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Structural Reliability Assessment of Stricken Oil Tanker in the Adriatic Sea

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Abstract

The aim of this paper is to present a methodology for the assessment of the structural reliability of an oil tanker damaged in a hypothetical collision accident in the Adriatic Sea. Monte Carlo simulation is employed to generate random damage scenarios. Assumption of the damage size is based on the numerical simulation of the ship-ship collision. Residual ultimate strength and still water bending moment distribution are determined based on the size and location of the damage. Structural reliability analysis is employed to determine the safety index with respect to the ultimate hull girder failure. Histograms of safety indices are thus obtained, representing new measures for the performance assessment of the damaged ship. If extended to more severe design wave environments and collision scenarios, the presented methodology may be used for general reliability-based comparison of different alternative designs of marine structures with respect to the accidental failure modes or for improvement of ship structural design rules.

Keywords: damaged oil tanker; residual strength; structural reliability; Adriatic Sea.

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1. Introduction

The concept of risk, applied in the shipping industry, and environmental issues have become very important factors in marine transportation. The concept of risk has two elements, i.e. the probability of an occurrence and its consequences. Oil tankers are potentially the most hazardous ships for marine environment, i.e. the consequences of structural damages of oil tankers are the most significant. Furthermore, among ship accidents, those resulting in collapse of the ship's hull and subsequent sinking have obviously the most severe consequences. Therefore, the calculation of failure probabilities with respect to the ultimate bending capacity of the ship is a vital part of the risk assessment process and is achieved by structural reliability approach (Teixeira et al. 2011). Research aimed at improving shipping safety, with a focus on accidental loads and on the hull girder strength after collision and grounding, is emphasized as one of the priorities in the field of marine structures where scientific development is required (Pedersen 2015).

An analysis of past accidents involving oil tankers, like Exxon Valdes, clearly shows enclosed waters are especially sensitive to oil tanker accidents. Therefore, there is a clear interest to minimize the environmental risk of maritime transportation in regions of huge importance for the livelihood of people. Such an area is the Adriatic Sea, the part of the Mediterranean Sea that separates the Apennine and Balkan peninsulas in the south and the Apennine and Dinara mountains in the north. Across the Mediterranean, the Adriatic Sea tanker traffic is very intense. More than a thousand tankers and 70 million tons of oil enter the Adriatic every year with a prospect of significant growth. Thus, the amount of transported oil increases by abt. 10% every 6 years (Mayer et al. 2004). On the other side, the Adriatic is also extremely important for tourism and fishing, on which the economy of both Italy and Croatia heavily depend. An oil tanker accident with a significant oil spill would therefore cause an irreversible ecological disaster with enormous economic losses (Klanac et al. 2013).

The hull-girder collapse of an oil tanker, in general, may be the consequence of unfavourable environmental conditions or an accident due to different ship design or operation errors. The most common ship accidents are ship-to-ship collisions and grounding (IMO, 2008). In the case of such an occurrence, the ship strength could be reduced, still water loads may increase and wave loads could become a cause of structural overloading. A damaged ship may collapse after a collision or grounding accident if she does not have adequate residual longitudinal strength. Such a collapse can occur when the hull's maximum residual load-carrying capacity is insufficient to sustain the corresponding hull-girder loads applied (Hussein & Guedes Soares 2009, Prestileo et al. 2013). Wave loads on intact oil tankers in the Adriatic Sea have been studied in Parunov and Senjanović (2005). The study showed the probability of a structural failure of an intact oil tanker due to purely environmental loads was almost negligible. However, the structural failure may occur due to collision, grounding or some other accident. In that case, the ship strength could be considerably reduced making wave loads, even of relatively low level, important for the structural safety assessment (Burić et al. 2012).

The aim of the present study is to propose a methodology for the assessment of structural reliability of an oil tanker that may be damaged in a collision accident in the Adriatic Sea. The flow chart of a collision accident is presented in Figure 1, where it may be seen that the collision affects the ultimate hull girder capacity in the damaged region, the still water bending moment (SWBM) distribution along the vessel as well as the vertical wave bending moments (VWBM). Whether the SWBM will increase or decrease depends on the damage size and location and flooded tanks. For tankers in full load condition, damage of ballast tanks in the midship region is typically the worst situation, leading to considerable increase of the SWBM. The most recent studies indicate that the transfer functions of the VWBM at midship slightly increase as a consequence of the flooding (Temarel et al. 2016). However, a milder wave environment and reduced exposure time compared to the design condition of intact ship have a much larger influence on the VWBM.

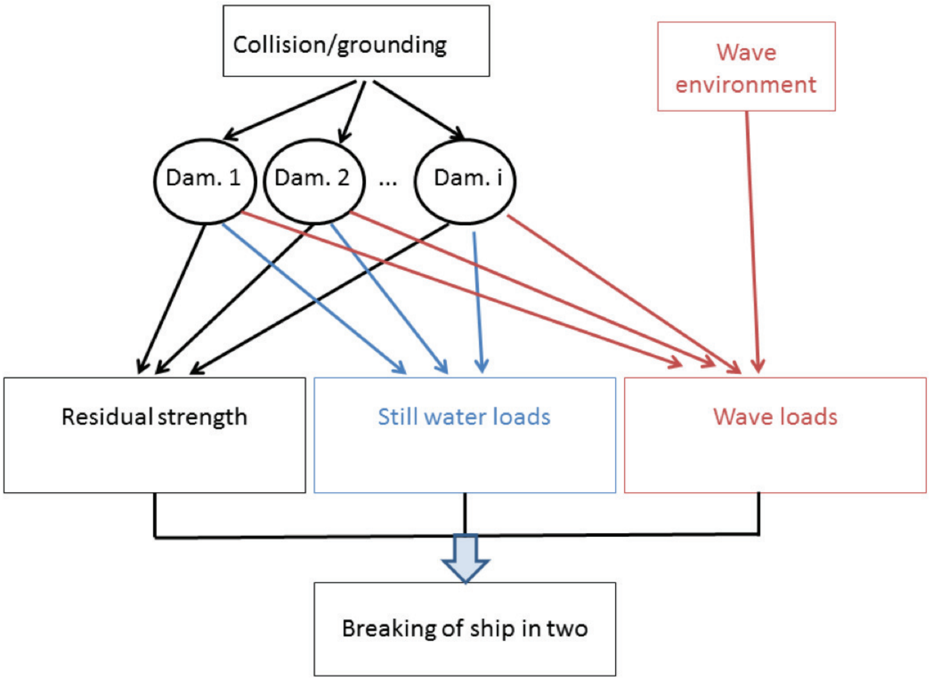

Fig. 1. Flowchart of ship behaviour following a collision accident.

The extent of the damage on the ship's hull after a collision accident depends on several parameters such as relative speed of ship in collision, contact angle, collision location along the vessel and structural configuration, among others. These parameters are in the present study assumed as random variables, described by probability density functions, depending on the geographical location concerned. Random realizations of collision parameters are defined by Monte Carlo (MC) simulation. For each realization, the damage size is determined based on the non-linear finite element method (FEM) numerical simulation of the ship-ship collision. For the resulting damage size and location, residual ultimate longitudinal strength as well as the SWBM distribution accounting for flooding of damaged compartments are determined. Finally, structural reliability approach is used to calculate failure probability during the salvage period for each randomly realized collision event. The approach represents an advancement with respect to the state of the art, because so far structural reliability studies have been mostly done by assuming damage in the shape of a box with dimensions determined according to different Rules or Guidance notes of classification societies or maritime authorities (ABS 1995, IACS 2014).

The present paper is organized as follows. Firstly, an analysis of shipping routes in the Adriatic Seas is performed and possible collision scenarios are chosen. In addition, probabilistic models of collision parameters are defined in the same section. In the next section, numerical simulation of a collision accident aiming to determine the location and the size of the damage is performed. Based on the limited number of simulations, a damage size is determined and described as a function of random collision parameters (collision speed, contact angle, collision location and displacement of striking vessel), representing the surrogate collision model. The surrogate model is then used in Monte Carlo method simulation to generate a large number of random damages. In the following sections, residual hull girder vertical bending capacity and the SWBM of the damaged ship are analysed using simulated damage size and location. Environmental conditions and wave loads on the damaged oil tanker in the Adriatic Sea are also described. Finally, structural reliability assessment of the damaged oil tanker with respect to the hull-girder collapse is performed for a period when the ship is towed to the safe location. A histogram of safety indices is thus obtained representing a performance measure of an oil tanker involved in an accident.

2. Analysis of shipping routes in the Adriatic Sea

The Adriatic Sea has approximately an elliptical shape with a length of about 800 km and a width of about 100 km, and it is connected to the Mediterranean Sea by the relatively narrow Strait of Otranto. The Adriatic Sea traffic of oil tankers is very intense with more than thousand tankers entering the Adriatic Sea every year, carrying more than 70 million tons of oil (Klanac et al. 2013).

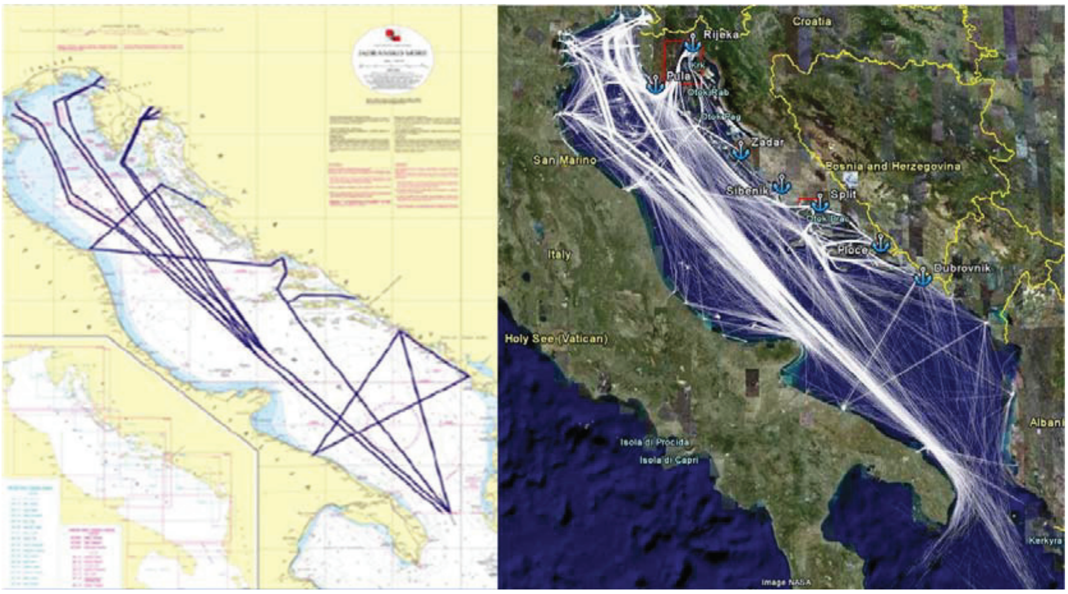

Fig. 2. Main longitudinal and transversal traffic routes in the Adriatic (left) and record of the traffic in September 2008 (right) (Zec et al. 2009).

A sailing route is generally defined as a sea band within which maritime traffic between ports normally takes place (Lušić and Kos 2006). Taking into account the route’s relative positions with respect to the coast, the sailing routes in the Adriatic Sea may be divided in longitudinal and transversal. The main longitudinal sailing route in the Adriatic connects the north Adriatic ports (Trieste, Monfalcone, Porto Nogaro, Venezia, Chioggia, Koper and Rijeka) with the Strait of Otranto on the south. The dominant position on that sailing route is held by the Croatian island of Palagruža, which is located in the middle of the Adriatic Sea, 68 NM south from the Croatian port of Split. The main transversal sailing routes in the Adriatic are between the main ports on the east coast (Rijeka, Zadar, Šibenik, Split, Ploče, Dubrovnik, Bar, Durres) and the ports on the western coast of the Adriatic (Ravenna, Ancona, Pescara, Bari, Brindisi). The main longitudinal and transversal traffic routes may be clearly identified in Figure 2.

Oil tankers in the Adriatic Sea normally take a longitudinal sailing route, whereas ferries connecting Croatian and Italian coasts keep a transversal route. This is identified as the main collision risk scenario, i.e. that a ferry sailing the transversal route strikes an oil tanker sailing the longitudinal route. The Aframax tanker is chosen as the struck ship, because such a ship is the most common type of oil tanker sailing the Adriatic, whereas a ferry of about 120 m in length and 5.7 m in draught, with a capacity of about 1000 passengers and 270 cars, is assumed to be the striking ship (Klanac et al. 2013).

Probability distribution of the striking vessel speed is assumed as normal distribution with a mean value equal to 13.3 kn and a standard deviation of 5.1 kn. These data are obtained by Automatic Identification System (AIS) (Zec et al. 2009). Collision speed of the striking vessel is conditioned by the service speed and uniformly distributed between the zero speed and 75% of the service speed, after which it triangularly decreases to zero at service speed (Klanac et al. 2013). On the other hand, the speed of the struck tanker is assumed to be equal to zero. Collision angle is assumed to be normally distributed, with the mean value of 93° and a standard deviation of 42°, whereas the distribution of collision location is uniform. Collision angle and location along the struck vessel are assumed on the basis of previous worldwide collision accidents data (Klanac et al. 2013). Probability density function of the displacement of the striking ship is assumed as an exponential distribution with the expected value equal to 6700 t, based on the traffic data (Zec et al. 2009). A summary of the random variables used to simulate random collision scenario is presented in Table 1.

Table 1. Random variables of the collision scenario.

Collision parameter	Distribution	Mean	Standard deviation
Speed v [kn]	Normal	13.3	5.1
Collision angle β [°]	Normal	93	42
Collision location x [m]	Uniform	118	68.13
Displacement of the striking ship Δ [t]	Exponential	1/6700	1/6700

3. Numerical simulation of collision accident in the Adriatic Sea

A collision between a tanker and a ferry is considered to be an accident with high probability in the Adriatic Sea and the numerical simulation of such an accident is performed by non-linear FEM analysis using LS-Dyna software. The situation during the impact may vary but it is reasonable to assume that the worst case scenario considers the bow of the ferry hitting the tanker nearly or exactly orthogonally. In that case the tanker's double hull may be breached, leading to oil spill and even fire. In 1987, in the Philippines, "MT Vector", carrying 8800 barrels of gasoline, collided with "MV Doña Paz" passenger ferry. The impact caused a fire that spread to "Doña Paz" and set the surrounding water surface on fire. With an estimated death toll of 4.375 people, this incident resulted in the deadliest ferry disaster ever and the biggest recorded in history during peace time (Perez 2011). In the present paper, the problem in focus is that structural reliability of the damaged tanker with respect to the residual ultimate hull girder strength is generally reduced compared to the intact condition.

In the present analysis, the Aframax class tanker is considered as the struck ship and a typical ferry sailing in the Adriatic on international routes as the striking ship. The main particulars for both the struck and the striking ship are listed in Table 2.

Table 2. Main struck and striking ship particulars.

Struck ship (tanker)		Striking ship (ferry)	
Lpp	236 m	*Lpp*	120.4 m
B	42 m	*B*	19.6 m
D	21 m	*D*	12.20 m
Scantling draught	15.1 m	Scantling draught	5.28 m
Displacement	133000 t	Displacement	6889 t
Max. service speed	15.3 kn	Max. service speed	21 kn
Ship centre of gravity by length (from L/2)	5.599 m	Ship centre of gravity by length (from fore perpendicular)	61.08 m
Ship centre of gravity height	12.050 m	Ship centre of gravity height above base line	8.38 m

Because a very fine mesh is required in the collision zone, only a portion of the struck ship is modelled, consisting of the half of three cargo holds. The striking ship bow is modelled in detail and the rest of the ship, i.e. ferry hull, is modelled appropriately by beam finite elements. Reference collision scenario set-up is presented on Figure 3 and described by the following list of parameters:

- Ferry is located in front of the middle cargo hold of a tanker,
- Collision is orthogonal,
- Speed of the tanker is 0 m/s,
- Speed of the ferry is 8 m/s,
- Draft of the tanker is 15.1 m,
- Draft of the ferry is 5.3 m

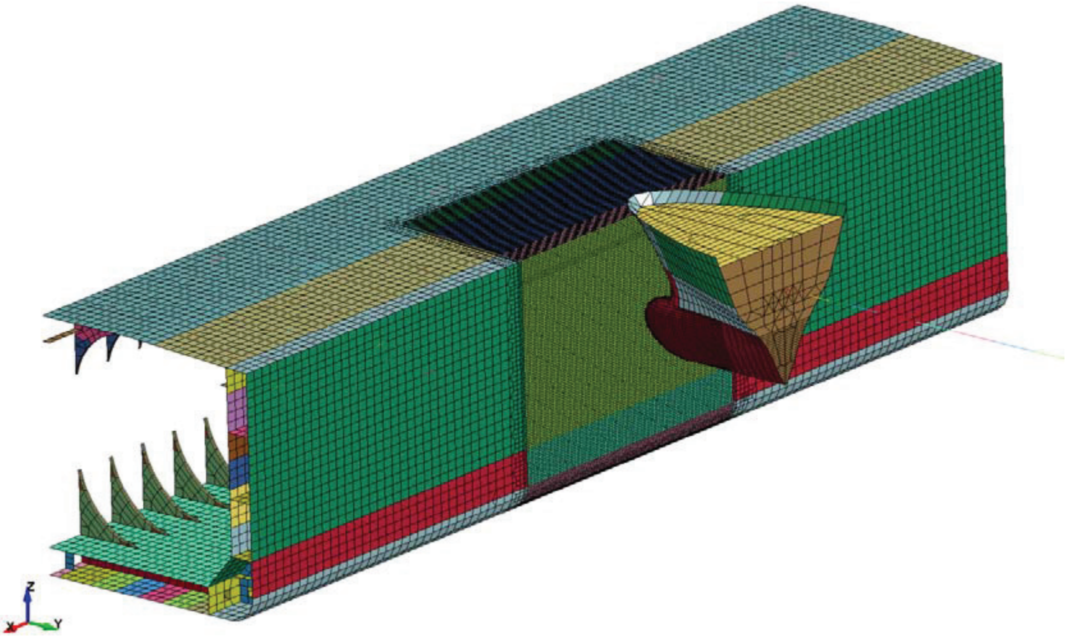

Fig. 3. Reference model collision set-up.

Zero speed of a struck ship is a common assumption in ship collision analysis due to several reasons. First, it is assumed that orthogonal collision with motionless struck ship represents the worst collision case, inducing the highest collision energy. Secondly, struck ships are frequently moored or at anchor and the USCG tanker collision data indicate that nearly 60% of collisions occur with struck ship zero speed (Brown, 2002). Finally, it is not known to the authors whether a ship collision analysis with struck ship speed different from zero has ever been made using finite element method. An overview of the impact scenario models including the struck ship speed distribution may be found in (Goerlandt et al., 2012).

A number of FEM analyses were performed and the following main parameters varied (Galletta 2015):

- Ferry collision speed: 2 m/s, 4 m/s, 6 m/s, 8 m/s (reference model), 10 m/s and 12 m/s.
- Impact location *x* = 87 m (aft cargo hold collision), x = 118 m (reference model), *x* = 148.5 m (bow cargo hold collision).
- Impact angle: -45°, -30°, -15°, 0° (reference model), 15°, 30° and 45°.
- Scaled striking ship length/mass: 4251 t, 6889 t (reference model), 13226 t, 23329 t and 41149 t

Explicit non-linear FE analysis is performed in LS-Dyna. An elastic-ideal plastic material model with an arbitrary stress versus strain curve is used, namely MAT_024. This is piecewise linear isotropic plasticity material model commonly used for the analysis of metallic materials. Detailed description of the mentioned material model may be found in LS-DYNA User's Manual (2014). Required true stress-strain curve is obtained from the in-house tensile test of Grade A steel specimen. Strain rate effects can be defined within the applied material model in several ways, but were not defined in the comparative collision analyses performed.

An automatic surface to surface contact algorithm was used to model contact between the ships in collision. In this algorithm attention is paid to the fact that in complex crash simulations the orientation of parts relative to each other cannot always be anticipated as the model undergoes large deformations (LS-DYNA User's Manual, 2014). Due to that, an automatic contact algorithm checks for penetration on either side of a shell element. When a contact is detected, a penalty method is used to estimate the contact forces. The penalty method uses the size of contact segments and its material properties to determine contact spring stiffness. A resulting contact force can be then easily calculated.

Situation at the end of reference model collision simulation is presented on Figure 4 (left). Due to the variation of the main parameters, hull breach will not be present in every collision scenario and the damage will vary too. Destruction of the structure and the plastic strain in the damaged area for the reference model is presented on Figure 4 (right). On the same figure the method of the damage volume measurement is indicated. The damaged structure has irregular shape and there is no easy way to appropriately measure the damage volume. Therefore, extension of the damage in all three axes is being concerned. Although the plastic strain does not extend entirely along a, b and c lines on Figure 4 (right), it is assumed that also a large portion of elastic deformation is present in the vicinity of the impact point that is also taken into account in this way. By multiplying measured values, the volume of damage is obtained and damage distribution for each main parameter variation determined.

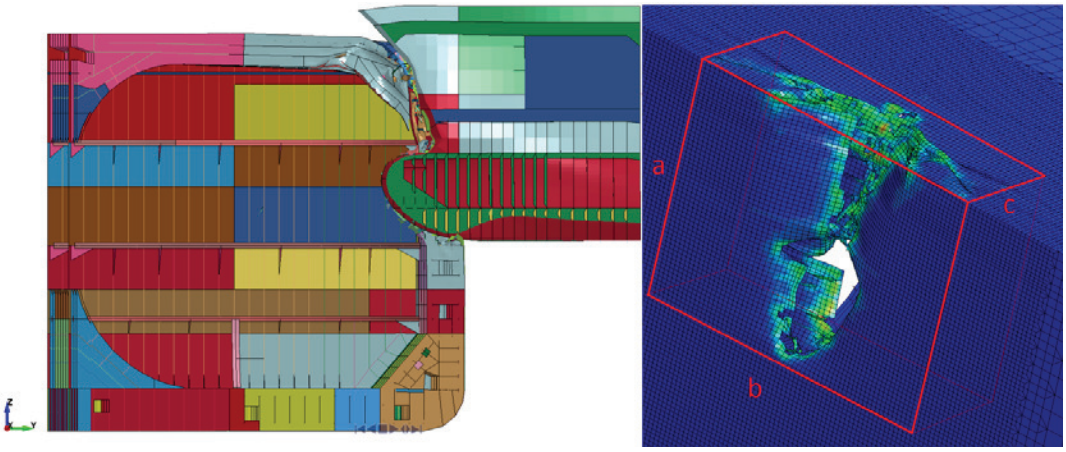

Fig. 4. Reference model collision: situation (left) and plastic strain (right) at *t*=2 s.

If the location and dimensions of the damage box are known, residual ultimate strength capacity of the hull girder in the damaged region, as well as change of the still water bending moment distribution due to compartments flooding may be determined. To determine directly the damage size for a large number of random collision parameters, time consuming and expensive numerical simulations are required. To overcome that difficulty, dimensions a, b and c of the damage box are presented as regression curves depending on collision parameters. Curves are presented in Figure 5.

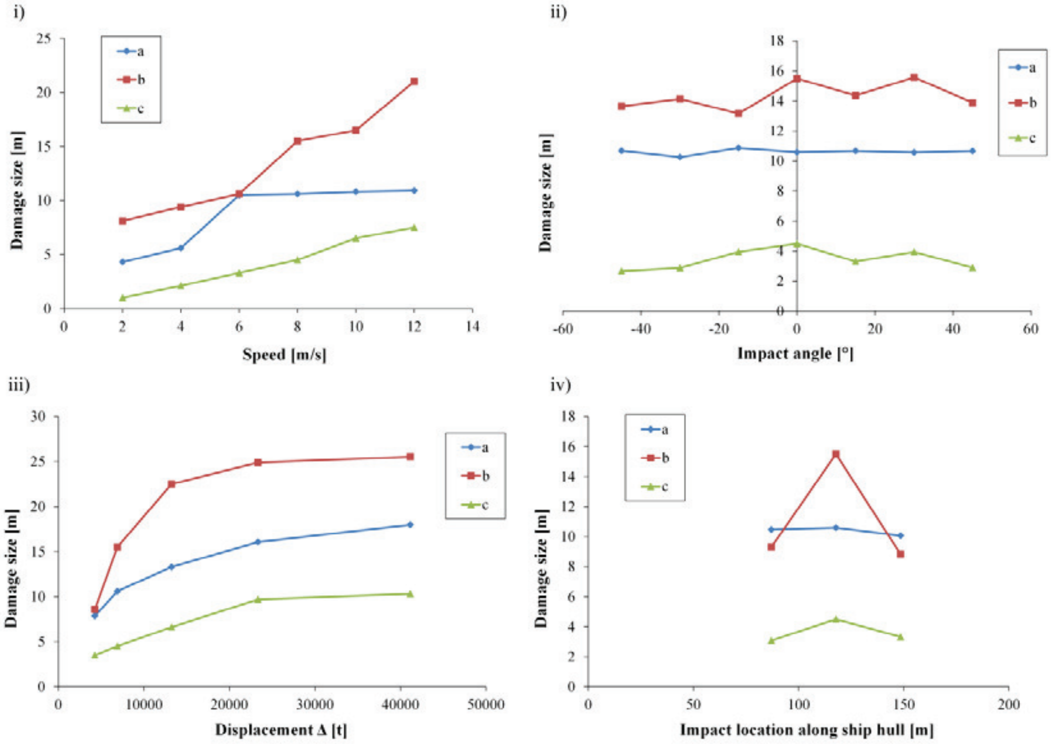

Fig. 5. Dependence of damage size on collision speed (i), impact angle (ii); striking ship displacement (iii); impact location along ship hull (iv).

The obtained trend of damage size can be explained as follows:

- The increase of the striking ship speed increases the damage in all directions; in particular the width of the damage is affected.
- The change of the impact angle results in destruction of different parts of the structure, but the overall effect is not accentuated and the damage size varies, however, not dramatically.
- The increase of striking ship displacement results in the increase of kinetic energy and the damage increases accordingly. Interestingly, the effect is pronounced more in the beginning of the trend.
- When the collision occurs away from the struck ship centre of gravity, part of the collision energy is used for the struck ship jaw motion resulting in less damage than in the case of centre of gravity collision, as it is clearly visible in the trend lines.

The location of the impact along the ship length affects the amount of damage significantly. When the impact occurs orthogonally in the vicinity of the tanker amidships, i.e. the struck ship's centre of gravity, most of the striking ship kinetic energy will be used for destruction and deformation of the tanker hull. In such case, only a fraction of the striking ship kinetic energy will be actually transformed into kinetic energy of the struck ship. But, when the impact occurs away from the struck ship's centre of gravity, the impact force will generate a yaw moment and the rotation of the struck ship. Due to that, part of the striking ship kinetic energy will be used for the struck ship's yaw motion and proportionally less energy will be used for destruction and deformation of the struck ship (Figure 5 iv).

Furthermore, it is assumed that the consequences of the collision are the same irrespective of the location along the cargo hold. This is obviously not true, as the damage size would not be the same, if collision occurred at the bulkhead or in the middle of the cargo hold, for the same combination of collision parameters.

Finally, the dependence of the damage size on the vertical location of the damage is not considered in the present paper. That would be of importance if, for example, different drafts of the struck ship were concerned. However, for the tanker in heavy fuel full load condition, the vertical location of the collision remains nearly the same.

Although the mentioned simplifications may not be as accurate as numerous direct numerical simulations, it is assumed herein that the presented approach is accurate enough to demonstrate the procedure. The regression model may be improved, or even direct simulation may be used for each simulation, but the procedure would basically be the same.

4. Hull girder residual ultimate longitudinal strength

The approach generally adopted in the calculation of the residual ultimate longitudinal strength of damaged ship considers that the elements within the damaged area are removed and the ultimate strength of the ship is recalculated using the simplified methods. The results of a benchmark study reported in (Guedes Soares et al. 2008), where the strength of a damaged ship hull was calculated with 3D nonlinear finite elements and was compared with the strength predicted by various codes based on the Smith method, demonstrate a good correlation overall.

In the present study, ultimate residual strength calculations in sagging are performed using the modified Paik-Mansour method (Paik et al. 2011). The method is an extension of the original Paik-Mansour (P-M) method, which is based on the assumed stress distribution over the hull cross section at the ultimate limit state in sagging (Paik & Mansour 1995), i.e. yield stress   is assumed for the outer bottom panel and ultimate stress   for the deck panel together with vertical structural elements. The modified P-M method assumes different bending stress distributions at the ultimate limit state for the yielded area, i.e. the vertical structure elements close to the tension flange may also have yielded before the hull girder reaches the ultimate limit state. The modified method involves two unknowns, i.e. the height of the buckled element region (hC) and the height of the yielded element region (hY). The condition that the summation of axial forces over the entire cross-section of the hull under a vertical bending moment becomes zero is insufficient to determine two unknowns, and thus an iteration process is required to determine the heights hC and hY. The method is considered as very practical for conceptual studies like the present one and also useful for definition of design equations as recommended by Yoshikawa et al. (2015).

The modified P-M method does not take into account the rotation of the neutral axis, so this effect is separately taken into account by the correction (Equation (1)) defined in Mumammad Zubair (2013):

$$\frac{M_V^u}{M_V^u\big|_{CASE2}} = \frac{I_{HH} I_{VV} - I_{HV}^2}{-(y_C - y_G) I_{HV} + (z_C - z_G) I_{HH}} \frac{(z_C - z_G)}{I_{VV}} \tag{1}$$

where:

y_C, z_C – location of the critical member on the ship main deck (main deck at CL)

y_G, z_G – centroid coordinates of the damaged cross section

I_{VV} – axial moment of inertia (vertical) of the damaged cross section relating y axis

I_{HH} – axial moment of inertia (horizontal) of the damaged cross section relating z axis

I_{HV} – centrifugal moment of inertia of the damaged cross section relating y and z axes

M_V^u – residual vertical hull girder strength in sagging including effect of rotation of NA

$M_V^u\big|_{CASE2}$ – residual vertical hull girder strength in sagging without rotation of NA.

It should be noted that one of the conclusions in Mumammad Zubair (2013) is that the reduction ratio of the residual hull girder strength due to the rotation of the neutral axis is almost negligible for the case of oil tankers having suffered outer shell damage while the inner side is intact. Therefore, in most of the cases, the effect of the rotation of the neutral axis will not have significant influence. Correction by Equation (1) for the rotation of neutral axis has the effect of reducing the ultimate longitudinal strength in sagging by up to 7%, in the case the inner hull is breached.

Results of the residual stress calculations are shown in Figure 6. It is assumed that the damage starts from the main deck. Two different cases are covered – damage of the outer shell only and damage of the outer and inner shell. The abscissa represents extent of the damage as a percentage of the ship depth, whereas the ordinate represents reduction of ultimate bending moment capacity with respect to the intact ship, expressed in percentage. It should be clarified that damage is assumed in the shape of the rectangular box, i.e. the same damage is assumed in the outer and inner shell, if the latter is damaged. More details on development of design equations presented in Figure 6 are given in Bužančić et al. (2015).

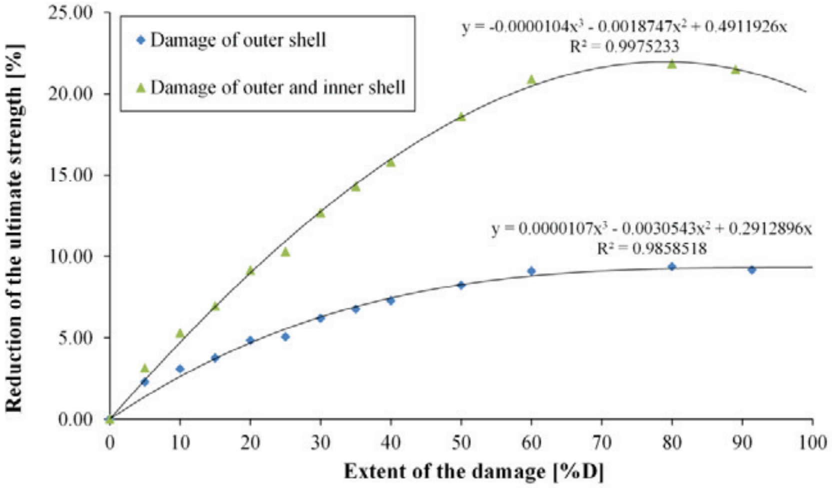

Fig. 6. Reduction of ultimate longitudinal strength of damaged Aframax oil tanker (Bužančić Primorac & Parunov 2015).

Curves from Figure 6 are employed in the paper in the following way. For each realization of the collision scenario in Monte Carlo (MC) simulations, depth of the damage is used to determine whether the inner hull is damaged or not and then one of two curves from Figure 6 is selected. Then, based on the damage height, reduction of the bending moment capacity with respect to the intact ship is calculated using formulae from Figure 6.

Ultimate bending moment capacity of intact sections along the ship is performed by progressive collapse analysis using the MARS software (Bureau Veritas, 2000). Three sections within cargo hold region are modelled; at midship section, at aft cargo hold no.6 and at fore cargo hold no. 2. Sections are presented in Figure 7.

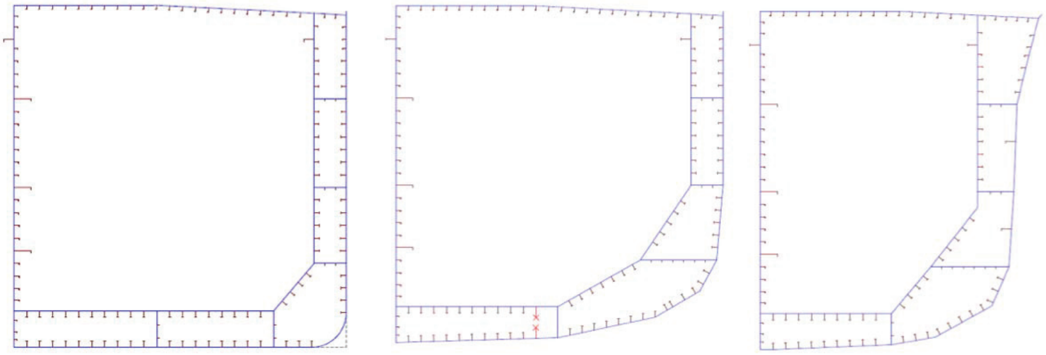

Fig. 7. Midship section (i), section in the aft cargo hold (ii) and section in the fore cargo hold (iii).

Calculated values of the ultimate longitudinal strength read 8470 MNm, 7127 MNm and 6001MNm for the midship section, section in the aft and fore holds, respectively. Ultimate bending capacity at other sections along the hull is obtained by linear interpolation.

For the structural reliability assessment, all uncertainty in the prediction of the ultimate strength is concentrated in a model uncertainty random variable χ_u, which takes into account both the uncertainty in the yield strength and the model uncertainty of the method to assess the ultimate capacity of the midship section, as both variables contribute to the ultimate bending moment. χ_u is defined as a log-normal distribution with a mean value of 1.1 and coefficient of variation of 0.12 (Parunov & Guedes Soares 2008).

5. SWBM of damaged ship

Hydrostatic analysis of damaged ship is performed using commercial software VeriSTAR Stability (Bureau Veritas, 2009). For each damage case generated by MC simulation, static equilibrium position and also distribution of the SWBM along the ship is found. Only full load condition on the scantling draught is considered in the present analysis. The SWBM of the intact ship at midship for that load condition reads 1556 MNm (sagging). It is assumed in the analysis that each damage case results in flooding of damaged compartments. Possibility that damage occurs entirely above still water level and that in such case compartment will not be flooded is not considered.

Typical distribution of the SWBM following a collision damage of the aft cargo tanks is presented in Figure 8. It may be seen that the maximum SWBM increases considerably compared to the SWBM in the intact condition. Also, the permissible SWBM is exceeded in the damaged condition. Furthermore, location of the maximum value is shifted toward damaged compartments.

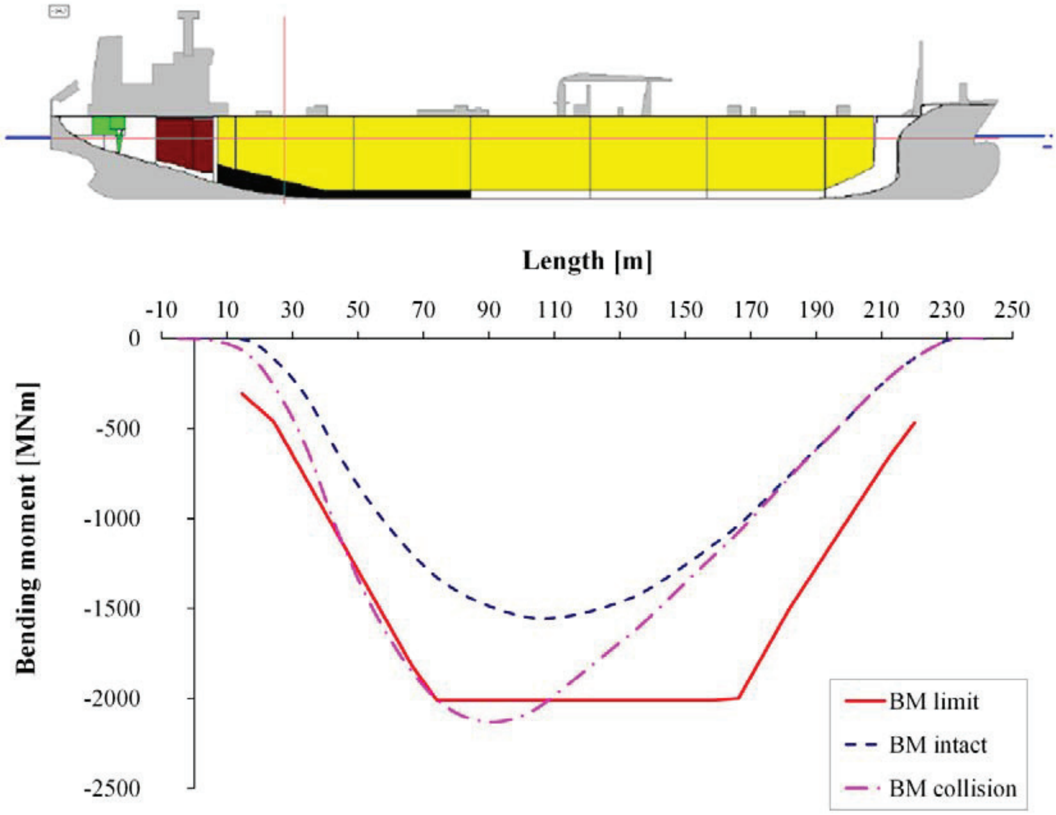

Fig. 8. Comparison of SWBM diagrams for intact and collision damage of Water Ballast Tanks (WBT) 5-6S.

In the present structural reliability analysis, the SWBM at midship of the intact ship is taken as a deterministic value since the analysis is done for each particular loading condition. Uncertainties in the calculation of the SWBM are taken into account by random variable with mean value equal to one and small coefficient of variation of 0.05 (Mansour & HØvem 1994).

In damaged condition, the SWBM along the vessel is determined by damage stability calculation, as described above. The SWBM in the damaged condition is also taken as deterministic value, whereas model uncertainty is assumed the same as for the intact ship.

6. Wave loads of damaged ship in the Adriatic Sea

As described in Section 2, collision damage is assumed to occur at the main sailing route in the Adriatic Sea, where the Croatian island of Palagruža takes the central place. Therefore, it is necessary to study the wave statistics in the Palagruža region.

The state of the art regarding wave statistics in the Adriatic Sea is represented by WorldWaves (WWA) database, containing data calibrated using different satellite missions and numerical wave model simulations. A grid with about 40 calibration points is available for the Adriatic Sea within WorldWaves (Barstov et al. 2003). In the present study, sea states statistics is generated using data originating from the WWA. Wave statistics is analysed for one location near the island of Palagruža with latitude-longitude coordinates: 42.5^0 north - 16.5^0 east. The extensive data set recorded from September 1992 until the end of January 2016 is used in the analysis. At every 6-hour interval, 33900 data about significant wave height and peak spectral period are available. The wave scatter diagram for that particular location is presented in Table 3 and the corresponding wave directions are shown in Figure 9.

Table 3. Wave scatter diagram for the sea area near Croatian island Palagruža.

Tp/HS	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	Sum
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4934	1666	14	0	0	0	0	0	0	0	0	0	0	6614
4	3552	6815	861	20	0	0	0	0	0	0	0	0	0	11248
5	589	3800	2616	666	36	0	0	0	0	0	0	0	0	7707
6	260	1114	1533	1256	500	113	5	0	0	0	0	0	0	4781
7	166	326	459	445	393	255	70	14	3	0	0	0	0	2131
8	93	103	138	159	128	111	91	51	21	7	1	0	0	903
9	28	68	36	44	54	38	38	22	12	5	1	1	1	348
10	11	29	14	10	13	11	10	7	2	1	4	1	0	113
11	4	8	4	2	0	1	0	0	0	0	0	0	0	19
12	8	3	4	1	0	0	0	0	0	0	0	0	0	16
13	14	0	1	0	0	0	0	0	0	0	0	0	0	15
14	4	1	0	0	0	0	0	0	0	0	0	0	0	5
Sum	9663	13933	5680	2603	1124	529	214	94	38	13	6	2	1	33900

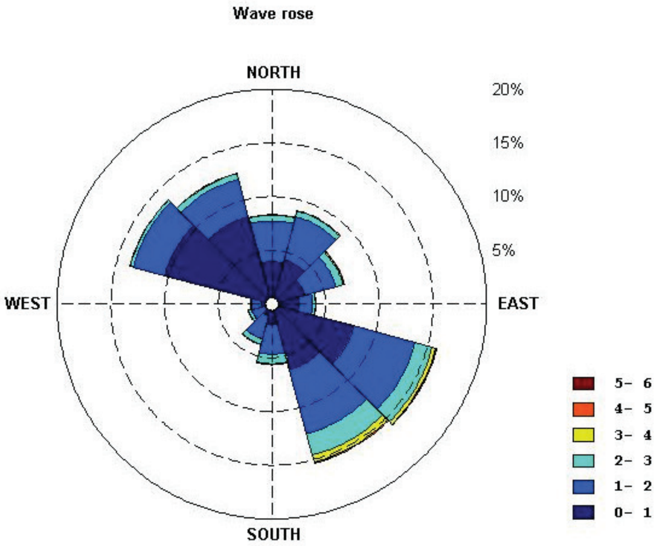

Fig. 9. Wave directions for latitude-longitude coordinates: 42.5° north, 16.5° east.

Wave scatter diagram shows expected concentration on low values and almost 70 percent of significant wave heights are less than one meter, whereas the average significant wave height reads 0.87 m. The most likely sea state in the particular location is described by significant wave height between 0.5 and 1 m and peak period between 3 and 4 s. The highest significant wave height of HS = 6.05 m was recorded on 8 December 1992 at 18 pm.

Charts for estimation of VWBM at amidships on damaged Aframax oil tanker in the Adriatic Seas are developed in Parunov and Ćorak (2015). Seakeeping assessment of damaged ship was performed by 3D panel method. It is assumed that the mass of the flooded seawater becomes an integral part of the ship mass and moves with the ship. Only one damage case with two flooded tanks in the midship region is used. The spectral analysis is performed using Tabain's wave spectrum, developed specifically for the Adriatic Sea (Tabain 1997). Squares of RAOs of VWBMs at amidships are multiplied by wave spectrum and thus a response spectrum is obtained. The area under the response spectrum curve represents a variance of the response, whereas the square root of the variance represents the standard deviation of the response process. Standard deviation of the VWBM at amidships is calculated for three different ship speeds (0, 5 and 10 knots) as well as for four different heading angles (180° - head seas, 135° - bow seas, 45° - quartering seas and 0° - following seas). Design charts are presented in Parunov and Ćorak (2015) for different significant wave heights, but only the result for HS = 4 m and HS = 6 m is reproduced in Figure 10.

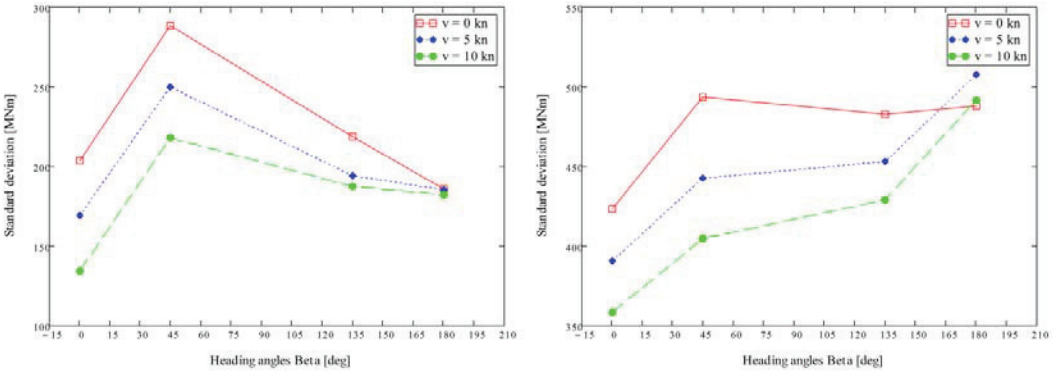

Fig. 10. Standard deviations of VWBM at amidships for different ship speeds and heading angles, $H_S = 4$ m (left), $H_S = 6$ m (right).

The long-term distribution of VWBM in the Palagruža region is calculated using a wave scatter diagram from Table 2 and design charts developed by Parunov and Ćorak (2015). Only head seas are assumed in the present study, as well as small forward speed of 5 knots. Exposure period until ship is towed to the safe harbour is assumed to be 12 h, what is reasonable considering the distance from the collision location to the nearest shore in the Adriatic. Based on such assumption, parameters of the extreme value (Gumbel) distribution of VWBM at amidships are calculated as:

- The most probable extreme value $x_e^* = 1048$ MNm
- Parameter of the Gumbel distribution $\alpha = 144$ MNm
- The mean value of the Gumbel distribution $\overline{x}_e = 1131$ MNm
- Standard deviation of the Gumbel distribution $\sigma_e = 184$ MNm

For comparison, IACS rule linear VWBM reads 3848 MNm. Therefore, the most probable extreme VWBM for 12-hour exposure period in the central Adriatic Sea amounts to 27% of the IACS rule VWBM.

In the present study, distribution of VWBM at other sections is obtained using distribution of VWBM proposed by Rules of classification societies (IACS 2014).

The VWBM is the load effect that exhibits considerable nonlinearity. The effect of nonlinear response is particularly significant for ships with a low block coefficient, leading to differences between sagging and hogging bending moments. The following nonlinear correction factors to improve linear predictions may be used:

$$\Phi_S = \frac{M_S}{M_L} = \frac{2R}{1+R} \quad , \quad \Phi_H = \frac{M_H}{M_L} = \frac{2}{1+R} \tag{2}$$

where R represents the ratio of the vertical wave bending moments in sagging and hogging from IACS UR S11 (IACS 2010):

$$\frac{M_S}{M_H} = R = \frac{C_B + 0.7}{1.73 \cdot C_B} \tag{3}$$

In the present case block coefficient C_B reads about 0.82 and therefore $R = 1.07$. From Equation 2, we may then calculate correction for sagging $\Phi_S = 1.03$.

Simplifications, assumptions and inaccuracies of the linear engineering models used to predict extreme VWBM on ship hull are taken into account by the modelling uncertainty χ_w. For the present study, χ_w is assumed to be a normally distributed random variable with the mean value equal to 1 and coefficient of variation equal to 0.1. The uncertainty of non-linear effects χ_{nl} is assumed to be a normally distributed variable with mean value equal to non-linear correction factor 1.03, whereas the coefficient of variation of this uncertainty is assumed to be 0.15 (Parunov & Guedes Soares, 2008).

7. Structural reliability analysis of damaged ship

Structural reliability analysis of the damaged ship is performed using First-Order Reliability Method (FORM) for each random damage scenario generated by MC simulation. With respect to the hull-girder ultimate failure under vertical bending moments the following limit state functions are used:

$$\chi_u M_{u0} - \left(\chi_{sw} M_{SW0} + \chi_w \chi_{nl} M_w\right) < 0 \tag{4}$$

$$\chi_u M_u - \left(\chi_{sw} M_{SW} + \chi_w \chi_{nl} M_w\right) < 0 \tag{5}$$

where M_{u0} is the deterministic ultimate hull-girder bending moment of the intact ship at midship section; M_u is the deterministic ultimate hull-girder bending moment of the damaged ship at damaged section; M_{sw0} the deterministic still-water bending moment of damaged ship at midship section; M_{sw} the deterministic still-water bending moment of damaged ship at damaged section; M_w the random variable extreme vertical wave bending moment in the reference period; χ_u, χ_w, χ_{nl}, χ_{sw} the random variables representing the modelling uncertainty of ultimate strength, linear wave load, non-linearity of wave load and still water load respectively.

Equation (4) represents the limit state function for intact section at amidships where the SWBM is modified according to damage stability calculations for the damage scenario obtained as an outcome of MC simulation. Therefore, it represents a ship structural reliability accounting only for load modification due to damage. Equation (5) represents the limit state function for damaged section of the hull where residual ultimate strength and load redistribution are calculated based on damage extent obtained for randomly generated collision scenario. The summary of the stochastic model employed is presented in Table 4.

Thus, for each damage scenario obtained by MC simulation, two safety indices are obtained – for damaged section and for the most loaded intact section at amidships. In the present study, it is assumed that the governing safety index is the minimum of these two values. For 1000 MC simulations, histograms of safety indices are obtained, Figure 11 (a-c). Figure 11a represents a histogram of safety indices for the damaged section. Figure 11b shows a histogram of safety indices for the most loaded intact section and Figure 11c presents the resulting histogram, i.e. the minimum value for each simulation. A total of 1000 simulations are considered as a sufficiently large sample, because average collision scenarios are of more interest and relevance than extremely rare and consequently unlikely collision scenarios that may occur with probability less than 1/1000.

Table 4. Summary of stochastic model adopted.

Variable	Distribution	Mean	COV
M_{u0} (MNm)	Deterministic	8470	
M_u (MNm)	Deterministic	Calculated by design equation (Fig. 4)	
M_{sw0} (MNm)	Deterministic	1556	
M_{sw} (MNm)	Deterministic	Calculated by damage stability analysis	
M_w (MNm)	Gumbel	2415	0.27
χ_{sw}	Gaussian	1.0	0.05
χ_u	Log-normal	1.1	0.12
χ_w	Gaussian	1.0	0.1
χ_{nl}	Gaussian	1.03	0.15

Safety indices in Figure 11 are grouped in intervals with width of 0.2. It may be seen that the most results are within the range β = 5.4–5.6, corresponding to the rather low failure probabilities P_f = 3.33e-8 – 1.07e-8. Reliability of the most loaded section (Figure 11b) dominates the results, although the overall minimum β = 4.45 is obtained for the damaged section (Figure 11a). Values of governing parameters for such the worst damage case are:

- M_u = 6634 MNm (78.3% M_{u0})
- M_{sw} = 1691 MNm (109% M_{sw0})
  (damaged Cargo Tank (CT) 4(S) / Water Ballast Tank (WBT) 4(S) and CT 5(S) / WBT 5(S))
- x = 103.4 m (damage location at amidships)

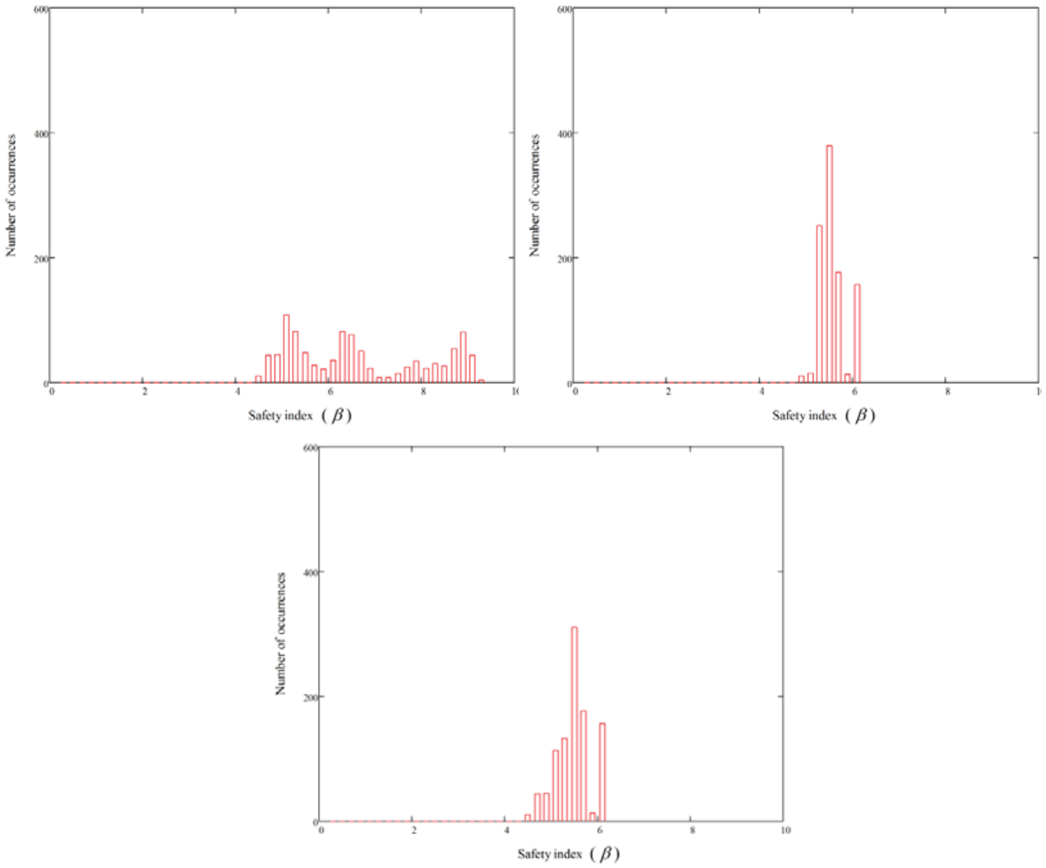

Fig. 11. Histograms of safety indices obtained by MC simulation (i – safety indices of damaged section, ii – safety indices of the most loaded section, iii – minimum safety indices between i and ii).

Therefore, the lowest safety index, occurring only once in 1000 MC realizations, is obtained for large damage at amidships, when two consecutive water ballast tanks and corresponding cargo tanks are damaged.

For the intact ship, when M_u = 8470 MNm and M_{sw0} = 1556 MNm, β = 5.5. Therefore, it belongs to the interval of 5.4 – 5.6 in Figure 12c, in which 31% of the MC simulations are placed. It is interesting to notice that even 72% of simulated damage cases result in safety index higher or equal to that of the intact ship. It should be clarified that intact ship means that the ship's structure is not damaged and that the SWBM is consequently not modified because of the damage, whereas the VWBM is taken from Table 3. One should not confuse the meaning of the intact ship in the present study with the traditional structural reliability analysis of seagoing ships, as in the latter case, the SWBM is a random variable as ship normally sails in different loading conditions and also wave load is calculated by long-term distribution for design operational scenario as well as for a longer exposure period.

To investigate the influence of the random numbers on histograms of safety indices, five different MC simulations are performed, using different sets of random numbers. Mean values μ and standard deviations σ are presented in the following Table 5.

As may be seen from Table 5, statistical properties of safety indices are almost insensitive to different sets of random numbers used in MC simulations. Based on that analysis, it may be concluded that the proposed methodology leads to stable results for histogram of safety indices.

Table 5. Mean values and standard deviations of safety indices for different MC simulations.

	Damaged section		Maximum loaded intact section		Resulting minimum safety index	
	μ	σ	μ	σ	μ	σ
RND Seed 1	3.628	1.483	2.470	0.142	2.422	0.213
RND Seed 2	3.623	1.487	2.469	0.144	2.421	0.216
RND Seed 3	3.63	1.487	2.468	0.144	2.422	0.213
RND Seed 4	3.618	1.494	2.468	0.144	2.415	0.221
RND Seed 5	3.626	1.486	2.469	0.145	2.422	0.213

8. Conclusions

Structural reliability of Aframax oil tanker hypothetically damaged in the Adriatic Sea is performed in the study. The approach is based on MC simulation, where random parameters are striking ship speed, collision speed, collision angle and striking ship displacement. Struck oil tanker is assumed to have zero speed and full load condition.

Damage size is determined by collision simulation performed using LS-Dyna software package. Increase in SWBM is obtained by damage stability analysis. Residual strength is calculated using design equations, based on the modified Paik-Mansour method.

As a result of the analysis, the safety index is represented in the form of a histogram, separately for the damaged section of the ship's hull and the most loaded intact section. Histogram of the safety index of the damaged section has a relatively high mean value and a large standard deviation, whereas the histogram of the most loaded intact section has a much lower mean value and a smaller standard deviation. The resulting safety index, determined as the minimum of two mentioned safety indices, has the mean value and the standard deviation fairly close to those of the most loaded intact section.

It was found that in 28% of simulated damage cases, the safety index of the damaged ship would be lower compared to the intact ship. The lowest safety index, obtained once in 1000 simulated damage cases, occurs for collision at midship, when the inner hull is breached.

The state of the art in the field of risk assessment of ship hull collapse due to collision is given by Youssef at al. (2014). In the present study, advancement is achieved by considering global load of the damaged ship and subsequent systematic reliability analysis, whereas Youssef at al. (2014) considered risk from the residual strength point of view and collision occurrence frequencies. However, there are some limitations of the present study and the most important ones are:

- Heel angle due to asymmetrical flooding is not considered. The assumption is justified for the full load condition, as in that case the heel angle is generally small. However, for other loading conditions, the effect of heel angle should also be taken into account.
- The influence of the horizontal bending moment is neglected in the present study. This is also justified for the Adriatic Sea, where wave loads are rather small. For other sea environments, however, and general design consideration, this effect is also to be included and structural reliability assessment under combined bending is required.
- The shape of the damage is assumed as the rectangular box starting from the main deck. Such approach is also justified as a relatively small ferry is assumed as the striking ship, based on the actual traffic conditions in the Adriatic. However, if the striking ship was another merchant ship with deeper draught, then the damage could have a more complex shape (Youssef at al. 2014).
- The wave load is in the present study calculated for one major damage case, with flooding of two ballast tanks in the midship region. This is reasonable assumption for the Adriatic Sea. For more severe wave environments, however, seakeeping assessment for actual damage conditions may be performed.

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