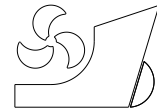


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RESIDUAL HULL GIRDER ULTIMATE STRENGTH OF DOUBLE HULL OIL TANKERS

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Summary

Within the scope of the presented work a hull girder ultimate strength analyses of the double hull oil tanker structures damaged by the collision or grounding is performed. An incremental-iterative progressive collapse analysis method prescribed by the forthcoming IACS Harmonized Common Structural Rules (H-CSR) is used for determination of the ultimate vertical bending moment and collapse sequence of the considered structures. Three characteristic variants of the oil tanker main frame cross sections of a different geometry and size (Aframax, Suezmax and VLCC) are considered. The position of a ship's side and/or bottom damage is defined in accordance with the IACS H-CSR. Proposed analytical formulations of the relationship between reduction of the hull girder ultimate vertical bending moment (with respect to the undamaged state) and damage size are based on the results of a systematic variation of a ship's side or bottom damage size. Finally, comparison of the collapse sequences determined for the undamaged and damaged state in upright position (defined by IACS H-CSR) of the considered structure of the Aframax ship example is performed.

Key words: Damaged ships; hull girder ultimate strength; grounding; collision; double hull tanker structure, residual strength.

1. Introduction

A large number of ship accidents resulting in a loss of cargo, pollution of the environment and a loss of human life still occur, despite the advancements in a ship design, production and navigation procedures. Accident scenarios typically include collision, grounding, fire and explosion. In that respect, it is of a great importance to ensure acceptable safety level for ships damaged in those accidents. When faced with any of these accidental situations, the ship operator's need to take rapid decisions regarding the salvage actions and further steps should be based on evaluation of the damage effects on the ships safety using the residual strength assessment procedure. Adequate hull girder strength in intact condition does not necessarily guarantee an acceptable safety margin in damaged conditions [1].

A draft of the IACS Harmonized Common Structural Rules (H-CSR) [2] has been released for the industry review in April 2013. In comparison to the IACS CSR currently in force [3] IACS H-CSR contains additional requirement regarding the residual strength of tankers and bulk carriers, i.e. the hull girder ultimate strength in prescribed damaged conditions. According to the IACS H-CSR, the residual strength is evaluated for the two specific accident scenarios: collision and grounding. A similar approach can be found in ABS Guide to accessing hull girder residual strength for tankers [4] but with the different request regarding extent of damage.

Among a number of the contemporary methods for the hull girder strength evaluation, various incremental-iterative progressive collapse analysis method based on Smith's approach [5] are arguably the most widespread. Furthermore, rules of many classification societies, including IACS CSR and IACS H-CSR, prescribe utilization of incremental-iterative procedures based on Smith's approach for evaluation of the longitudinal ultimate load-capacity of ship structures both in intact and damaged condition. Overview of various existing methods for the hull girder ultimate strength calculation in intact condition can be found in [6-10], while the critical review of their accuracy can be found in [11, 12]. Recently, the residual hull girder strength has been investigated through two different approaches: nonlinear FEM [13, 14 and 15]. and progressive collapse methods (PCM) based on Smith's approach using incremental-iterative or pure incremental procedures [16-20].

When the cross section is asymmetrically damaged like in a way of collision damaged, the neutral axis (NA) rotates and the problem can be treated as biaxial bending problem. Recently several procedures have been suggested to include NA shift into account. Choung et al. [21] provided two convergence criteria to find translational and rotational locations of the neutral axis plane for intact and damaged vessels. Definition of three types of asymmetries of a ship section was proposed: material-, load-, and geometry-induced asymmetries. Concept of moment plane (MP) was introduced to define the heeling angle of ship section. It is suggested that force equilibrium and force vector equilibrium criteria are both necessary to determine new position of NA due to both translational and rotational shifts. Recently Fujikubo et al. [22] have suggested updated pure incremental method (PCM) to derive the biaxial bending moment-curvature relationship taking into account the rotation and translation of the neutral axis in asymmetrically damaged hull girders, while Makouei et al. [23] further tested the accuracy of method presented by Fujikubo. However this effect is much more expressed for a single skin bulk carrier structures compared to double hull tanker structures examined in the research performed by Fujikubo et al. [22].

Intention of the present study is to investigate the influence of the damage size on the ultimate hull girder capacity of oil tankers for the two characteristic types of accidents: collision and grounding. Proposed analytical formulations of the relationship between the reduction of the hull girder ultimate bending moment (with respect to the undamaged state) and damage size are based on the analysis of the results of a systematic variation of damage extent of ship's side or bottom.

2. Capacity models of considered hull girder structures

Three characteristic variants of the double hull oil tanker midship sections of a different geometry and size (Aframax, Suezmax and VLCC) are considered. All examined structures are designed according to the pre-CSR requirements of different classification societies. The main particulars of the tanker structures considered by this study are given in Table 1. Examined structures denoted as models M2 and M3 (Suezmax and VLCC tanker) belong to the standard set of the ISSC benchmark examples and all relevant data regarding their material and geometric properties are given in Technical Committee IV.2. [9].and Technical

Committee III.1 [8]. Figures 1-3 illustrates one-bay structural models at midship section of all considered structures in intact condition. Structural model definition, essential for all ultimate bending capacity calculations performed by the co-authors for the purposes of the present paper is done using the computer program MAESTRO [24]. For all models no corrosion deduction has been implemented, so as-built scantlings were used for the study.

Table 1 Main particulars of the examined ships

	M1 - Aframax tanker	M2 - Suezmax tanker	M3 - VLCC tanker
L_{BP} (m)	235	265	320
B (m)	42	46.4	58
D (m)	21	23.2	30
C_B (-)	0.86	0.83	0.82

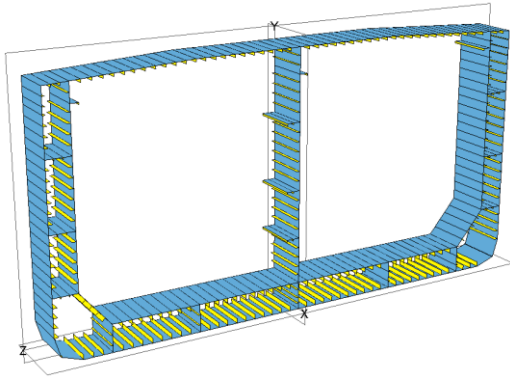


Fig. 1 Structural model of the Aframax double hull oil tanker (model M1).

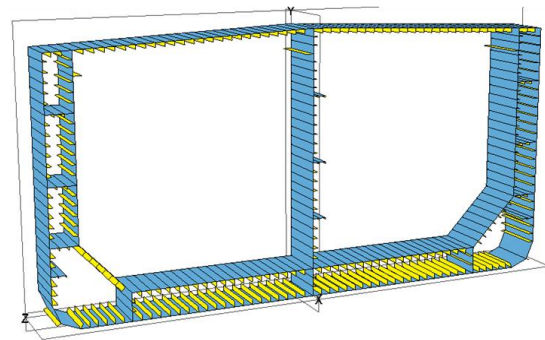


Fig. 2 Structural model of the Suezmax double hull oil tanker (model M2).

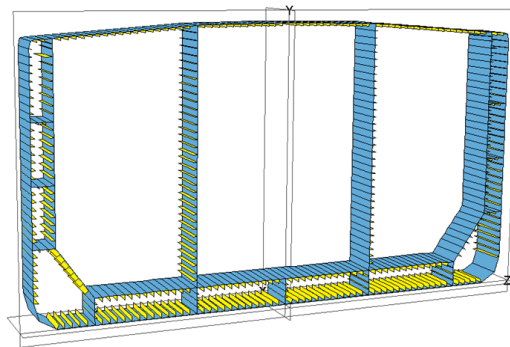


Fig. 3 Structural model of the double hull VLCC (model M3).

3. Damage scenarios

The damage due to grounding and collision are the most common reasons of the destruction of ship structures. Ship to ship collision causes the bow of the striking ship to collapse and the side of the struck ship to be damaged. It is the most destructive among all possible damages. Ship grounding on rock(s) results in a cutting or crushing of the bow

bottom [20]. The basic definition of the damage extent in this study was performed according to IACS H-CSR [2] and a specified extent of damage for collision and grounding type of accident is illustrated by Figures 4 and 5, respectively. The hull girder ultimate bending capacity with the specified damage extents is to be checked.

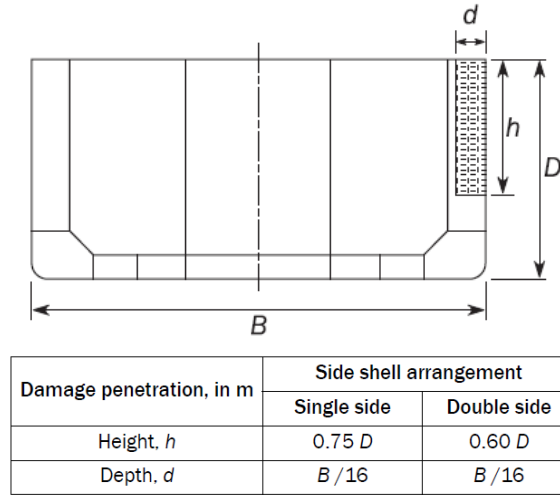


Fig. 4 Damage extent for collision specified by IACS H-CSR [2].

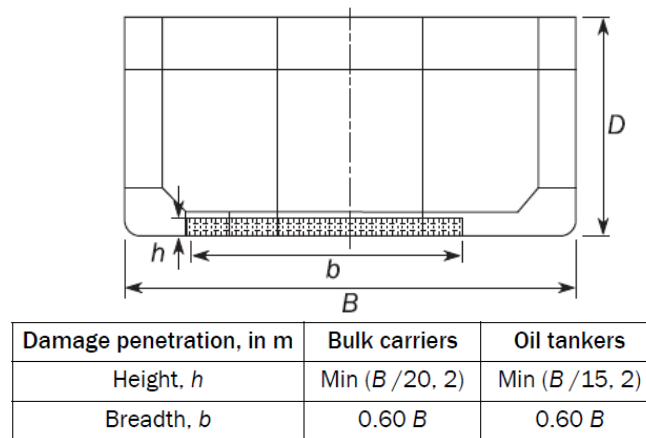


Fig. 5 Damage extent for grounding specified by IACS H-CSR [2].

As stated by Notaro et al. [13] the ultimate capacity in damaged condition is not largely influenced by the shape and the longitudinal extension of the damage. The main factor leading the capacity reduction is the vertical and transversal extent of the damage. With respect to those remarks the performed systematic variation of a damage size is based on the following principles:

- For the collision case depth of the damage penetration is kept constant ($d=B/16$), as specified by the Rules, while the damage penetration height h is systematically varied from $0.1D$ to $0.8D$, with the step of $0.1D$. For this case the damage is on one side only and located immediately below the freeboard deck;
- For the grounding case height of the damage penetration is kept constant ($h=\text{min}(B/15, 2)$) as specified by the Rules, while the damage penetration breadth b is systematically varied from $0.1B$ to $0.8B$, with the step of $0.1B$. For this case the damage is considered to be located symmetrically from the CL on PS and SB side.

Nine different models were generated for the each of three tankers (eight damaged and one intact) and used for each damage case. Several examples of a damaged ship models are presented in Figures 6 and 7 for the collision and grounding case, respectively.

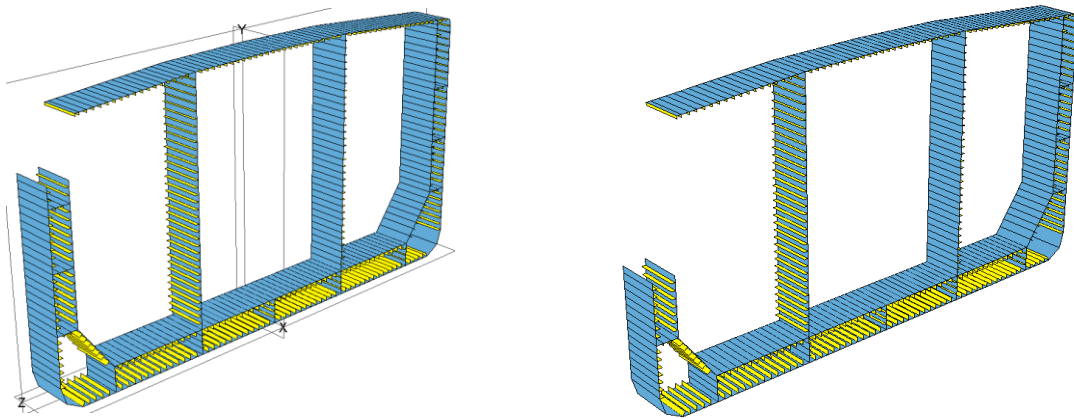


Fig. 6 VLCC oil tanker midship section (M3), relevant for collision case with damage size of $0.2D$ and $0.5D$

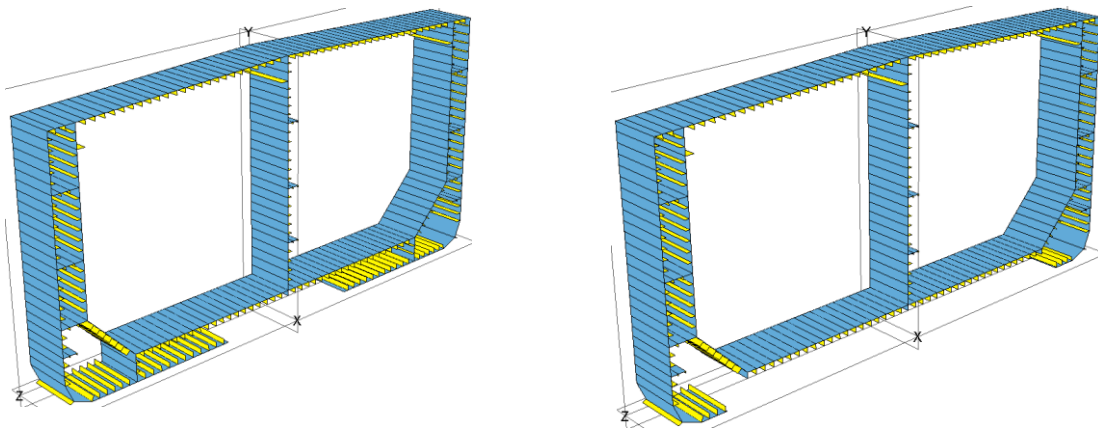


Fig. 7 Suezmax oil tanker midship section (M2), relevant for grounding case with damage size of $0.3B$ and $0.8B$

4. Hull girder ultimate strength results

Imminent occurrence of the inter-frame collapse prior to any other feasible global collapse mode ensures that the global structural behaviour of the complex monotonous thin-walled structures submitted to flexure can be idealized in accordance with the beam bending theory during the whole collapse process. This implication represents the fundamental premise of the Smith's method [5] which is considered to be the first among established progressive collapse analysis methods that incorporate more sophisticated consideration of the structural collapse sequence and structural post-critical response of structural elements. Development of the original method subsequently stimulated proposition of various methods based on Smith's approach [16, 25, 26]. In shipbuilding practice, rules of many classification societies and their associations [2, 3] prescribe utilization of the incremental-iterative procedures based on Smith's approach for evaluation of longitudinal ultimate capacity during the structural design synthesis. The ultimate vertical bending moment capacities of the hull girder transverse section, in hogging and sagging conditions, are defined as the maximum values of the curves of the vertical bending moment capacity versus the curvature χ of the transverse section considered. The curve is obtained through an incremental-iterative approach. Within the framework of this paper, IACS incremental-iterative progressive collapse analysis method is employed, as previously implemented within OCTOPUS [27] computer program. In performed calculations several assumptions were made:

- Calculation procedure for the vertical ultimate bending moment capacities of a damaged section is same as for the intact condition and follows recommendations given in IACS;

- Damaged area, as defined in Ch. 3, carries no loads and is therefore removed from the models;
- Only vertical bending is considered. The effects of the shear force, torsion loading, horizontal bending moment and lateral pressure are neglected;
- The ultimate bending capacity of the damaged transverse cross section is calculated with the model kept in upright position and a neutral axis rotation is not considered. Implication of that assumption, and possibly error can be advocate to be below 10 % due to fact that the same method is defined in H-CRS [2] with prescribed safety factor equal to $C_{NA}=1.1$ for collision and $C_{NA}=1.0$ for grounding case. Some suggestions regarding the inclusion of the neutral axis rotation are given in Choung et al. [21] and Fujikubo et al. [22]). Fujikubo et al. [22] also reported that influence of NA rotation on hull girder ultimate strength is very low for tankers in collision case. For bulk carriers the effect is more significant due to single side shell structure and around 8% reduction of ultimate strength can be expected for 70% side damage.

In this study the residual strength index (*RIF*), originally introduced by Fang and Das [28] and used by Hussein and Soares [20], as a way to compare the ultimate strength capacity of the damaged hull ($M_{U,Damage}$) with the intact one ($M_{U,Intact}$), is used to systematically investigate the relationship between the ultimate strength capacity and a damage size:

$$RIF = \frac{M_{U,Damage}}{M_{U,Intact}} \quad (1)$$

Similar approach can be used to compare other relevant sectional characteristics (A , I_y , W_D , W_B) of the damaged and intact hull girder cross sections:

$$RIF - A = \frac{A_{Damage}}{A_{Intact}}; RIF - I_y = \frac{I_{y,Damage}}{I_{y,Intact}}; RIF - W_D = \frac{W_{D,Damage}}{W_{D,Intact}}; RIF - W_B = \frac{W_{B,Damage}}{W_{B,Intact}} \quad (2)$$

where A_{Damage} and A_{Intact} are cross sectional area in damaged and intact condition, respectively; $I_{y,Damage}$ and $I_{y,Intact}$ are vertical moments of inertia for cross sections in damaged and intact condition, respectively; $W_{B,Damage}$ and $W_{B,Intact}$ are bottom sectional modulus in damaged and intact condition, respectively; $W_{D,Damage}$ and $W_{D,Intact}$ are deck sectional modulus in damaged and intact condition, respectively.

4.1. Grounding case

Summary of the obtained results for the grounding case is given in Table 2.

Damage ratio λ for grounding has been specified as breadth of damage area (b_{damage}) divided by the breadth of the ship (B), see Table 2.

From the presented results it can be noted that the reduction of the hull girder ultimate bending moment, expressed through the *RIF*, is larger in the hogging than in the sagging case for all evaluated tankers. Data given in Table 2 enable easy establishment of the dependence between the reduction of the cross sectional characteristics (*RIF* - A , I_y , W_D , W_B) and *RIF*.

For example, a damage size ratio of $\lambda = 0.6$ in the grounding case (specified by the IACS (2014) as the requested damage value), cause average reduction of the cross section area by 13.9%. At the same time, the ultimate hogging and sagging moments are reduced in average (for all three models) by 19.7% and 8.3%, respectively. Graphical presentation of the relationship between *RIF* and a damage size ratio is presented in Figure 8. From the data

presented in Table 2 and Figure 8, a linear equations are proposed to describe the relationship between the RIF and a damage size ratio ($\lambda = b_{damage}/B$):

$$RIF_{grounding-SAGG} = 1.008 - 0.158\lambda \quad (3)$$

$$RIF_{grounding-HOGG} = 1.006 - 0.341\lambda \quad (4)$$

Hussein and Guedes Soares published [15] a similar research and specified a unique expression for the double hull oil tanker structure:

$$RIF_{grounding} = 1.02 - 0.254\lambda \quad (5)$$

Table 1 Residual strength index for grounding.

Damage ratio:	M1-Aframax tanker					
$\lambda=b_{damaged}/B$	RIF_{M-sagg}	RIF_{M-hogg}	RIF_A	RIF_{I_y}	RIF_{W_D}	RIF_{W_B}
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.988	0.966	0.973	0.969	0.988	0.992
0.2	0.977	0.934	0.952	0.942	0.976	0.983
0.3	0.966	0.907	0.931	0.914	0.964	0.975
0.4	0.951	0.867	0.907	0.881	0.949	0.938
0.5	0.933	0.829	0.877	0.839	0.929	0.864
0.6(H-CSR request)	0.910	0.789	0.853	0.802	0.910	0.804
0.7	0.891	0.760	0.833	0.768	0.892	0.752
0.8	0.859	0.713	0.800	0.713	0.862	0.671
	M2-Suezmax tanker					
$\lambda=b_{damaged}/B$	RIF_{M-sagg}	RIF_{M-hogg}	RIF_A	RIF_{I_y}	RIF_{W_D}	RIF_{W_B}
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.991	0.975	0.977	0.972	0.989	0.950
0.2	0.980	0.947	0.955	0.944	0.977	0.902
0.3	0.968	0.912	0.931	0.911	0.963	0.849
0.4	0.953	0.873	0.906	0.876	0.947	0.795
0.5	0.937	0.830	0.882	0.838	0.929	0.740
0.6(H-CSR request)	0.922	0.797	0.860	0.803	0.912	0.692
0.7	0.902	0.757	0.838	0.766	0.892	0.643
0.8	0.874	0.707	0.807	0.714	0.864	0.578
	M3-VLCC tanker					
$\lambda=b_{damaged}/B$	RIF_{M-sagg}	RIF_{M-hogg}	RIF_A	RIF_{I_y}	RIF_{W_D}	RIF_{W_B}
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.987	0.967	0.977	0.974	0.989	0.952
0.2	0.976	0.941	0.956	0.947	0.977	0.906
0.3	0.964	0.912	0.935	0.919	0.964	0.861
0.4	0.950	0.879	0.910	0.886	0.948	0.808
0.5	0.935	0.849	0.889	0.856	0.934	0.762
0.6(H-CSR request)	0.920	0.823	0.870	0.827	0.919	0.722
0.7	0.899	0.792	0.850	0.794	0.901	0.677
0.8	0.876	0.757	0.824	0.754	0.879	0.624

Collapse sequences in hogging and sagging are analyzed in detail for undamaged and damaged case ($\lambda = 0.6$) for all three examined cross sections. Vertical bending moment capacity versus the curvature χ curve is presented for the undamaged and damaged conditions for the Aframax tanker model in hogging, see Figure 9, as an example.

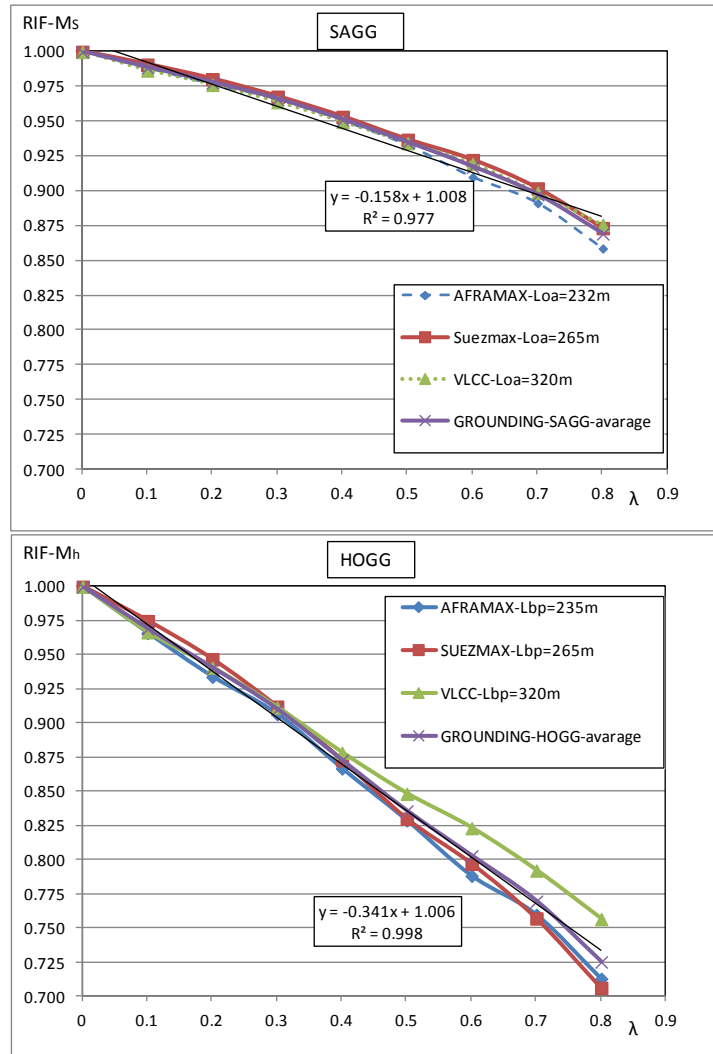


Fig. 8 RIF for grounding in sagging and hogging cases.

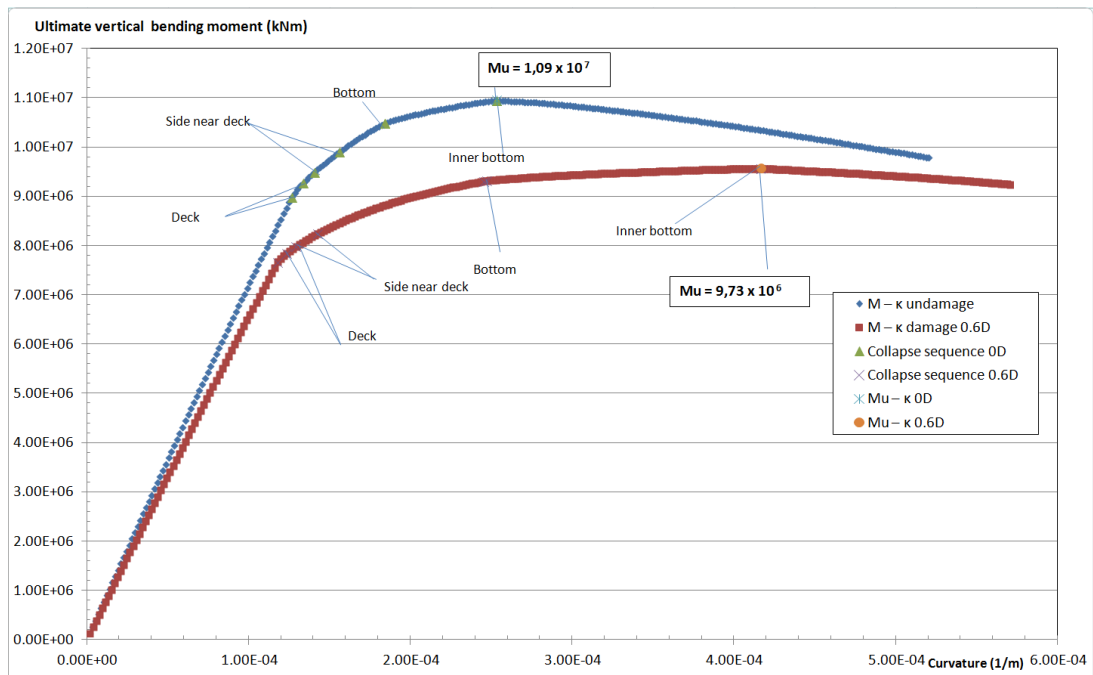


Fig. 9 Collapse sequences of Aframax tanker in grounding, hogging case.

Due to the reduced cross section, it can be noted that the damaged section has reduced bending stiffness and reaches the ultimate bending capability faster than the undamaged section. Also, the damaged section reaches the ultimate bending capacity at the lower curvature compared to the undamaged section.

Due to the ineffectiveness of the damaged bottom plating, which does not contribute to the bending stiffness of the cross section, the inner bottom plating is imposed with the higher compressive load. When inner bottom structure collapses due to buckling, the damaged section reaches the ultimate bending capacity. It can be noted that the undamaged section reached its ultimate bending capacity just after the bottom plating collapsed, but without the collapse of the inner bottom plating. Furthermore, it can be also noticed that the deck structure is the structural part that collapses first, due to the high tensile stresses in both cases.

In-house software OCTOPUS [27] used in this study enables identification of the characteristic structural collapse sequence accounting for the load-shedding effect during the progressive load incrementation. This capability can enable determination of more rational distributions of the longitudinally effective material within the process of concept design synthesis, i.e. during the consideration of various topologic variants and/or materially-geometrical properties of the feasible structural cross-sections, since it can point to the more efficient ways of required structural safety level accomplishment. Furthermore, collapse sequence can also be considered as a rational pathfinder during the material reduction process of the initially over-dimensioned cross section (for the case of structural safety criteria over-satisfaction).

4.2. Collision case

Summary of the obtained results for the collision case are given in Table 3.

Damage ratio λ for the collision is specified as the height of the damage area (h_{damage}) divided by the depth of the ship (D), see Table 3.

From the presented results it can be noted that the reduction of the hull girder ultimate bending moment expressed through residual RIF is larger in sagging than in hogging case for all evaluated tankers. This is the opposite trend with respect to the findings obtained for the grounding case.

Case with damage size ratio of $\lambda = 0.6$ (specified by the IACS H-CSR [2] as requested damage value), causes an average reduction of the cross sectional area by 11.5%. At the same time, the ultimate hogging and sagging moments are reduced in average (for all three models) by 12.2% and 18.8%, respectively.

Graphical presentation of the relationship between the RIF and a damage size ratio is presented in Figure 10.

From the data presented in Table 3 and Figure 10, a linear equations can be used to represent the relationship between the RIF and a damage size ratio ($\lambda = h_{damage}/D$):

$$RIF_{collision-SAGG} = 0.9927 - 0.5802\lambda + 0.4516\lambda^2 \quad (6)$$

$$RIF_{collision-HOGG} = 0.9948 - 0.3494\lambda + 0.2544\lambda^2 \quad (7)$$

In [20], Hussein and Guedes Soares proposed a unique expression for the double hull oil tankers:

$$RIF_{collision} = 0.98 - 0.084\lambda \quad (8)$$

Table 3 Residual strength indices for collision.

Damage ratio:	M1-Aframax tanker					
$\lambda=h_{damaged}/D$	<i>RIF_M-sagg</i>	<i>RIF_M-hogg</i>	<i>RIF_A</i>	<i>RIF_I</i>	<i>RIF_W_D</i>	<i>RIF_W_B</i>
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.925	0.951	0.973	0.948	0.896	0.978
0.2	0.895	0.932	0.958	0.928	0.898	0.978
0.3	0.848	0.907	0.936	0.911	0.869	0.979
0.4	0.827	0.894	0.921	0.905	0.857	0.982
0.5	0.810	0.882	0.902	0.902	0.849	0.987
0.6(H-CSR request)	0.802	0.874	0.879	0.901	0.846	0.990
0.7	0.802	0.873	0.861	0.901	0.847	0.988
0.8	0.803	0.872	0.836	0.897	0.850	0.974
	M2-Suezmax tanker					
$\lambda=h_{damaged}/D$	<i>RIF_M-sagg</i>	<i>RIF_M-hogg</i>	<i>RIF_A</i>	<i>RIF_I</i>	<i>RIF_W_D</i>	<i>RIF_W_B</i>
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.931	0.959	0.975	0.953	0.929	0.987
0.2	0.897	0.937	0.960	0.935	0.902	0.984
0.3	0.856	0.910	0.939	0.920	0.877	0.986
0.4	0.837	0.895	0.922	0.914	0.865	0.989
0.5	0.826	0.882	0.903	0.912	0.859	0.994
0.6(H-CSR request)	0.820	0.873	0.885	0.912	0.858	0.996
0.7	0.820	0.869	0.862	0.911	0.859	0.990
0.8	0.821	0.869	0.852	0.909	0.861	0.983
	M3-VLCC tanker					
$\lambda=h_{damaged}/D$	<i>RIF_M-sagg</i>	<i>RIF_M-hogg</i>	<i>RIF_A</i>	<i>RIF_I</i>	<i>RIF_W_D</i>	<i>RIF_W_B</i>
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.934	0.957	0.975	0.949	0.928	0.981
0.2	0.896	0.935	0.960	0.929	0.899	0.977
0.3	0.860	0.917	0.942	0.915	0.876	0.978
0.4	0.834	0.903	0.926	0.908	0.864	0.981
0.5	0.818	0.892	0.906	0.905	0.857	0.986
0.6(H-CSR request)	0.813	0.888	0.891	0.904	0.855	0.988
0.7	0.811	0.887	0.873	0.904	0.856	0.986
0.8	0.812	0.886	0.853	0.767	0.857	0.976

Collapse sequences in hogging and sagging are analysed in detail for the undamaged and damaged cases ($\lambda = 0.6$), for all three examined cross sections. Vertical bending moment capacity versus the curvature χ curves are presented for the undamaged and damaged conditions for Aframax tanker model in sagging, see Figure 11, as an example.

A similar collapse sequences are identified for the damaged and undamaged conditions in the hogging and sagging case. The critical structural part which collapses first is the deck and after the part of the side structure (outer and inner) collapsed, the cross section reached its ultimate bending moment capacity.

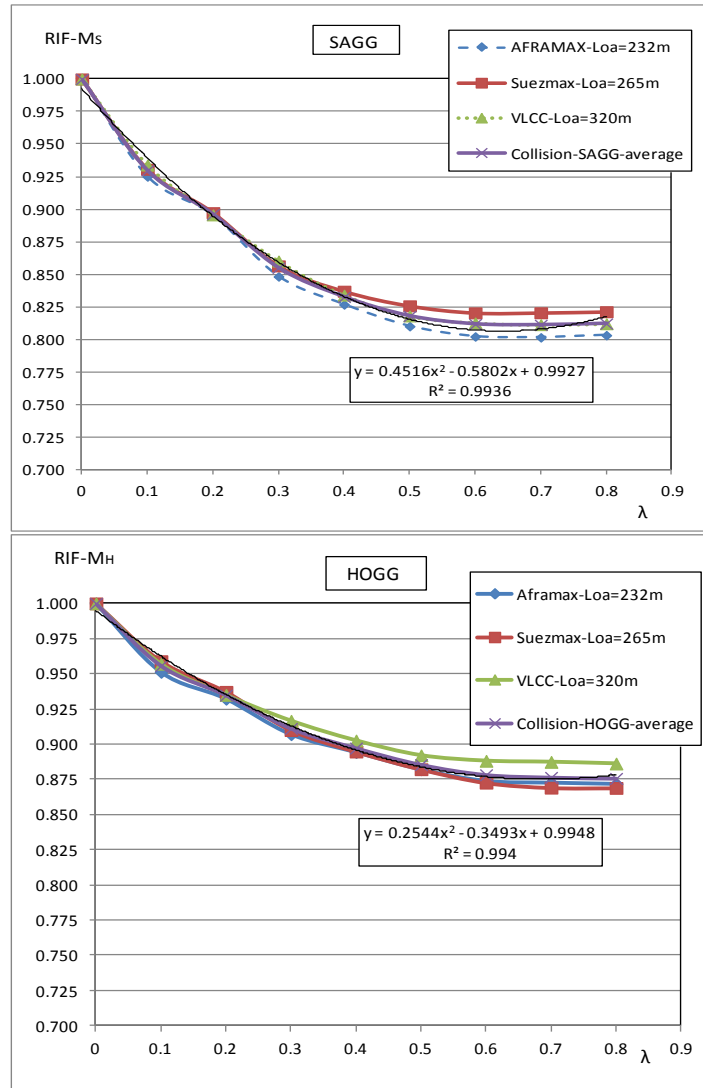


Fig. 10 RIF for collision in sagging and hogging case.

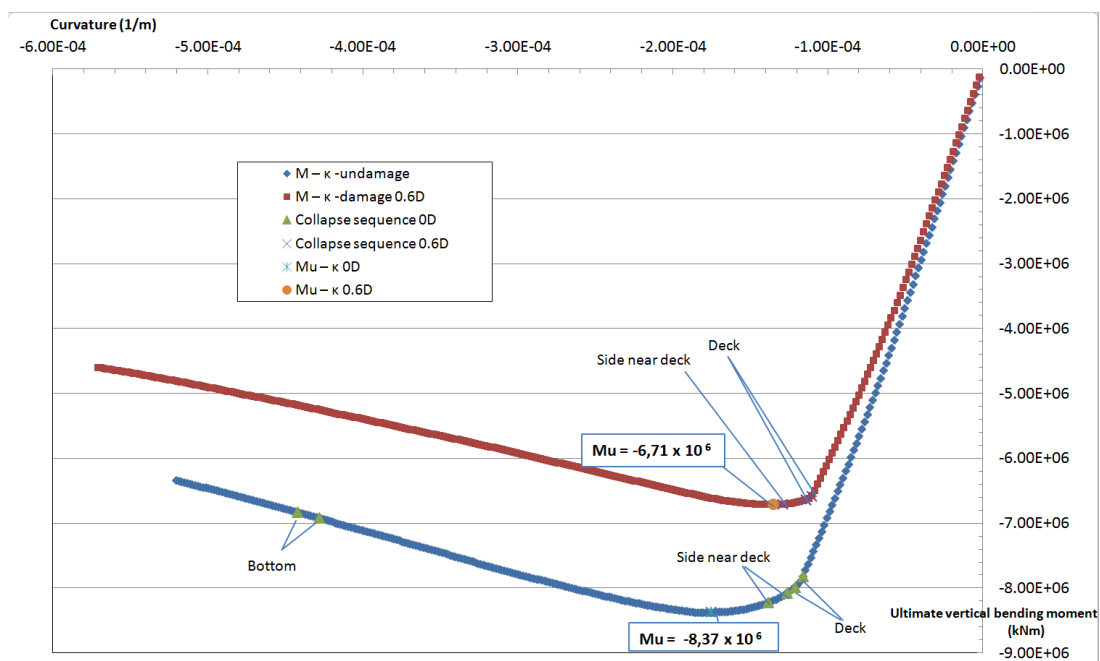


Fig. 11 Collapse sequences of Aframax tanker in collision, sagging case.

5. Conclusions

Intention of the present study was to investigate the influence of the damage size on the ultimate hull girder capacity of the oil tankers for the two characteristic types of accidents: collision and grounding, using an IACS incremental-iterative progressive collapse analysis method.

Influence of the different ship size, structural configuration and damage extent (size and location) in collision and grounding on the hull girder residual ultimate strength has been systematically investigated. Analytical formulations of the relationship between reductions of the hull girder ultimate bending moment (with respect to the undamaged state) and a damage size ratio has been proposed based on the analysis of the results of a systematic variation of damage extent of ship's side or bottom. Those design equations and associated diagrams can be used for the rapid assessment of the hull girder residual ultimate strength and give first basis for the emergency situation decision making.

In-house software used in this study enables identification of the characteristic structural collapse sequence and can be used for determination of more rational distributions of the longitudinally effective material within the design process.

Future investigation will go a step further with respect to the extension of the employed progressive collapse analysis method regarding the possibility to calculate vertical and horizontal ultimate bending moments and to enable rotation of the cross sectional neutral axis in damaged conditions.

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