

Enhanced Design Equations for the Residual Strength Index of Oil Tankers Subjected to Collision and Grounding

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Abstract

In this study, we evaluate the residual longitudinal strength index of three double-hull oil tankers—Aframax, Suezmax, and very large crude carrier (VLCC)—based on collision and grounding scenarios by employing an improved progressive collapse method (PCM). We define the extent of damage based on the IACS-CSR. This study mainly contributes to the extraction of new quadratic equations, which are derived from 51 analytical simulations using curve-fitting. The objective is to establish the relationship between residual strength index (RSI) and damage size ratio (DSR). The proposed PCM incorporates the neutral axis (NA) rotation, overcoming a critical limitation in previous methodologies. Results indicate that not considering NA rotation can lead to a 26% overestimation of RSI. Furthermore, the results of grounding scenarios indicate a larger RSI reduction under hogging conditions than that under sagging conditions; this is attributed to the progressive deck failure and buckling of the inner bottom plating. A comparative analysis shows that inner hull damage significantly deteriorates the RSI reduction, emphasizing the need for refined structural integrity evaluations. Additionally, we analyze the factors affecting the longitudinal strength behavior of damaged ships. The newly extracted RSI–DSR equations and diagrams can be used in practice for rapid damage assessment and RSI estimation, contributing to improvements in ship structural safety and reliability.

Keywords Ship collision and grounding; IACS-CSR; Progressive collapse method (PCM); Residual strength index (RSI); Oil tankers

1 Introduction

The maritime industry is crucial in global trade, where

Article Highlights

- New quadratic equations improve the accuracy of RSI–DSR results for oil tankers, outperforming previous linear models.
- Grounding causes a larger RSI reduction under hogging conditions than that under sagging conditions.
- Not considering the NA rotation can lead to a 26% overestimation of RSI, emphasizing its critical role.

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oil tankers represent a significant portion of this sector. Oil tankers transport ~26% of the total volume of world seaborne trade (Setyohadi et al., 2018). However, incidents such as collisions and groundings frequently compromise the structural integrity of these vessels, leading to catastrophic failures and environmental disasters (Samuelides et al., 2008; Pedersen, 2010; Huynh et al., 2021; Ma et al., 2024). On July 19, 2024, an accident between Hafnia Nile (a 2017-built 74189 DWT product tanker) and Ceres I (a 2001-built tanker) occurred in Singapore waters. As shown in Figure 1, the collision resulted in a fire. Two seafarers onboard Hafnia Nile suffered minor injuries; no confirmation of oil spillage was reported. Although ensuring the safety of the crew and mitigating the environmental impact are top priorities, assessing the residual strength of the hull girder after such incidents is also vital. This assessment facilitates the rapid planning of salvage and rescue operations, ensuring the safety and operability of the damaged vessel.

The performance of double-hull oil tankers after collisions was investigated in previous studies of Parunov et al. (2017), Wu et al. (2018), and Alie et al. (2024), emphasizing the importance of understanding ship structural responses and potential damages. The ultimate hull girder capacity, which is a fundamental strength criterion for ship safety, should be evaluated not only for intact vessels but also for vessels in post-damage conditions. In response, the International



Figure 1 Thick plumes of smoke arising from two oil tankers off the coast of Singapore (RSAF, 2024)

Association of Classification Societies (IACS, 2024) introduced additional requirements in the Common Structural Rules for Bulk Carriers and Oil Tankers (CSR) regarding residual strength to specifically address two accident scenarios: collision and grounding. These requirements, which were released in a review in April 2013, align with the International Maritime Organization (IMO, 2010) Goal-Based New Ship Construction Standards (GBS), which mandate that the structural design of a ship must ensure sufficient residual strength to withstand collisions or grounding.

Various methods, including assumed stress distribution, nonlinear finite element analysis (NLFEA), the intelligent supsize finite element method (ISFEM), and the progressive collapse method (PCM) (Paik, 2018), have been proposed for calculating the hull girder strength of both intact and damaged ships. The stress distribution method originally developed by Caldwell (1965) is limited to simple structural geometries and does not consider the post-collapse strength reduction under compression. Maestro and Marino (1989) extended Caldwell's formulation to biaxial bending and modified the method to estimate the effect of the damage caused by ship grounding or collision on the ultimate hull girder strength. Paik et al. (2013) proposed the modified Paik–Mansour (P–M) method, which improves the bending stress distribution at the ultimate limit state of the yielded area; however, it does not consider post-collapse behaviors, potentially leading to strength overestimation. This method (Paik et al., 2012b) introduced an innovative methodology, i.e., the residual strength–damage index (R–D) diagram approach, for assessing damage in the ship structure caused by grounding. A decade later, Kim et al. (2024) updated the grounding damage data used in these diagrams, incorporating results from 12 different ship types and sizes, enhancing insights into hull girder collapse due to grounding.

Advances in computer technology have made NLFEA feasible, thus providing a reliable and accurate method for evaluating various influencing parameters such as initial imperfections, secondary loadings, in-service degradation, and the use of different materials. In recent studies (Cerik et al., 2019; Prabowo et al., 2020; Liu et al., 2021; Saputra et al., 2024), NLFEA has been applied to

the assessment of structural damage in hulls caused by ship collisions or groundings. However, it exhibits significant limitations, including extensive modeling, long computation time, and reliance on the engineer's expertise, particularly in the nonlinear analysis of large structures. Efforts to overcome these limitations have resulted in ISFEM developed by Hughes and Paik (2010). ISFEM reduces the degrees of freedom, employs large structural elements, while maintains accuracy; it is considered an “intelligent” method because of its ability to preformulate the highly nonlinear behavior of large structural elements, enabling an efficient assessment of the failure modes and structural responses.

Among the existing methods, PCM, which is based on Smith's approach (Smith, 1977), is the most frequently used for evaluating the ultimate strength; it incorporates a sophisticated approach for assessing the structural collapse sequence and post-ultimate strength response of the structural elements. However, its accuracy largely depends on effectively predicting the average compressive strength of stiffened panels and their load-shortening and elongation behaviors. Another limitation of PCM is the difficulty in accurately tracing the instantaneous position of the neutral axis (NA), which translates and rotates under asymmetrical forces caused by structural damage. Despite this, PCM is widely used because of its computational efficiency and easy implementation. Li and Kim (2022) employed PCM to evaluate the damage index-based residual ultimate strength of grounded double-hull oil tankers. In shipbuilding practice, classification societies such as the American Bureau of Shipping (ABS, 2024), Bureau Veritas (BV, 2023) and Lloyd's Register (LR, 2022) recommend the use of PCM based on Smith's approach for evaluating the longitudinal capacity during structural design synthesis.

In this study, the obtained PCM results were used to derive the relationship between the residual strength index (RSI) and the damage size ratio (DSR). By applying curve-fitting techniques, we extracted new quadratic equations to describe this relationship. RSI is a critical parameter for assessing the remaining strength of a vessel after damage; it can be applied to accident investigation, fleet evaluation for maintenance schedules and safety upgrades, as well as the design of vessels with improved residual strength. Several factors, including material properties, damage extent, structural configuration, and loading conditions, affect RSI. Alongside RSI, DSR is an important metric for assessing damage severity relative to the overall structural capacity. Empirical formulas characterizing the RSI–DSR relationship have been proposed in many studies; however, they contain inherent errors caused by the limitations in the methods used to estimate the residual longitudinal strength; in particular, the effects of the NA rotation (NAR) are overlooked. Andrić et al. (2015) developed linear equations that show the relation between residual strength and damage

extent in double-hull oil tankers without considering NAR. The results from their study will be used as a comparative tool to show the effect of NAR on the estimated bending moment of the hull girder and gradually on the extracted RSI–DSR equations and diagrams.

To address this gap, we incorporate NAR into the analytical formulation of PCM to improve the accuracy of the RSI calculations. Systematic investigations by the authors (Ramos et al., 2024b) have demonstrated that not considering NAR can lead to the overestimation of residual strength. Further studies by Makouei et al. (2015), Muis Alie et al. (2016), Tekgoz et al. (2018), and La Ferlita et al. (2022) indicated the necessity of including NAR in the PCM-based evaluations. IACS-CSR guidelines suggest calculating the ultimate longitudinal strength of a damaged section using PCM while initially neglecting NAR effects, followed by a 10% reduction to account for its influence. However, this reduction factor lacks full justification because the actual reduction ratio depends on the location and severity of the cross-section damage.

2 Materials and methods

2.1 Model structure

According to the UN Trade and Development Statistics Handbook (UNCTAD, 2023) and Clarkson Research, in January 2023, the global merchant fleet included ~105 500 vessels of at least 100 GT, where 56 500 ships exceeded 1000 GT. As illustrated in Figure 2, from 1983 to 2023, oil tankers have consistently dominated the global fleet, demonstrating the broad applicability of the design equations and diagrams developed in this study. The Aframax-class double-hull oil tanker (T1) is based on the study conducted by Andrić et al. (2015) and complies with the 2014 CSR. Its cargo tank area is longitudinally divided into six pairs of oil tanks along with corresponding pairs of water ballast tanks. The Suezmax-class double-hull oil tanker (T2) and the very large crude carrier VLCC (T3) are described in the International Ship and Offshore Structures Congress (ISSC) reports of Yao et al. (2000) and Paik et al. (2012a). Figure 3 shows the midship sections of these oil tanker models and their principal particulars. Figure 4 illustrates the distribution of the above three oil tanker models based on their dimensions.

2.2 Ship damage scenarios

Ship grounding and collision incidents are among the primary causes of structural damage to ships. Over the past two decades, Deng et al. (2022) analyzed maritime accidents in China; they found that ~41% of vessel incidents involved collisions, whereas ~4% involved groundings. The structural reliability of ship hulls after various acci-

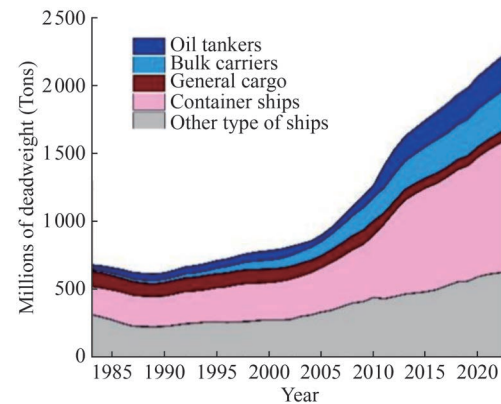


Figure 2 Global fleet composition based on vessel type (UNCTAD, 2023)

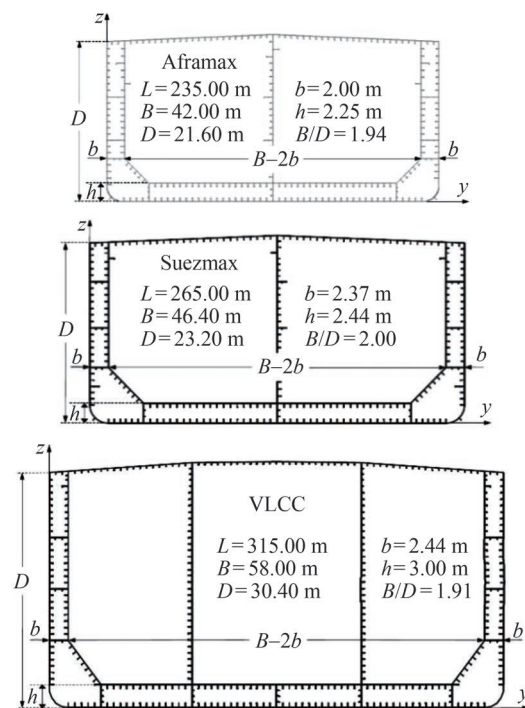


Figure 3 Midship cross-sections of double-hull oil tanker models and their principal particulars (Andrić et al., 2015)

dents has been investigated in several studies, including Bužančić Primorac et al. (2020). Pilatis et al. (2024) examined the size and location of ship damage in collision, grounding, and hull failure scenarios. Additionally, the accident frequency prediction and damage extent estimation have been investigated by Guedes Soares and Teixeira (2001), Zhang et al. (2019), Maternová et al. (2023), and Yıldız et al. (2024); however, estimating the possibility of accidents and extent of ship structural damage remains a complex challenge. Two widely adopted types of approaches have been proposed: probabilistic and deterministic. The probabilistic approach, which is based on the IMO probability density functions, considers parameters such as verti-

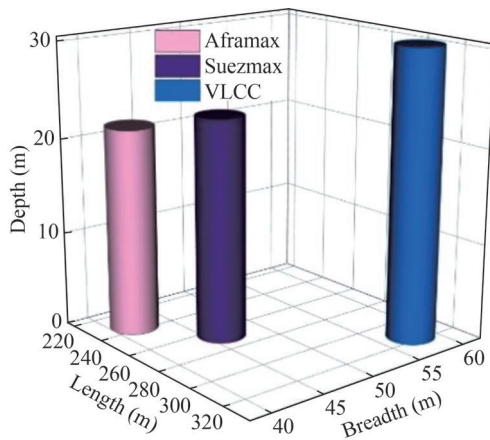
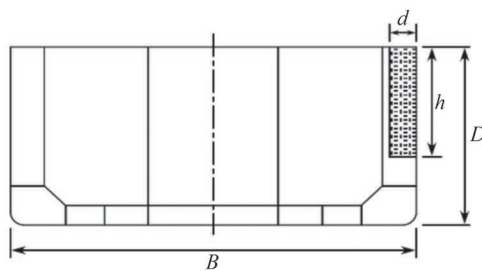


Figure 4 Distribution of the oil tanker models based on their length, breadth, and depth

cal penetration, transverse extent and location, as well as rock penetration angle (for ship grounding). In contrast, the deterministic approach adheres to the classification society regulations. In this study, we employ a deterministic approach following IACS-CSR to model the extent of ship damage, as shown in Figure 5.

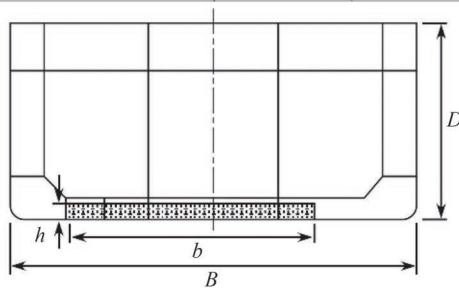
The main factors that affect the reduction in the hull girder

Damage penetration, in m	Side shell arrangement	
	Single side	Double side
Height, h	$0.75D$	$0.60D$
Depth, d	$B/16$	$B/16$



(a) Collision

Damage penetration, in m	Bulk carriers	Oil tankers
Height, h	$\text{Min}(B/20, 2)$	$\text{Min}(B/15, 2)$
Breadth, b	$0.60B$	$0.60B$



(b) Grounding

Figure 5 Damage extent for collision and grounding (IACS, 2024)

strength are the vertical penetration (depthwise damage), transverse extent (breadthwise damage), and the transverse location of the damage. Damage located along the ship centerline is symmetrical, indicating ship grounding, whereas offset damage is asymmetrical, indicating ship collision. Asymmetrical damage affects NA behavior, necessitating the consideration of NAR effects and stress redistribution. The longitudinal extent of damage (lengthwise damage) is generally disregarded because the evaluation of the residual ultimate strength primarily focuses on its cross-sectional reduction at the damage location. This principle is also considered in probabilistic approaches.

According to CSR, in collision scenarios, the damage penetration depth remains constant ($d = B/16$); the damage height (h) varies from $0.1D$ to $0.8D$ with $0.1D$ increments. The specified damage penetration height is set to $0.6D$. The damage penetration is applied unilaterally just below the freeboard deck. In grounding scenarios, the penetration height ($h = \min(B/15, 2)$) remains constant, whereas the damage breadth (b) varies from $0.1B$ to $0.8B$ with $0.1B$ increments. The specified damage penetration is set to $0.6B$. Grounding damage is applied symmetrically along the centerline. All damage extents are measured from the molded lines of the ship.

Based on these parameters, in this study, we considered nine distinct hull integrity states, which include the intact and eight damage states with varying damage extents for both collision and grounding. A total of 51 cases are analyzed to establish the relationship between the RSI and DSR in oil tankers.

2.3 Methodology used for the calculation of the hull girder strength

A major limitation of existing PCMs addressed in this study is the accurate tracing of the instantaneous position of the NA. PCM by IACS-CSR considers only the force equilibrium criterion (Equation (1)), which ensures that tensile and compressive forces above and below the NA are balanced, causing vertical NA translation (NAT). Although this approach is sufficient for intact hulls—where the geometry, load, and material symmetry requirements are met—it becomes inadequate in asymmetrical damage conditions, such as hull damage due to collision. In such cases, the asymmetry in both the geometry and load distribution (once water ingress occurs) leads to erroneous results because the NA both translates and rotates.

To address this issue, we introduce the improved PCM, which considers NAR by integrating an additional force vector equilibrium criterion, as formulated by Choung et al. (2012) (Equation (2)).

$$\frac{|F_c - F_t|}{|F_c + F_t|} \leq \zeta_T \quad (1)$$

$$\frac{\pi}{2} - \zeta_R \leq \cos^{-1} \left(\frac{\mathbf{F} \cdot \mathbf{M}}{\|\mathbf{F}\| \|\mathbf{M}\|} \right) \leq \frac{\pi}{2} + \zeta_R \quad (2)$$

where F_c is the resultant compressive forces due to hull girder moment, F_t is the resultant tensile forces, $\mathbf{F}$ is to the force vector, and $\mathbf{M}$ is the hull girder moment vector. The convergence factor ζ_T is typically set to <1%, whereas the convergence factor ζ_R is set below 0.1° .

The proposed PCM exploits the stochastic nature of the multi-objective particle swarm optimization (MOPSO) algorithm, conducting a random search across all possible NA locations while minimizing the convergence factor for both the force and force vector equilibrium. The algorithm

flowchart is presented in Figure 6. As shown in the authors' previous study (Ramos et al., 2024a), MOPSO-based PCM is fast, reducing the computational time by a factor of 20 compared with the PSO-based Smith method. The comparison was conducted using the double-hull VLCC model (T3). Similar reductions in computational time were consistently observed under various conditions: upright intact, intact with a heel, upright damaged, and damaged with a heel. In addition, the accuracy of the proposed method in tracing the NA motion per curvature is superior compared with that of the linear-search-based Smith method (Li et al., 2018). Furthermore, its accuracy in estimating the ultimate and residual bending moments is better than that of the PCM described in IACS-CSR.

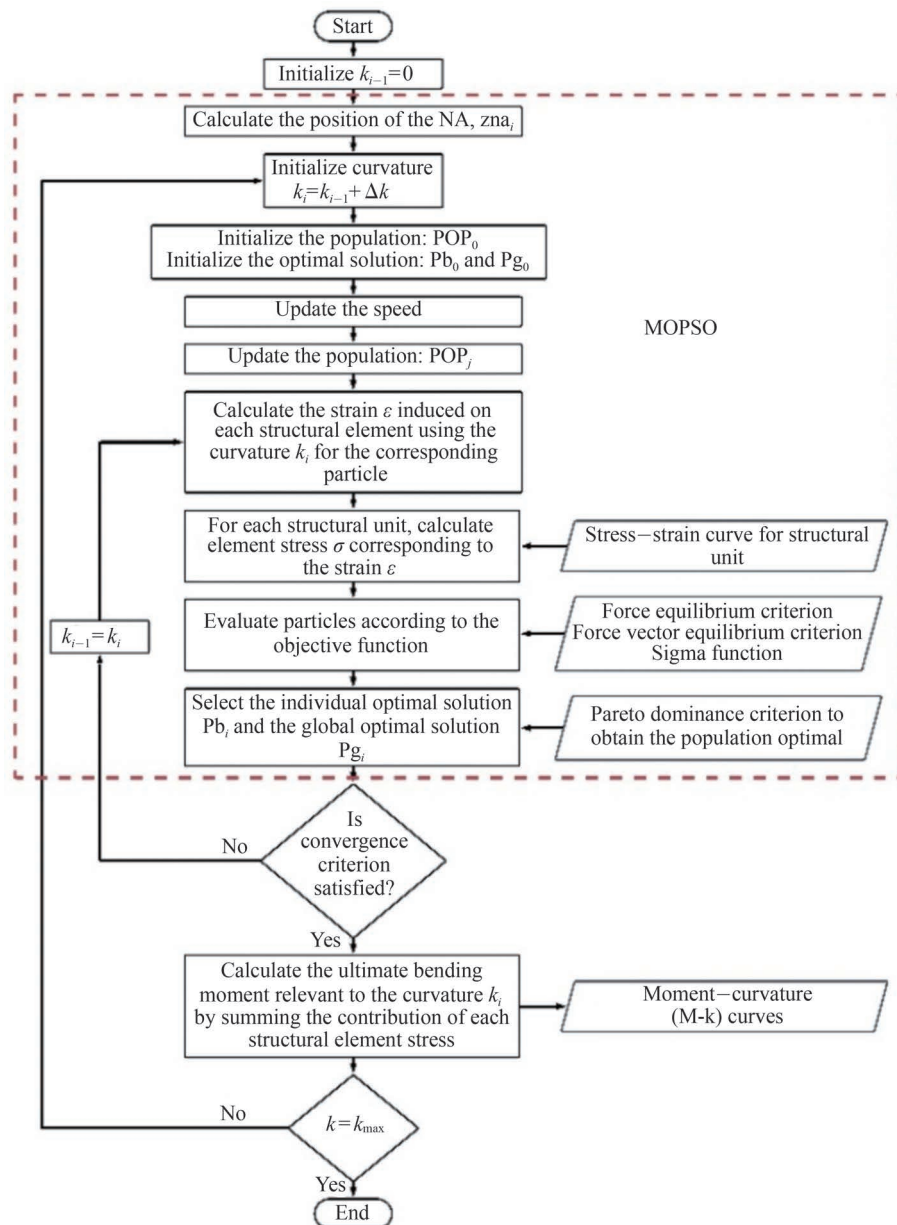


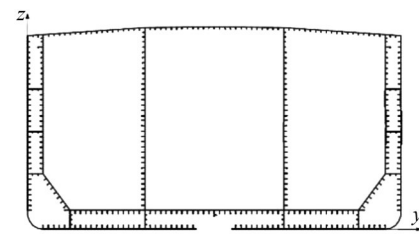
Figure 6 MOPSO-based PCM flowchart (Ramos et al., 2024a)

Table 1 Total number of structural elements in each damage scenario

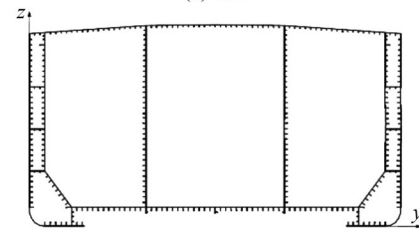
Scenario	Total number of structural elements		
	T1	T2	T3
Grounding	0.1B	325	352
	0.2B	317	340
	0.3B	305	328
	0.4B	297	320
	0.5B	285	308
	0.6B	277	296
	0.7B	265	284
	0.8B	247	270
Collision	0.1D	331	357
	0.2D	325	352
	0.3D	313	340
	0.4D	309	334
	0.5D	303	322
	0.6D	293	316
	0.7D	287	310
	0.8D	275	298

Additionally, the proposed PCM is easy to implement because it does not require extensive user knowledge and needs only two key inputs: 1) stiffener specifications and 2) structural configurations for damage cases, making it well-suited for the preliminary design phase. However, accurate data on the stiffener dimensions and types are crucial, as this information is used for model preparation, which typically requires only a few hours compared with the several weeks required in 3D methods. The input file must specify the dimensions and locations of the stiffeners/plates, which are categorized by type—plate, angle bar/L-bar, bulb-flat/at-bar, tee bar, or hard corner—and their initial yield strengths. The input file consists of 484, 370, and 342 structural elements (plates or plate–stiffener combinations) for T1, T2, and T3, respectively; however, based on the extent of damage, these numbers may vary under different collision and grounding scenarios, as shown in Table 1. When determining whether a stiffener element should be considered damaged, the connection between the stiffener and the attached plate must be included within the extent of damage. Plates and stiffeners of the inner bottom and inner-hull longitudinal bulkhead are generally considered intact unless the extent of damage exceeds the molded distance from the inner bottom or inner-hull longitudinal bulkhead plate to the hull envelope plate. Figures 7 and 8 present examples of the double-hull VLCC (T3) in grounding and collision scenarios, respectively, providing a clear visualization of the hull cross-section damage.

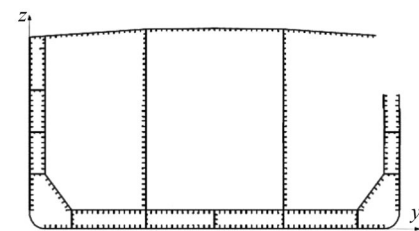
In this study, we considered only symmetrical ship grounding damage cases; this is consistent with IACS-CSR (as explained in Section 2.2), which defines the extent of grounding symmetrically about the ship centerline ($B/2$). As a



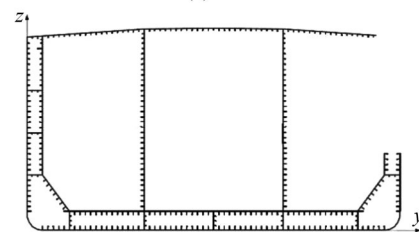
(a) 0.1B



(b) 0.7B

Figure 7 Midship section of the double-hull VLCC (T3) illustrating grounding damage with size ratios of 0.1B and 0.7B

(a) 0.3D



(b) 0.6D

Figure 8 Midship section of the double-hull VLCC (T3) illustrating collision damage with size ratios of 0.3D and 0.6D

result, the induced damage only causes vertical NAT with no expected rotational shift. Nevertheless, the MOPSO-based PCM employed in this study incorporates a force vector equilibrium criterion that enables the detection of NAR under symmetrical or asymmetrical damage conditions. In symmetrical damage scenarios, such as those shown in Figure 7, the outputs are consistently zero NAR values across all hull curvatures. In contrast, in asymmetrical damage scenarios, such as those shown in Figure 8, the method outputs non-zero NAR values. This built-in flexibility ensures that the algorithm is not limited to idealized cases and can be applied to a broad range of hull conditions.

We made the following assumptions regarding the proposed PCM: 1) In the residual bending moment calculation for a damaged section, we followed the same procedure as that for an intact condition; the main difference is

the consideration of NAR for asymmetrical damage cases. 2) To model ship damage caused by collision or grounding, we removed the affected elements within the transverse cross-section of the hull girder because these elements do not carry loads, following the approach proposed by Gordo and Guedes Soares (2000), which has been widely adopted in several studies (Guedes Soares et al., 2008; Khan and Das, 2008; Hussein and Guedes Soares, 2009). 3) The resultant bending moment can be decomposed into the vertical and horizontal load-carrying capacities of the hull girder, neglecting the effects of shear force, torsion loading, and lateral pressure. 4) In the calculation of the ultimate bending capacity of the damaged transverse cross-section, we assumed that the model is in an upright position. A detailed discussion on the formulation of the MOPSO-based PCM is provided by Ramos et al. (2024a).

3 Results and discussion

3.1 Verification of the proposed PCM

Before investigating the relationship between RSI and DSR, we validated the proposed MOPSO-based PCM with other existing methods included in the ISSC benchmark studies of Yao et al. (2000) and Paik et al. (2012a), as well as another related research. A comparison of the ultimate

strength for the three tanker models in intact condition is presented in Table 2. To avoid ambiguity, the following abbreviations used in Table 2 are clarified: ANSYS and ABAQUS refer to NLFEM software programs, ALPS/HULL is an ISFEM simulation tool, and the organizations referenced in the ISSC reports include PNU (Pusan National University), IRS (Indian Register of Shipping), CR (China Corporation Register of Shipping), and UoG (University of Geneva). Figures 9–11 show the moment–curvature curves.

For T1, the PCM proposed by Parunov et al. (2017) yielded results closest to those obtained in this study, estimating the hull girder bending capacity with ~3% deviation under both hogging and sagging conditions. In contrast, the NLFEM (proposed by the same authors) showed the greatest difference, with deviations of ~3.45% and ~11.75% under hogging and sagging conditions, respectively. The PCM results from Andrić et al. (2015) were relatively lower, with differences of ~4.67% for hogging and ~10.39% for sagging. These deviations can be attributed to the different modeling techniques, particularly in element discretization and the inclusion of hard-corner elements. Another factor is that the T1 model used in this study was based solely on the data contained in the referenced studies.

For T2, all CSR-based methods (derived from Smith's approach) provided relatively higher estimates; the highest deviation of 24.41% and 18.96% under hogging and sagging conditions, respectively, was observed between the results obtained using CSR (CR) and those using the pro-

Table 2 Comparison of the proposed algorithm with existing methods regarding ultimate strength for T1, T2, and T3 in the intact condition subjected to sagging and hogging bending moments

Method	Ultimate bending moment of the hull girder (GN·m)					
	T1		T2		T3	
	Hog.	Sag.	Hog.	Sag.	Hog.	Sag.
ISSC 2000	Smith (Chen)	–	–	–	27.40	24.33
	Smith (Cho)	–	–	–	28.66	20.80
	Smith (Yao)	–	–	–	28.88	20.80
	Smith (Rigo)	–	–	–	28.31	19.57
	Modified P–M (Rigo)	–	–	–	25.61	24.07
ISSC 2012	ANSYS (PNU)	–	–	14.07	11.15	27.34
	ANSYS (IRS)	–	–	–	–	30.11
	ABAQUS (CR)	–	–	16.16	14.26	31.01
	ALPS/ HULL (PNU)	–	–	13.31	11.10	25.59
	CSR (BV)	–	–	–	–	23.43
	CSR (CR)	–	–	19.05	14.61	29.85
	CSR (PNU)	–	–	15.71	12.42	28.42
	RINA Rules (UoG)	–	–	–	–	28.20
	Modified P–M (PNU)	–	–	13.97	12.21	25.67
	PCA (Andrić et al., 2015)	10.70	8.37	–	–	–
This study	NLFEM (Parunov et al., 2017)	11.60	10.47	–	–	–
	PCM (Parunov et al., 2017)	11.57	9.61	–	–	–
		11.20	9.24	14.40	11.84	28.58
					21.79	

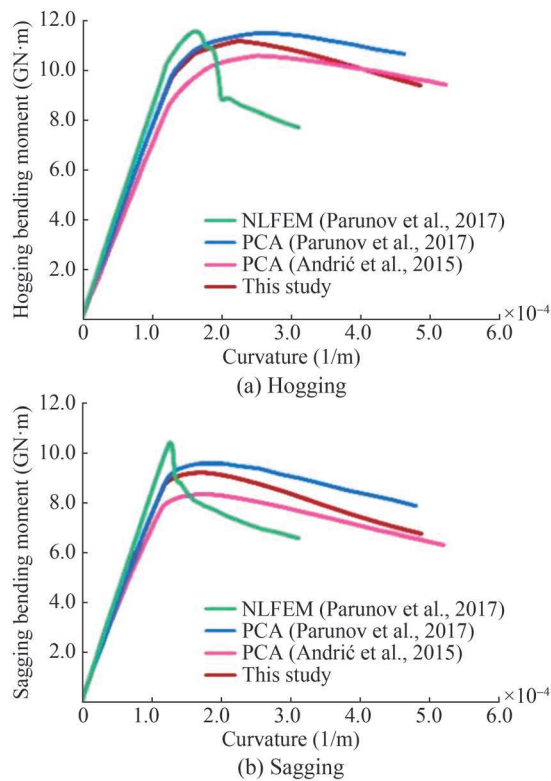


Figure 9 Comparison of the bending moment–curvature curves for T1 in the intact condition obtained using different methods under hogging and sagging conditions

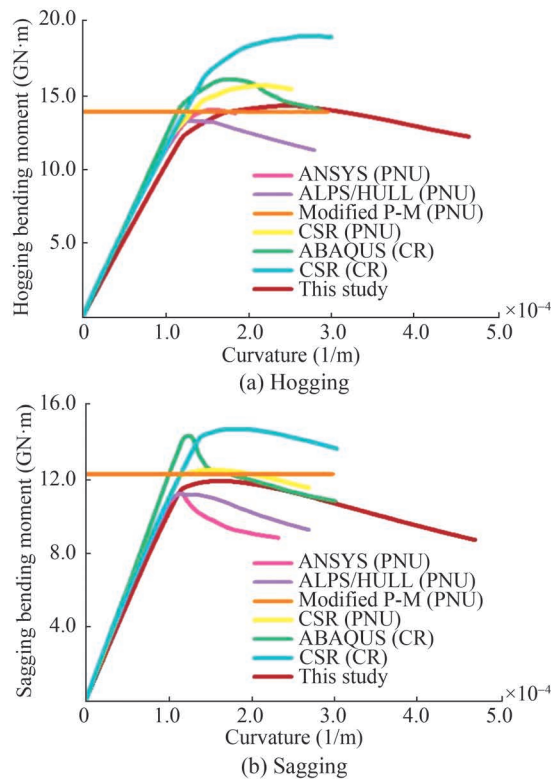


Figure 10 Comparison of the bending moment–curvature curves for T2 in the intact condition obtained using different methods under hogging and sagging conditions

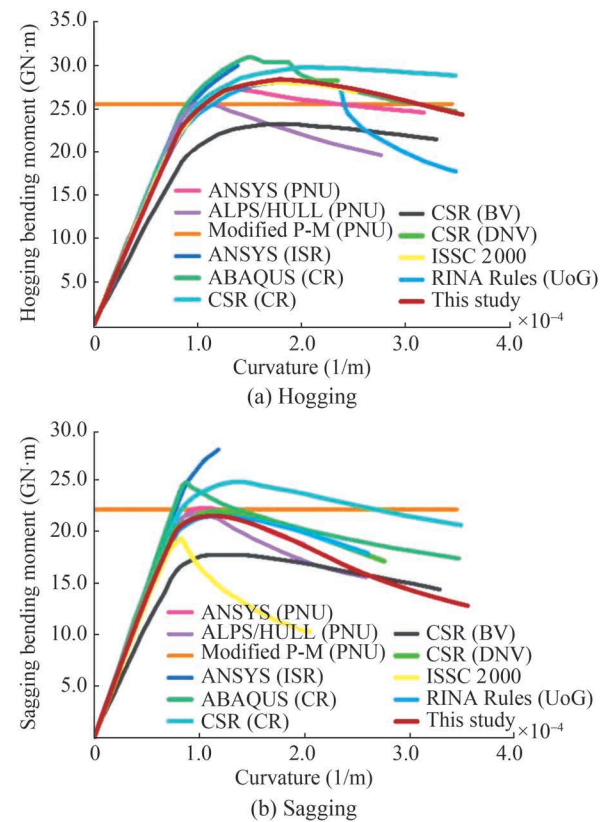


Figure 11 Comparison of the bending moment–curvature curves for T3 in the intact condition obtained using different methods under hogging and sagging conditions

posed PCM method. Among the candidate methods from the ISSC reports, the modified P–M (PNU) approach shows the best agreement with this study; the deviation is $\sim 3\%$ under both hogging and sagging conditions.

For T3, in the ISSC 2000 report, the method by Cho demonstrated the least deviation from this study's findings, with differences of $\sim 0.25\%$ for hogging and $\sim 4.76\%$ for sagging. Meanwhile, in the ISSC 2012 report, CSR (BV) presented a highly conservative estimation of the bending moment, deviating by $\sim 21\%$. The least deviation in this report was observed in the CSR (PNU) method.

3.2 Extraction of the RSI – DSR equations and diagrams

The general procedure for extracting quadratic equations and diagrams that describe the relationship between RSI and DSR is illustrated in Figure 12. We employ a deterministic approach, which can be modified to incorporate a probabilistic approach or apply a numerical method.

The process begins by defining the structural topology of the ship, including its type, dimensions, and material properties. The deterministic aspects of damage parameters and the methodology for calculating the residual ultimate hull strength in each damage scenario have been previously dis-

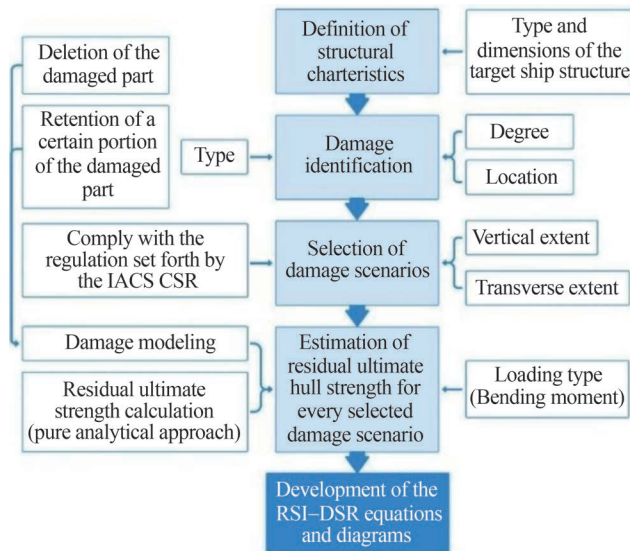


Figure 12 General procedure for the extraction of the RSI-DSR equations and diagrams

cussed. DSR represents the severity of damage and is obtained using Equations (3) and (4). In Equation (3), the original breadth refers to the ship breadth; in Equation (4), the original depth refers to the depth of the ship.

$$\text{Grounding case: DSR}(\lambda) = \frac{\text{Damaged Breadth}}{\text{Original Breadth}} \quad (3)$$

$$\text{Collision case: DSR}(\lambda) = \frac{\text{Damaged Height}}{\text{Original Depth}} \quad (4)$$

RSI, which was originally introduced by Fang and Das (2004) and later utilized by Hussein et al. (2009), compares the residual strength of a damaged hull $M_{U, \text{Damage}}$ with the ultimate strength of an intact hull $M_{U, \text{Intact}}$. The same approach can be extended to other sectional characteristics, such as the cross-section area A , vertical moments of inertia I , bottom sectional modulus W_B , and deck sectional modulus W_D , although it is based on Equation (5). After determining the RSI values in each damage scenario for the oil tanker models, the RSI-DSR data points are plotted to construct design diagrams. Using curve fitting in the regression analysis, quadratic equations can be formulated to describe the RSI-DSR relationship.

$$\text{RSI} = \frac{M_{U, \text{Damage}}}{M_{U, \text{Intact}}} \quad (5)$$

$$\text{RSI}_A = \frac{A_{\text{Damage}}}{A_{\text{Intact}}} \quad (6)$$

$$\text{RSI}_I = \frac{I_{\text{Damage}}}{I_{\text{Intact}}} \quad (7)$$

$$\text{RSI}_{W_B} = \frac{W_{B, \text{Damage}}}{W_{B, \text{Intact}}} \quad (8)$$

$$\text{RSI}_{W_D} = \frac{W_{D, \text{Damage}}}{W_{D, \text{Intact}}} \quad (9)$$

3.2.1 Ship grounding scenarios

Table 3 summarizes the RSI values obtained for different DSRs for three oil tankers subjected to grounding, showing the differences in the structural response under sagging and hogging conditions. Under hogging conditions, the reduction in the bending capacity of the hull girder is larger than that under sagging conditions. For example, at the CSR-specified DSR value of 0.6, the average reduction in the ultimate bending moment reaches 31.5% and 14.1% under hogging and sagging conditions, respectively.

Table 3 Summary of the RSI values obtained for different DSRs in three oil tankers subjected to grounding

Aframax-class double-hull oil tanker (T1)		
Damage size ratio (DSR)	Residual strength index (RSI)	
	Hogging	Sagging
0 (intact)	1.000	1.000
0.1	0.942	0.988
0.2	0.890	0.975
0.3	0.823	0.951
0.4	0.759	0.919
0.5	0.684	0.875
0.6 (specified in CSR)	0.608	0.823
0.7	0.530	0.755
0.8	0.450	0.680
Suezmax-class double-hull oil tanker (T2)		
Damage size ratio (DSR)	Residual strength index (RSI)	
	Hogging	Sagging
0 (intact)	1.000	1.000
0.1	0.957	0.991
0.2	0.905	0.979
0.3	0.841	0.962
0.4	0.782	0.933
0.5	0.711	0.890
0.6 (specified in CSR)	0.633	0.834
0.7	0.547	0.767
0.8	0.488	0.717
Double-hull VLCC (T3)		
Damage size ratio (DSR)	Residual strength index (RSI)	
	Hogging	Sagging
0 (intact)	1.000	1.000
0.1	0.968	0.988
0.2	0.939	0.977
0.3	0.911	0.964
0.4	0.869	0.946
0.5	0.846	0.935
0.6 (specified in CSR)	0.818	0.920
0.7	0.787	0.899
0.8	0.749	0.875

The graphical representation of the RSI–DSR relationship for different grounding scenarios is shown in Figure 13. We observe that the expected trend—RSI decreases as DSR increases, is verified, indicating an increase in structural weakening as the extent of damage increases. Based on these data, we extracted the quadratic Equations (10) and (11) corresponding to the sagging and hogging conditions. The obtained coefficients of determination corresponding to the hogging and sagging conditions were $R^2 = 0.8320$ and $R^2 = 0.8462$, respectively; these values indicate an acceptable statistical correlation. In structural mechanics and naval architecture, R^2 values above 0.80 are widely accepted as indicative of good model performance (Kim et al., 2020).

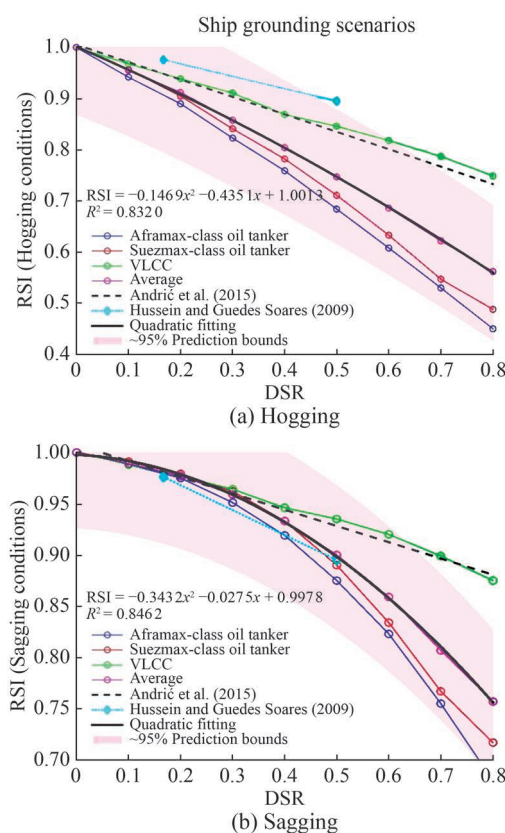


Figure 13 Relationship between DSR and RSI in ship grounding scenarios under hogging and sagging conditions

To obtain further insights into the reliability of the extracted RSI–DSR regression models, we included ~95% prediction bounds in Figure 13. These bounds represent the expected range within which future RSI values are likely to be included for a given DSR. Although the actual data points exhibit relatively low scattering behavior at low DSRs, the prediction bounds appear wide in this region. This is attributed to the curvature of the fitted quadratic model and its overall residual distribution rather than the variability in the structural response. Despite these variations, most data points fall within the prediction bands under both hogging

and sagging conditions, validating the robustness of the quadratic models.

We observe that data scattering increases as DSR increases, particularly beyond $DSR = 0.4$. This can be attributed to the increasing severity of damage, where failure mechanisms shift from localized yielding or buckling to more complex and progressive collapses involving multiple structural components. At high DSRs, the effect of cross-sectional variability, including geometry and stiffener arrangement as well as plate–stiffener interaction, becomes evident. These interactions introduce second-order effects, such as NA migration and instability interactions.

Although higher-degree polynomial models potentially enhance numerical fitting, they are often avoided in engineering practice because of risks related to overfitting and the loss of physical interpretability. Quadratic models provide a practical balance between model accuracy and computational simplicity.

$$RSI_{\text{grounding_hogg}} = 1.0013 - 0.4351\lambda - 0.1469\lambda^2 \quad (10)$$

$$RSI_{\text{grounding_sagg}} = 0.9978 - 0.0275\lambda - 0.3432\lambda^2 \quad (11)$$

$$RSI_{\text{grounding_hogg}} = 1.006 - 0.341\lambda \quad (12)$$

$$RSI_{\text{grounding_sagg}} = 1.008 - 0.158\lambda \quad (13)$$

$$RSI_{\text{grounding}} = 1.02 - 0.254\lambda \quad (14)$$

To verify our results, we compared them with those obtained using literature-based RSI–DSR models. Andrić et al. (2015) proposed linear regression models (Equations (12) and (13)), which tend to overestimate RSI at high DSRs when applied to the same damage scenarios; in T1, the overestimation is up to 26.3% for $DSR = 0.8$ under hogging conditions. The results obtained using these models agree well with the T3 results but deviate as the extent of damage increases. Hussein and Guedes Soares (2009) proposed a generalized formulation (Equation (14)) for double-hull oil tankers, not distinguishing between hogging and sagging conditions. Compared with the results obtained using the proposed PCM method and those obtained using Andrić’s method, the results obtained using Hussein’s and Guedes Soares’ show an overestimation of the residual strength under hogging conditions; however, they are more conservative under sagging conditions. The quadratic equations proposed in this study exhibit increased sensitivity to damage at high DSRs, especially under sagging conditions.

Recently, Kim et al. (2024) extracted RSI–DSR equations from ISFEM simulations performed using ALPS/HULL; these equations provide high accuracy by considering local buckling, imperfections, and cross-section damage. However, ISFEM requires detailed 2D modeling, access to commercial software, and considerable computational effort. Moreover, the resulting R–D diagrams are case-specific,

and their direct verification against actual simulation results can be challenging.

In this study, we additionally examined the post-ultimate strength behavior of oil tanker models. Figures 14–16 show the variation in the ultimate and residual strengths with hull curvature for different DSRs. The results reconfirm that the loss in the bending moment capacity under hogging conditions is higher than that under sagging conditions.

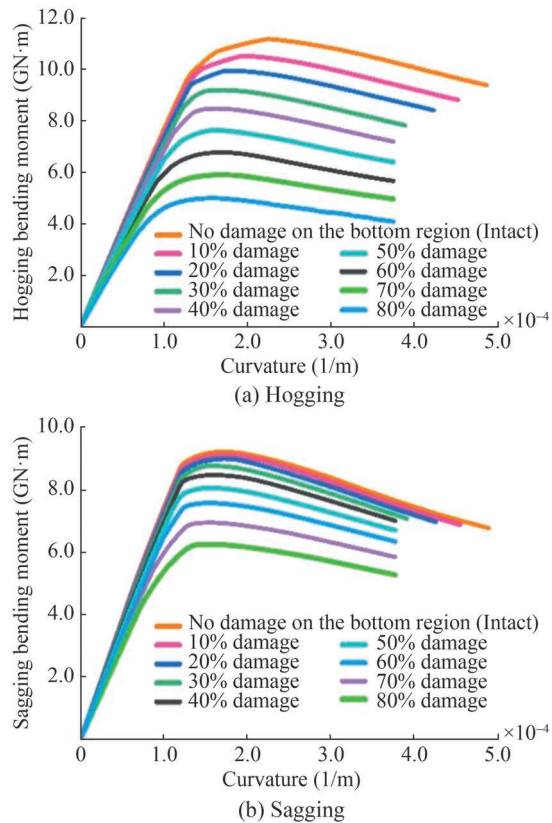


Figure 14 Comparison of the ultimate and residual strengths under hogging and sagging conditions at different DSRs for T1 subjected to grounding

1) Hogging conditions: damage on the bottom region of the hull mainly affects the outer shell plating, which is crucial in resisting compressive stress. As DSR increases, the effectiveness of the bottom plating decreases, leading to a reduction in bending stiffness. Consequently, the inner bottom plating is subjected to high compressive loads until it collapses due to buckling; this indicates that the maximum residual strength of the damaged section has been reached. Additionally, the deck structure collapses because of the applied high tensile stress. Although the collapse sequence may not be visually shown, it can be checked using the output PCM data, which indicates the characteristics of the structural collapse.

2) Sagging conditions: the outer shell plating is vital for tensile load transfer, whereas the inner bottom plating contributes less to pure tension but provides redundancy in case

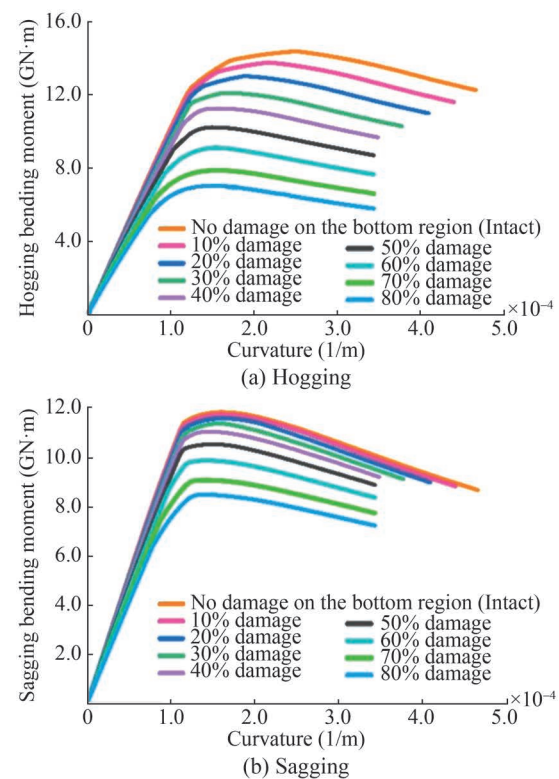


Figure 15 Comparison of the ultimate and residual strengths under hogging and sagging conditions at different DSRs for T2 subjected to grounding

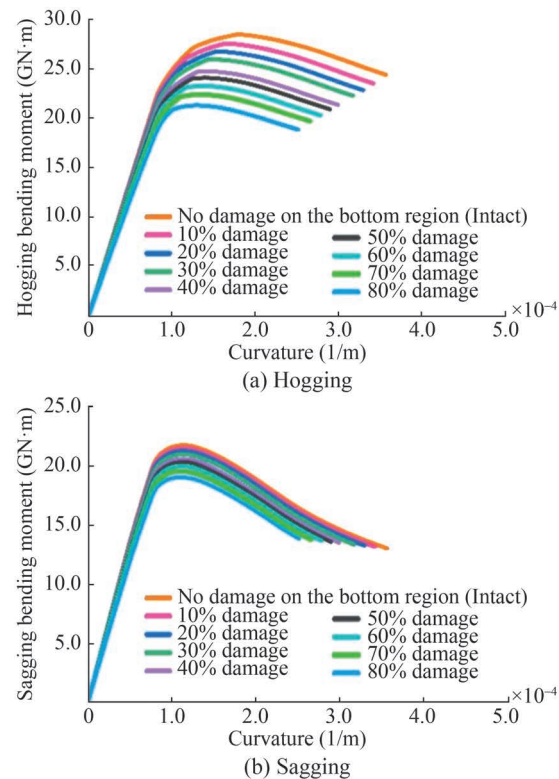


Figure 16 Comparison of the ultimate and residual strengths under hogging and sagging conditions at different DSRs for T3 subjected to grounding

the outer shell fails; under this condition, it exhibits a steep downward slope in its load-carrying capacity after its ultimate strength is reached, particularly in T3.

3.2.2 Ship collision scenarios

Table 4 summarizes the RSI values obtained for different DSRs for three oil tankers subjected to collision-induced damage. The average reduction in the residual hull girder strengths for the specified IACS-CSR DSR value of 0.6 is 15.3% and up to 19.6% under hogging and sagging conditions, respectively. Unlike grounding, where the obtained RSI values for sagging conditions are typically higher than those obtained under hogging conditions, the opposite trend is observed in collision: the obtained RSI values are lower under sagging conditions, particularly as DSR increases; these results are consistent with those reported by Andrić et al. (2015). The differences in the RSI results obtained under hogging and sagging conditions are attributed to the fact that damage due to sagging is mainly caused by the tensile yielding of the bottom plating and the buckling of the deck plating. In severe cases, the deck may also be subjected to compressive yielding following local buckling. Even if the bottom structures remain intact, they cannot effectively compensate for the loss of side shell integrity, resulting in higher strength degradation under sagging conditions than under hogging conditions.

The graphical representation of the RSI–DSR relationship for different collision scenarios is shown in Figure 17. Quadratic regression models were derived for both hogging (Equation (15)) and sagging (Equation (16)) conditions. The obtained values of the coefficients of determination were very high, i.e., $R^2 = 0.9853$ and $R^2 = 0.9889$ for the hogging and sagging conditions, respectively, indicating excellent fitting and consistency across different oil tankers. To obtain further insights into the reliability of these models, we included ~95% prediction bounds. Compared with the prediction bounds of the grounding scenarios, those of the collision scenarios are noticeably narrower, particularly at low DSRs, where the structural behavior remains largely predictable. The prediction bounds exhibit modest widening at high DSRs; this is more evident under sagging conditions.

Figure 17 shows that the RSI curves for hogging exhibit minimal spread for T1, T2, and T3, indicating a low sensitivity to geometric variations in different oil tanker types. However, a sharp nonlinear decrease in RSI is observed beyond DSR = 0.4 under sagging conditions. This is attributed to the compounding effects of shell loss and reduced tension-bearing capacity at the bottom of the hull. The prediction bounds remain narrow in both cases, further validating the reliability of the extracted regression models.

$$RSI_{\text{collision_hogg}} = 0.9960 - 0.3505\lambda + 0.1719\lambda^2 \quad (15)$$

$$RSI_{\text{collision_sagg}} = 0.9946 - 0.5367\lambda + 0.3623\lambda^2 \quad (16)$$

$$RSI_{\text{collision_hogg}} = 0.9948 - 0.3493\lambda + 0.2544\lambda^2 \quad (17)$$

Table 4 Summary of the RSI values obtained for different DSRs in three oil tankers subjected to collision

Aframax-class double-hull oil tanker (T1)		
DSR	RSI	
	Hogging	Sagging
0 (intact)	1.000	1.000
0.1	0.964	0.943
0.2	0.938	0.909
0.3	0.910	0.869
0.4	0.892	0.845
0.5	0.874	0.824
0.6 (specified in CSR)	0.854	0.808
0.7	0.840	0.801
0.8	0.833	0.800
Suezmax-class double-hull oil tanker (T2)		
DSR	RSI	
	Hogging	Sagging
0 (intact)	1.000	1.000
0.1	0.962	0.940
0.2	0.942	0.913
0.3	0.912	0.872
0.4	0.890	0.842
0.5	0.867	0.819
0.6 (specified in CSR)	0.849	0.808
0.7	0.837	0.804
0.8	0.826	0.802
Double-hull VLCC (T3)		
DSR	RSI	
	Hogging	Sagging
0 (intact)	1.000	1.000
0.1	0.945	0.925
0.2	0.917	0.887
0.3	0.897	0.859
0.4	0.874	0.829
0.5	0.856	0.809
0.6 (specified in CSR)	0.838	0.796
0.7	0.825	0.787
0.8	0.818	0.969

$$RSI_{\text{collision_sagg}} = 0.9927 - 0.5802\lambda + 0.4516\lambda^2 \quad (18)$$

$$RSI_{\text{collision}} = 0.98 - 0.084\lambda \quad (19)$$

Compared with literature-based models, the linear equations proposed by Andrić et al. (2015) (Equations (17) and (18)) tend to overestimate RSI because they do not consider the effects of NAR, especially beyond DSR = 0.3; for DSR = 0.8, the deviation reaches 19.5% under hogging conditions. Compared with the results of this study, the generalized equation proposed by Hussein and Guedes Soares (2009) (Equation (19)) significantly overestimates RSI under both hogging and sagging conditions. This is mainly attributed to their generalized approach, which

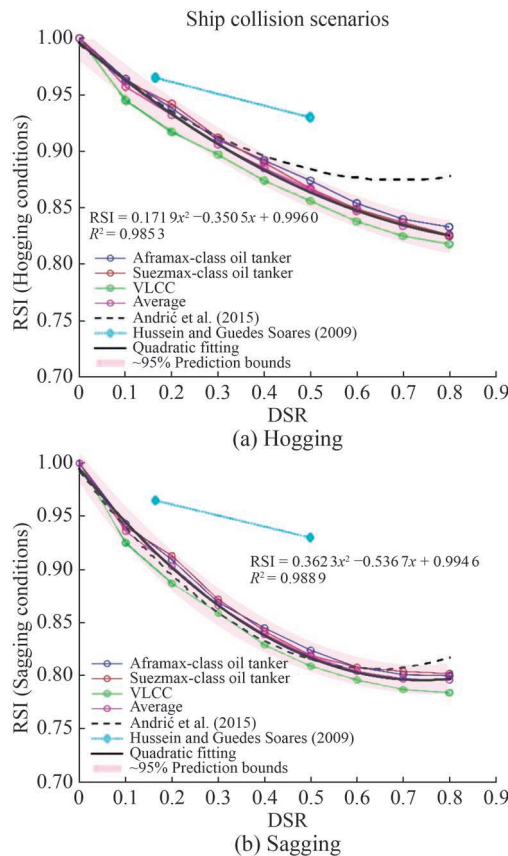


Figure 17 Relationship between DSR and RSI in ship collision scenarios under hogging and sagging conditions

does not distinguish between bending modes (hogging vs. sagging) and does not consider the effects of NAR.

Figures 18–20 show a comparison of the ultimate and residual bending moments for T1, T2, and T3, respectively. It is observed that the damaged hull cross-sections reach maximum strength at lower curvatures compared to the intact ones. In grounding scenarios, where the moment–curvature pattern in the plastic region varies among T1, T2, and T3, the collision scenarios exhibit consistent patterns across all models.

Compared with the rapid strength reduction observed in ship grounding, the reduction in the vertical load-carrying capacity of the hull girder in ship collision is slower as the extent of damage in the starboard side shell increases. This is because, in the simulated collision scenarios, the bottom and deck structures remain mostly intact, allowing the hull girder to retain a significant portion of its load-bearing capacity, particularly under hogging conditions. Additionally, as the NA gradually shifts toward the damaged side shell on the starboard side, the stress is redistributed more effectively, providing some structural compensation.

An intriguing observation is that the hogging bending moment for all three oil tanker models in the intact and damaged conditions with varying DSRs terminates at nearly the same curvature and bending moment. In this study, the

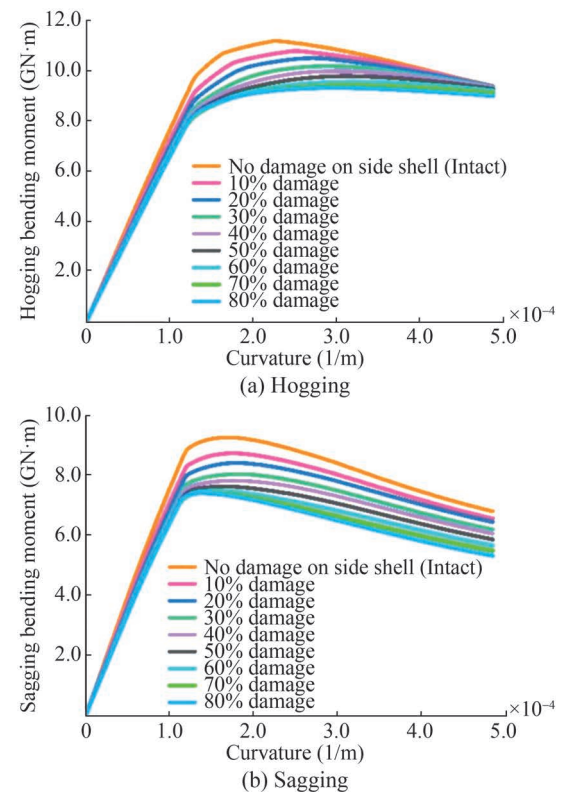


Figure 18 Comparison of the ultimate and residual strengths under hogging and sagging condition at different DSRs for T1 subjected to collision

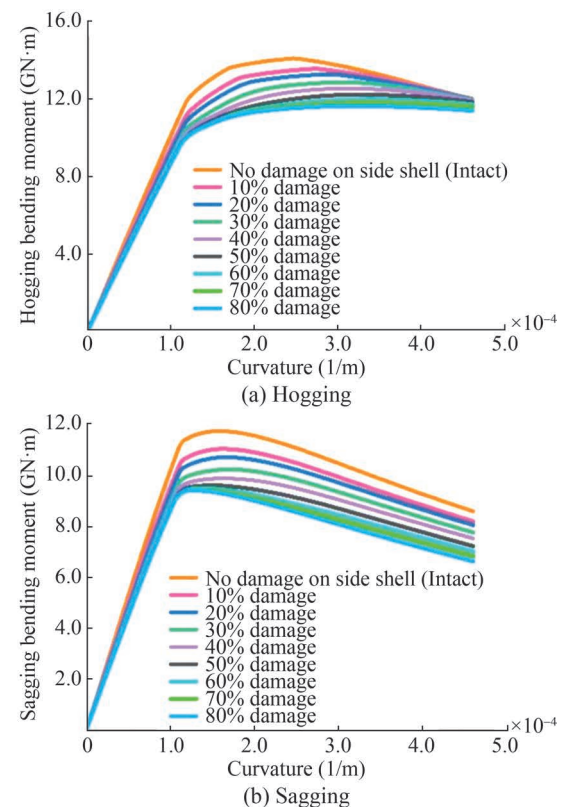


Figure 19 Comparison of the ultimate and residual strengths under hogging and sagging at different DSRs for T2 subjected to collision

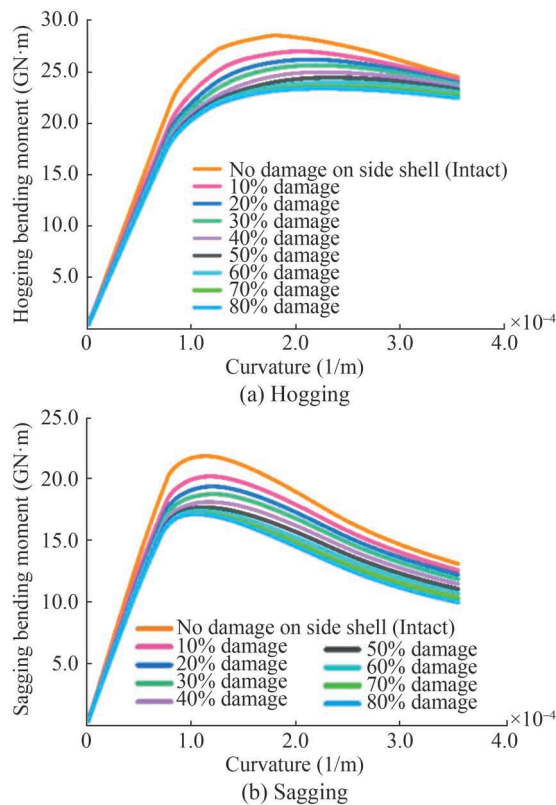


Figure 20 Comparison of the ultimate and residual strengths under hogging and sagging conditions at different DSRs for T3 subjected to collision

termination criterion for the PCM is to stop calculations when the compressive strain applied to any element within the cross-section reaches four times the yield strain (the recommended IACS-CSR limit is three times the yield strain). This extension in the compressive strain limit is essential for monitoring the post-ultimate stress behavior and the actual collapse mechanisms because structural failure does not necessarily coincide with reaching the ultimate residual strength; instead, deformation and stress redistribution continue beyond this point. This is caused by plastic strain accumulation rather than initial material yielding. Under hogging conditions, failure initiates through bottom structure buckling and compression failure, occurring at similar strain limits regardless of the tanker model or DSR, resulting in a consistent final curvature.

Under sagging conditions, the collapse sequence in collision scenarios begins at the deck, followed by the upper side shell plating; the bottom plating collapses only after the ultimate residual strength in the cross-section reaches its maximum value.

NAR is a critical factor affecting the residual ultimate strength of asymmetrically damaged ships. Therefore, in this study, it is examined in detail. Figures 21–23 show the NA motion as a function of the hull curvature for T1, T2, and T3, respectively, for different DSRs (0.2, 0.4, 0.6, and 0.8).

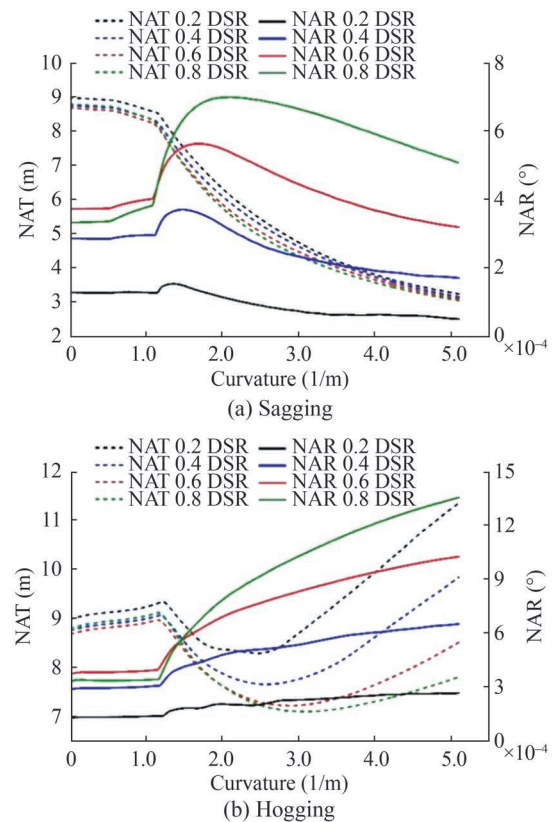


Figure 21 NA motion vs. hull curvature for T1 under sagging and hogging conditions for different DSRs

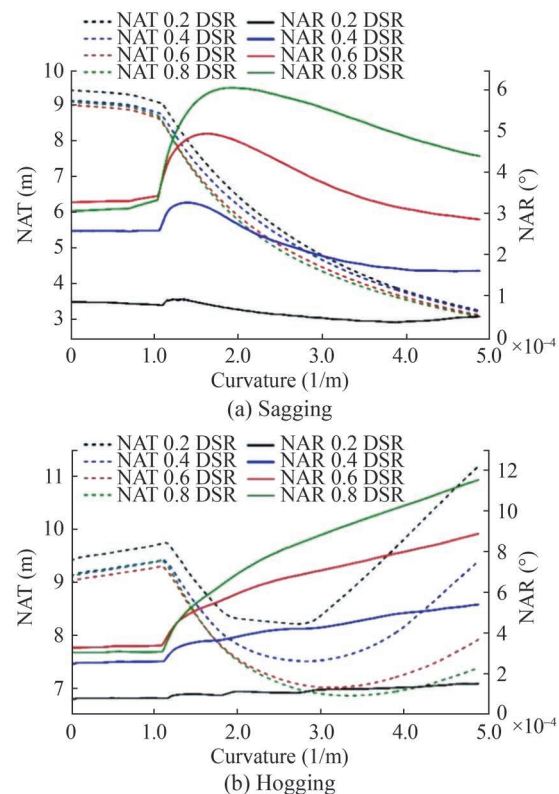


Figure 22 NA motion vs. hull curvature for T2 under sagging and hogging conditions for different DSRs

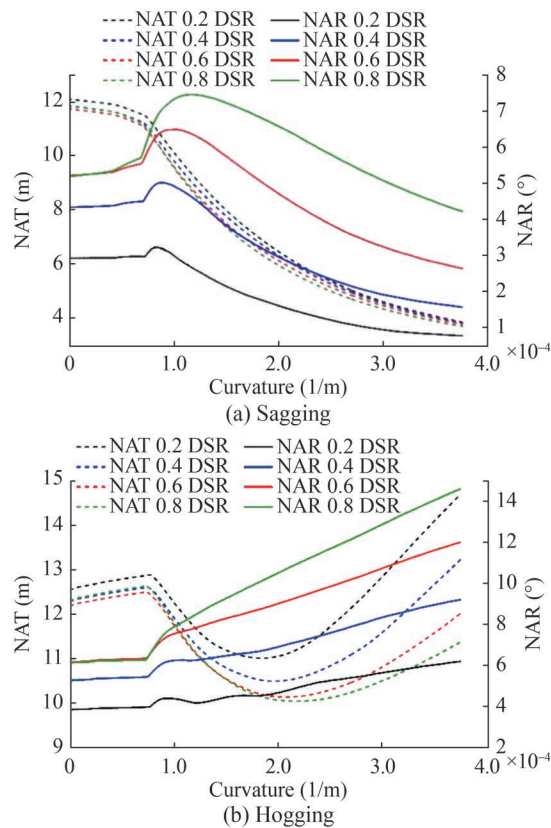


Figure 23 NA motion vs. hull curvature for T3 under sagging and hogging conditions for different DSRs

The results show that as the curvature increases, the NA undergoes both vertical translation and rotational displacement. We observe a consistent trend, where NAT decreases as DSR increases, whereas NAR increases as DSR increases; this pattern holds for all three oil tanker models. The magnitude of NAR increases noticeably at high hull curvatures; this is more evident under hogging than under sagging conditions when considering the transition from the initial to the ultimate strength value.

In the elastic regime, NAR remains linear for all DSRs. However, as the structure transitions into the plastic regime, NAR increases significantly, and the differences in NAR across DSRs become distinguishable. For T3, this transition occurs early for a curvature of $\sim 1.0 \times 10^{-5}$; for T1 and T2, the transition occurs slightly later for a curvature of $\sim 1.5 \times 10^{-5}$. This behavior is also reflected in the corresponding final curvatures of the oil tanker models.

The variation in NAT for different DSRs is relatively small under sagging conditions but becomes evident under hogging conditions, particularly at high curvatures.

3.3 Reliability of prediction of the proposed quadratic equations

To further assess the reliability of the prediction of the proposed RSI–DSR regression formulas (Equations (10)

and (11) for ship grounding as well as Equations (15) and (16) for ship collision), additional progressive collapse analyses were conducted for oil tanker models T1, T2, and T3 using two intermediate DSR values (0.25 and 0.65); these values were not included in the original regression fitting dataset. The additional simulation results presented in Table 5 were used to evaluate the model's extrapolation capability over a wide range of severe damages.

Table 5 RSI values obtained from additional simulations for DSR = 0.25 and DSR = 0.65

Ship grounding scenarios			
DSR	Model	RSI	
		Hogging	Sagging
0.25	T1	0.857	0.963
	T2	0.873	0.971
	T3	0.925	0.970
0.65	T1	0.569	0.789
	T2	0.590	0.800
	T3	0.803	0.909
Ship collision scenarios			
DSR	Model	RSI	
		Hogging	Sagging
0.25	T1	0.924	0.889
	T2	0.927	0.893
	T3	0.907	0.873
0.65	T1	0.847	0.804
	T2	0.843	0.806
	T3	0.832	0.792

In the ship grounding scenarios, the RSI values obtained using the regression models for DSR = 0.25 under hogging and sagging conditions were 0.883 and 0.969, respectively; for DSR = 0.65, the corresponding RSI values were 0.656 and 0.835. The differences between the predicted and simulated RSI values for DSR = 0.25 are relatively small, i.e., 2.6%, 1.0%, and 4.2% for T1, T2, and T3, respectively, under hogging conditions; under sagging conditions, the corresponding differences are much smaller, i.e., 0.6%, 0.2%, and 0.1%. However, for DSR = 0.65, the corresponding differences are higher, i.e., 8.7%, 6.6%, and 14.7%, respectively, particularly under hogging conditions; under sagging conditions, the corresponding differences are 4.6%, 3.5%, and 7.4%. These higher discrepancies at increased damage levels reflect the growing variability in progressive collapse mechanisms under severe structural degradation. Nevertheless, all results remain within acceptable limits in the early-stage strength assessment.

In ship collision scenarios that involve asymmetrical damage and the impact of NAR, the performance of the regression models is notably stronger. The predicted RSI values for $DSR = 0.25$ under hogging and sagging conditions were 0.919 and 0.883, respectively; for $DSR = 0.65$, the corresponding values were 0.841 and 0.799. Excellent agreement was observed between the predicted and simulated RSI values. Specifically, under hogging conditions, the differences for $DSR = 0.25$ are 0.5%, 0.8%, and 1.2% for T1, T2, and T3, respectively; under sagging conditions, the corresponding differences are 0.6%, 1.0%, and 1.0%. For $DSR = 0.65$, the agreement is further improved; under hogging conditions, the corresponding differences are 0.6%, 0.2%, and 0.9%, respectively; under sagging conditions, the corresponding differences are 0.5%, 0.7%, and 0.7%. These small differences confirm the robustness of the proposed regression models under asymmetrical damage conditions and demonstrate the importance of incorporating NAR in the PCM formulation.

3.4 Contribution of the outer and inner shell structures to strength

The contribution of the outer and inner shell structures in double-hull oil tankers to strength has been briefly analyzed; the damage scenarios were mainly based on the IACS-CSR regulations. In ship collision scenarios, both the outer and inner side shells are damaged, whereas in ship grounding scenarios, only the outer bottom shell is affected. This limitation restricts further observations on the implications of hull girder strength when either both (inner and outer) or only the outer structures are damaged in these scenarios. The outer shell (bottom and side) mainly acts as the “first line of defense” against external loads, such as hydrostatic pressure, wave-induced forces, and impact loads, which significantly contribute to the global bending stiffness of the hull girder. The inner shell plating, which acts in conjunction with the outer shell within the double-hull structure, improves the local and global strength and prevents oil spillage or water ingress in case of damage.

In the residual ultimate strength analysis, particularly in PCM, the load-end shortening response of the plating panels is crucial in determining their contribution to the overall hull strength; the contributions of the inner and outer shells vary depending on their location in the hull cross-section. To investigate this contribution, we considered both the bottom and side structures using a double-hull VLCC (T3) and set damage scenarios using $DSR = 0.2$, 0.4, 0.6, and 0.8 for both the grounding and collision cases. We performed additional simulations, considering the following cases: 1) both the outer and inner bottom shells are affected in grounding scenarios; 2) only the outer side shell is damaged in collision scenarios for different DSRs. Figure 24 shows that under hogging conditions, the damage in the outer and inner bottom shells results in signifi-

cantly lower bending moments than those obtained when only the outer shell is damaged. For $DSR = 0.2$, the difference in the residual bending moment between the two cases is <5%. However, for $DSR = 0.8$, the difference reaches 40%, indicating the importance of the inner bottom structure regarding hull girder strength; compared with the bending moment of the intact hull, the total reduction in hull girder strength is ~55%. This result indicates a severe loss of strength when both the inner and outer shells are damaged in ship grounding accidents. Additionally, grounding-induced damage is more sensitive to hogging bending moments than sagging bending moments.

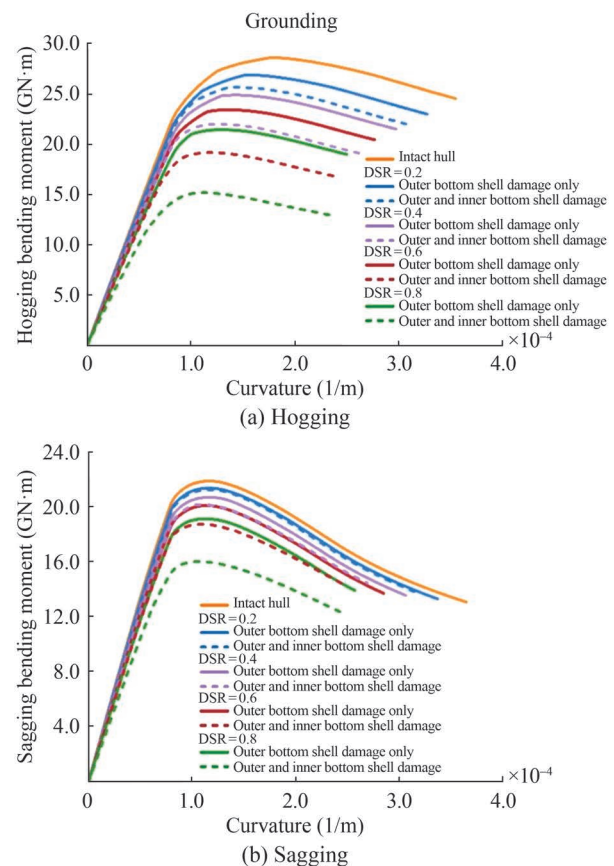


Figure 24 Moment–curvature curves for an intact hull, damage in the outer bottom shell, and combined damage in the outer and inner bottom shells under hogging conditions and sagging conditions in ship grounding

Under sagging conditions, the difference between the damage in the outer shell only and that in the outer and inner shells is small because, in the former case, the vessel retains some load-bearing capacity; however, in the latter case, the bending moments are significantly reduced. For $DSR = 0.2$, the difference is ~0.5%, increasing to ~19% for $DSR = 0.8$; compared with the intact hull, the total reduction is ~50%. Furthermore, the slope of the post-ultimate bending moment under sagging conditions decreases sharply, indicating localized yielding and fast progressive

collapse of the bottom structures.

Figure 25 shows increased strength degradation when both the outer and inner side shells are damaged; the strength degradation increases as DSR increases. This indicates that the inner shell failure has a compounding effect on strength reduction. For all cases, the hogging moments are higher than the sagging moments, although the strength is slightly more sensitive to increasing damage under sagging conditions than under hogging conditions. Under hogging conditions, when the outer side shell is damaged only, the percentage reduction in the residual ultimate bending moment relative to the intact-hull case for $DSR = 0.2$ is 5.25%; when both the outer and inner side shells are damaged, the corresponding reduction is 8.07%. For $DSR = 0.8$, these values reach 33.33% and 38.6%, respectively. Under sagging conditions, the corresponding reductions for $DSR = 0.2$ are 5.41% and 9.19%; they increase to 37.84% and 44.86%, for $DSR = 0.8$. These results confirm that inner shell damage significantly reduces the hull girder strength. The failure of the inner side shell, which acts as a secondary structural reinforcement, leads to a loss in the load redistribution capacity, reduction in the effective moment of inertia, reduced compressive side contribution under sagging conditions, increased asymmetry in the load-carrying behavior, and loss in protective redundancy.

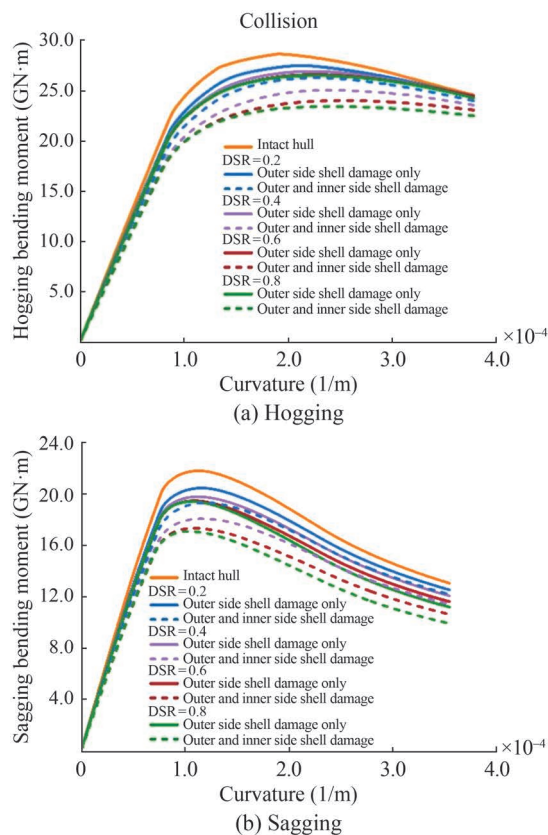


Figure 25 Moment–curvature curves for an intact hull, damage in the outer side shell, and combined damage in the outer and inner side shells under hogging conditions and sagging conditions in ship collision

3.5 Practical applications of the extracted RSI–DSR equations and diagrams

The enhanced RSI–DSR relationships developed in this study provide a wide range of practical applications spanning across the design, operational, regulatory, and research domains. These quadratic equations and diagrams provide a robust yet computationally lightweight framework for assessing the residual load-carrying capacity of damaged hull girders, especially in grounding or collision scenarios; their applications are outlined as follows:

1) Rapid strength and computationally efficient evaluation. The extracted RSI–DSR equations provide a fast and reliable means for estimating the residual strength without resorting to high-fidelity numerical simulations such as NLFEA. The method requires only basic geometric inputs (i.e., stiffener and plating details), making it highly suitable for use in early-stage design iterations or time-sensitive evaluations. The RSI–DSR framework provides a rapid evaluation of the bending moment degradation across a wide range of extents of damage with minimal computational effort, avoiding the need for full 2D/3D modeling or commercial software tools.

2) Emergency response and post-accident decision-making. In real-time emergencies, such as ship grounding or side-shell collision, the RSI–DSR diagrams provide a systematic and quantifiable method for evaluating the residual structural capacity. This enables rapid and informed decision-making regarding whether a vessel can safely proceed to a port, requires temporary reinforcement, needs to be towed, or abandoned. The simplicity and speed of the RSI–DSR approach make it especially useful for onboard evaluations and their integration into decision-support systems.

3) Support for regulatory compliance and safety margins. The RSI–DSR framework can assist classification societies and regulatory bodies in defining the strength, safety margins, and damage acceptance criteria. By aligning with the IACS Unified Requirements and IMO performance standards, such as the requirement for new vessels to retain at least 90% of their ultimate longitudinal strength, the proposed framework provides a rational basis for evaluating compliance with regulations. Furthermore, the RSI–DSR curves can be incorporated into the development of rules for residual strength checks and post-damage condition assessments.

4) Integration into structural health monitoring (SHM) systems. The RSI–DSR framework is well-suited for implementation in shipboard SHM systems. By assessing the hull girder loading conditions and the observed or measured extents of damage, the RSI–DSR equations can support predictive maintenance strategies and real-time updates for assessing residual strength.

5) Benchmarking and validation of computational models. Beyond their practical use, the RSI–DSR equations serve

as a valuable benchmarking tool for validating the results obtained from other progressive collapse models, including PCM variations, NLFEA, and damage mechanics-based approaches.

4 Factors affecting the longitudinal strength behavior of a damaged hull

In this section, we present a brief comparative analysis of the factors affecting the longitudinal strength behavior of a hull girder subjected to damage. In the previous section, we focused solely on the extent and location of damage; here, we expand this discussion to include the loading conditions and the ship size because these parameters also affect the residual bending strength of damaged ships. Because of the limitations of the proposed fully analytical PCM, this study does not consider other influential factors such as corrosion wastage (aging effects), initial geometric imperfections, residual stresses, or extreme temperature variations that affect vessels operating in ice-covered waters. Despite their critical importance, these aspects are beyond the scope of our current methodology and should be investigated in future work.

4.1 Impact of loading conditions

Regarding the impact of loading conditions on the residual bending strength of damaged ships, we only considered the bending moments (hogging and sagging) in the damaged hull cross-sections examined in this study; the torsional moments or other loading effects were not considered. Based on the results shown in Figures 13 (grounding scenarios) and 17 (collision scenarios), a summary of our findings is presented in Table 6. These findings are consistent with those reported by Andrić et al. (2015).

Table 6 Summary of the strength reduction findings for hull girders subjected to grounding and collision damage

Grounding		Collision	
Loading Condition	Findings	Loading Condition	Trend
Hogging	Noticeable and fast strength reduction	Hogging	Moderate strength reduction
Sagging	Moderate strength reduction	Sagging	Noticeable and fast strength reduction

4.2 Impact of ship size

The lengths of the oil tanker models analyzed in this study vary; the lengths of the Aframax (T1), Suezmax (T2), and double-hull VLCC (T3) are 235, 265, and 315 m, respectively. This variation allows for an easy investigation of the impact of the ship size on the residual bending strength

of damaged ships. Although previous studies mainly focused on hull cross-sections as the main contributors to the residual ultimate strength, they did not consider the ship length. Here, we include the impact of ship length.

Figures 13 and 17 show a notable relationship between RSI and DSR regarding ship size. In collision scenarios, RSI in larger vessels decreases more uniformly and gradually as DSR increases, reflecting greater sensitivity to side shell damage. In contrast, smaller vessels tend to retain slightly higher RSI values across the same damage range, possibly due to fewer structural elements being affected.

In grounding scenarios, however, the trend is reversed. Despite some data scatter, smaller ships such as the Aframax experience a steeper and more rapid reduction in RSI, particularly under sagging, as damage increases. Larger ships maintain relatively higher RSI, indicating that the progressive nature of bottom damage disproportionately affects smaller hulls.

5 Conclusions

In this study, we conducted a comprehensive investigation into the relationship between RSI and DSR in three double-hull oil tankers—Aframax, Suezmax, and VLCC. In the analysis, we employed a newly developed PCM, enhanced by a MOPSO algorithm that accounts for NAR, ensuring more accurate residual strength predictions than those reported in classic PCM-based approaches; additionally, we addressed the issues of overestimated predictions. Our results showed that in ship grounding scenarios, the reduction in hull carrying capacity under hogging conditions is larger than that under sagging conditions. The structural collapse was initiated in the deck region due to high tensile stress; the maximum residual strength was reached after the failure of the inner bottom plating. The quadratic equations extracted for grounding scenarios showed improved accuracy over previous linear models. In collision scenarios, the obtained RSI values were lower under sagging conditions than those under hogging conditions, indicating consistency with previously reported results. Additionally, we analyzed the impacts of the inner and outer shells as well as those of other factors on the longitudinal strength of damaged hulls.

The strength results predicted using the proposed RSI–DSR models were validated by performing additional simulations using intermediate DSR values (0.25 and 0.65); the obtained results were in close agreement with the regression results, further supporting the robustness and reliability of the extracted quadratic equations.

In future work, we will focus on enhancing the proposed PCM by considering the possibility of overall ship collapse, comparing the results with the interframe collapse predictions of IACS-CSR, and integrating the impact of lateral

pressure and initial imperfections. Furthermore, the study will be extended to other merchant marine vessels, including container ships, bulk carriers, passenger ships, and general cargo ships, to further validate the applicability of the extracted RSI–DSR equations and diagrams.

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