been carried out by a dedicated programme, developed in Matlab (MathWorks, 2014), requiring about 25 min on a standard 16 GB RAM computer desktop to perform 10^{10} simulations.

6.2. ISSC oil tanker and bulk carrier

Failure probabilities of ISSC oil tanker and bulk carrier are listed in Table 7 and plotted in Fig. 8(a) and (b), respectively. Based on current results, IACS and IMO collision damage models lead to comparable values of sagging failure probabilities. In this respect, IACS values are slightly higher than IMO ones for the ISSC oil tanker, while the opposite holds true for the ISSC bulk carrier. This outcome is mainly due to the incidence on oil tanker residual strength of inner side longitudinal bulkhead that is always damaged according to the IACS model, while it is characterized by a 30% exceedance probability level, if collision penetration depth of IMO database is applied, so leading to higher failure probabilities in the former and lower values in the latter case. The opposite holds true for the single side ISSC bulk carrier, as the complete loss of the hopper tank, that may occur if IMO database is applied, leads to slightly higher failure probabilities, as regards the IACS collision damage model. Finally, in both cases GOALDS database leads

Table 6
Convergence test of Monte Carlo simulation.

N	IACS oil tanker		IACS bulk carrier	
	Sag	Hog	Sag	Hog
1.E+05	1.180E-04	2.060E-07	1.310E-04	1.648E-06
1.E+06	1.163E-04	1.236E-07	1.352E-04	1.205E-06
1.E+07	1.165E-04	1.566E-07	1.341E-04	1.191E-06
1.E+08	1.167E-04	1.469E-07	1.344E-04	1.237E-06
1.E+09	1.167E-04	1.478E-07	1.343E-04	1.238E-06
1.E+10	1.167E-04	1.462E-07	1.343E-04	1.242E-06

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Table 7
Sagging/hogging failure probabilities for ISSC oil tanker and bulk carrier.

Test case	IACS		GOALDS		IMO	
	Sag	Hog	Sag	Hog	Sag	Hog
ISSC oil tanker	1.167E-04	1.462E-07	1.165E-03	3.697E-05	7.867E-05	3.645E-07
ISSC bulk carrier	1.343E-04	1.242E-06	2.119E-03	8.431E-04	2.983E-04	5.545E-05

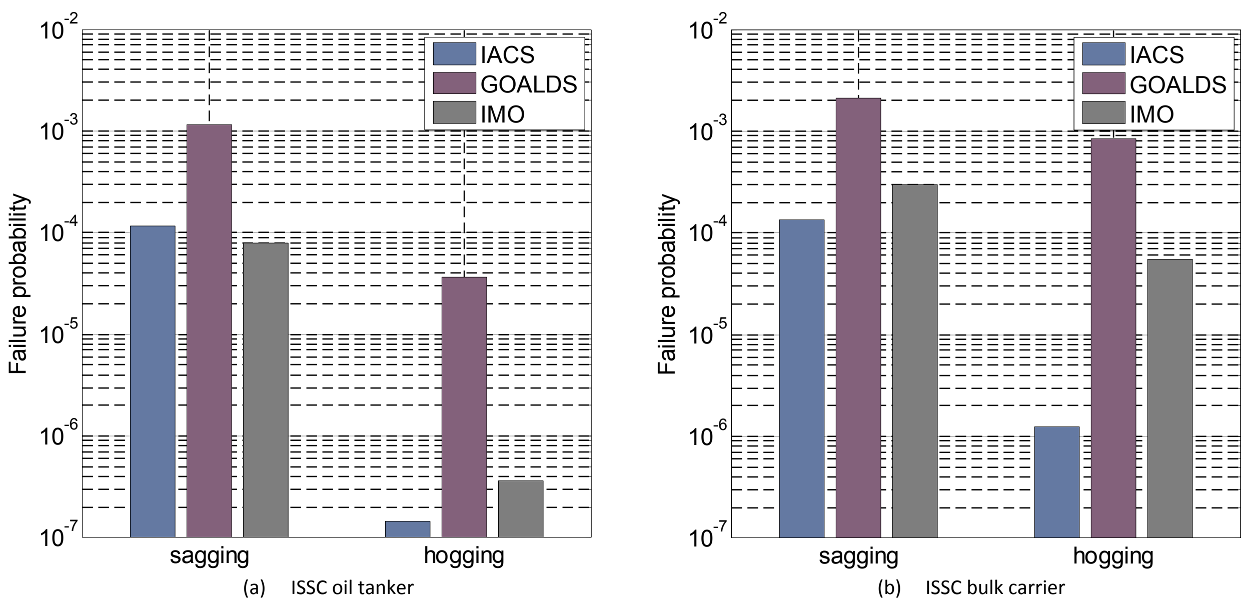

Fig. 8. Sagging/hogging failure probabilities.

to sagging failure probabilities one order of magnitude higher than IACS and IMO ones. This outcome is mainly due to collision penetration depth statistics, provided by GOALDS database and extending up to half the ship breadth, that produce a consistent decrease of hull girder residual strength and consequent increase of sagging failure probability.

As concerns hogging failure probabilities, current results show a strong dependence on the applied damage model, mainly due to collision penetration height, equal to 0.60/0.75 times the ship moulded depth, based on IACS model for double/single side ships, and extending up to the keel line, if GOALDS and IMO collision damage models are applied. In this respect, double bottom structures may be involved in the damaged area, based on GOALDS/IMO statistics, so leading to a consistent increase of hogging failure probabilities. Nevertheless, current values are always negligible, if compared to relevant sagging ones, in compliance with the main outcomes of IACS (2015b) reliability analysis, which implies that only failure in sagging needs to be investigated for practical engineering purposes, independently of the applied collision damage model.

7. Incidence of corrosion wastage on sagging failure probability

The incidence of corrosion additions (IACS, 2015a) on hull girder residual strength statistical properties and reliability in sagging condition is investigated, on the basis of three different wastage scenarios:

(i) *Gross scantlings (GS)*: based on as-built scantlings of all structural members;
(ii) *Hull girder net scantlings (HGNS)*: based on 50% corrosion deduction, applied to as-built scantlings of all structural members;
(iii) *Local net scantlings (LNS)*: based on 100% corrosion deduction applied to as-built scantlings of all structural members.

Residual strength probability functions of ISSC oil tanker and bulk carrier, based on gross (continuous lines), hull girder net (dashed lines) and local net (dot lines) scantlings, are reported in Fig. 9(a)—(f) for IACS, GOALDS and IMO collision damage models. In this respect, sagging residual strength follows the lognormal distribution, independently of the applied corrosion wastage model, with slightly decreasing standard deviations, when moving from gross to local net scantling conditions, as gathered from the increasing peakedness of relevant probability curves. As concerns the stochastic collision damage models, in both cases bimodality occurs, even if in all cases Ashman parameter is higher for GOALDS than IMO database statistics. In the former case bimodal distribution is characterized by a secondary function which is more peaked than the primary one, with increasing

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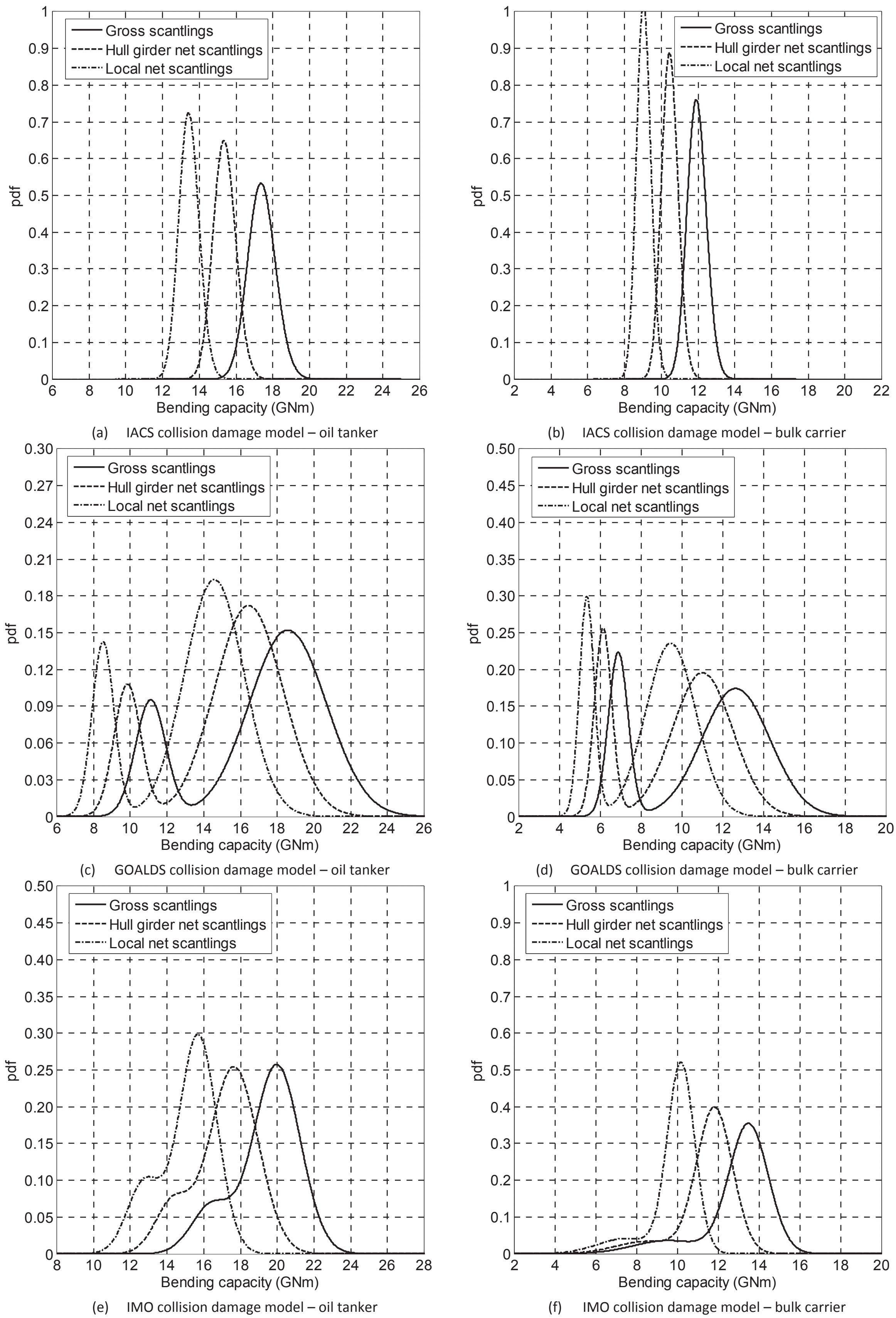

Fig. 9. Incidence of corrosion on hull girder residual strength statistical properties.

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Table 8
Sagging failure probabilities for ISSC oil tanker and bulk carrier.

Collision damage model	ISSC oil tanker			ISSC bulk carrier		
	Gross scantlings	Hull girder net scantlings	Local net scantlings	Gross scantlings	Hull girder net scantlings	Local net scantlings
IACS	1.622E-05	1.167E-04	6.353E-04	1.692E-05	1.343E-04	7.895E-04
GOALDS	6.526E-04	1.165E-03	2.012E-03	1.449E-03	2.119E-03	3.073E-03
IMO	1.154E-05	7.867E-05	3.671E-04	1.413E-04	2.983E-04	8.109E-04

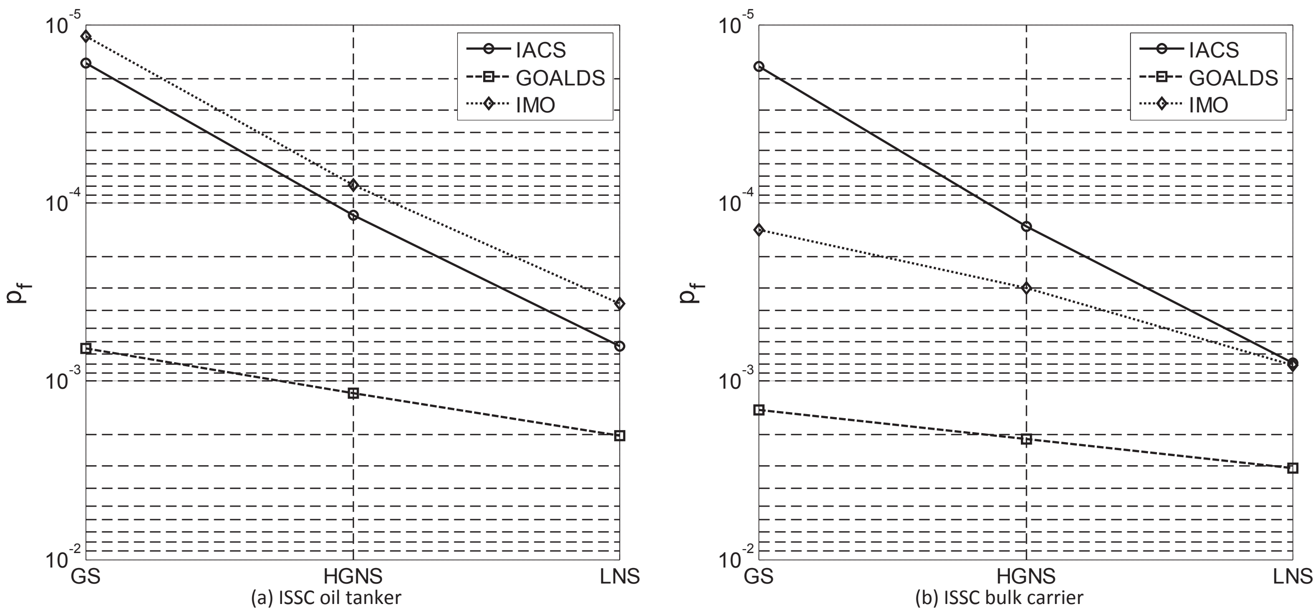

Fig. 10. Incidence of corrosion wastage on sagging failure probabilities.

maxima when moving from gross to local net scantling conditions. In the latter case, bimodality is slightly less marked, even if it is always characterized by increasing peakednesses of both primary and secondary distributions, when moving from gross to local net scantlings. Finally, Table 8 and Fig. 10(a) and (b) report sagging failure probabilities for both ISSC oil tanker and bulk carrier, based on GS, HGNS and LNS conditions. Continuous, dashed and dot lines refer to IACS, GOALDS and IMO collision damage models, respectively.

Based on current results, failure probabilities increase when moving from gross to local net scantling conditions, as it could be predictable. Anyway, couplings between corrosion wastage and collision damage models are noticeable, as IACS and IMO failure probabilities increase much more rapidly than GOALDS ones. Furthermore, while IACS failure probabilities are lower than relevant IMO ones for the ISSC oil tanker, the opposite holds true for the ISSC bulk carrier, mainly due to the different lower tails of relevant bimodal distributions, as gathered from Fig. 9(c)−(f), respectively. Finally, GOALDS database leads to failure probabilities at least one order of magnitude higher than relevant ones based on IACS and IMO collision damage models, depending on corrosion wastage level.

8. Conclusions

A comparative analysis among deterministic and stochastic collision damage models has been performed by Monte Carlo simulation, to investigate the incidence of randomness due to collision penetration depths and heights on hull girder sagging/hogging residual strength statistical properties and reliability. In this respect, the deterministic collision model provided in the “Harmonized Common Structural Rules for Oil Tankers and Bulk Carriers” (IACS, 2015a) is applied and compared with two probabilistic models. The former is derived by the recently developed GOALDS database statistics for collision and grounding events (IMO, 2012), the latter is actually embodied by MEPC.110(49) Resolution (IMO, 2003), providing guidelines for alternative design of oil tankers, based on the comparative analysis of ship outflow performances with relevant values of a reference double-hull vessel, complying with Regulation 13(F) of Marpol 73/78. Hull girder residual strength has been estimated by a modified incremental iterative method, to account for neutral axis rotation, due to cross section asymmetry following collision events. Statistical properties of hull girder residual strength have been assessed on the basis of net scantling approach (IACS, 2015a), accounting for yield strength randomness of all structural elements and relevant bias, as regards reference Rule values for ordinary and high tensile steels. Hence, reliability analysis is performed to investigate the incidence of collision damage models on hull girder sagging/hogging failure probabilities. Finally, the incidence of corrosion wastage on hull girder residual strength and reliability is investigated, focussing on three different scenarios: gross, hull girder net and local net scantlings, respectively. Based on current results, the following main outcomes have been achieved:

(i) Statistical properties of hull girder residual strength depend on the applied collision damage model. In this respect, hull girder capacity follows the lognormal distribution, based on IACS deterministic model, while bimodality occurs, if GOALDS and IMO database statistics are applied. In this respect, bimodality is much more evident for GOALDS than IMO model, mainly due to statistics of collision penetration depth, extending up to 50% and 30% times the ship breadth, inward from the side shell, in the former and latter case, respectively.

(ii) Sagging/hogging failure probabilities, after a collision event, depend on residual strength statistical properties. Particularly, IACS and IMO collision damage models furnish comparable results, while failure probabilities, based on GOALDS database statistics, are one order of magnitude higher. This outcome is mainly due GOALDS residual strength bimodality that is much more pronounced than relevant one, based on IMO stochastic model. Nevertheless, in all cases hogging failure probabilities are negligible, as regards sagging ones, in accordance with the main outcomes of IACS (2015b) reliability model.

(iii) Based on a comparative analysis among gross, hull girder net and local net scantlings, corrosion wastage models play a fundamental role, not only in the assessment of residual strength statistical properties and failure probability levels, as it could be predictable, but also in a comparative analysis among different collision damage models. In this respect, differences between deterministic and stochastic load combination methods decrease when moving from gross to local net scantling conditions. Furthermore, while IMO database statistics lead to higher failure probabilities as regards the IACS one for the ISSC oil tanker, the opposite holds true for the ISSC bulk carrier.

Based on current results, the present analysis, which is one of the first attempts of investigating the incidence of deterministic and stochastic collision damage models on oil tanker and bulk carrier reliability, highlights the need for aligning collision damage models embodied within different Rules. In this respect, if collision penetration depth and height statistics, provided by the recently developed GOALDS database, is confirmed forward in time, residual strength check criteria, that are unlikely to be dimensioning effective on the basis of IACS (2015a) collision damage model, may acquire a more essential role in the longitudinal strength scantling procedures of oil tankers and bulk carriers. Anyway, current outcomes need to be further investigated and a more representative sample of test cases needs to be analysed, in order to verify the availability of current procedures and, eventually, provide a new benchmark study to update actual residual strength check criteria.

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