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STATISTICS OF STILL WATER BENDING MOMENT OF DAMAGED SUEZMAX OIL TANKER

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ABSTRACT

The aim of the paper is to create statistical model of still water bending moment of Suezmax double hull oil tanker damaged in collision or grounding accident, by applying the same random variables assumption and concept already developed for an Aframax oil tanker. Monte Carlo simulation is employed to generate possible damage scenarios according to IMO Resolution MEPC.110(49) from 2003. For each damage case, maximum bending moments for whole ship and damaged area are calculated by hydrostatic software. Histograms of relative bending moments are then created and appropriate probability distribution fitted. The results are treated in a way to take into account correlation between damage location and maximum bending load. Comparison of the Aframax and Suezmax probability distribution parameters is also performed. The purpose of developed probabilistic models is application in structural reliability studies of damaged ship.

1. INTRODUCTION

The structural failure of the oil tanker may occur due to unfavorable environmental conditions or due to human errors during the design or operation of the ship. The most frequent types of tanker accidents are collision with another ship or grounding. In case of such an accident, the ship strength could be significantly reduced while still water and wave loads could become considerable cause of the structural overloading (Hussein and Guedes Soares 2009, Luis et al. 2009). The well-known accident of a single hull oil tanker „Prestige“ in 2002. is example of the sinking with the spillage due to structural overloading after improper procedure onboard the damaged ship, where counter-flooding reduced the heel angle, but contributed to the much higher shear forces and bending moments (Santos and Guedes Soares 2008).

Still water loads can be evaluated from proper consideration of the mass and buoyancy distribution over the ship length. In damaged condition, effects of flooding of different types of ship compartments and the corresponding oil outflow are to be taken into account. Although ship hull may collapse due to excessive bending moment during any of three distinct flooding phases (transient, progressive and final phase), second and third phases are considered particularly dangerous because these may last from a several minutes to hours, while the duration of transient phase is measured in minutes or even seconds (Santos and Guedes Soares 2008, Rodrigues et al. 2015). Only the final equilibrium stage is considered in this paper.

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It is known that still water bending moments (hereinafter SWBM) can be significantly increased during ship damage event due to ingress of water (Downes et al. 2007). SWBM for ship in damaged condition may be expressed by the following simplified expression (Hussein and Guedes Soares 2009):

$$M_S^D = K_{US} \cdot M_S \tag{1}$$

where M_{SD} is the SWBM of damaged ship; K_{US} the factor of increase of SWBM; M_S the SWBM of intact ship.

According to the various available researches and rules, factor of increase K_{US} of SWBM is defined separately for hogging and sagging condition. Values for K_{US} in hogging/sagging proposed by ABS 1995 read 1.10/0.90, while IACS 2014 proposed values 1.10/1.10. Concerning researchers, Luis et al. 2009 proposed K_{US} for hogging and sagging (1.10 and 1.50), while most of the others proposed K_{US} values for sagging only, ranging from 1.45 to 2.38 (Jia and Moan 2008, Hussein and Guedes Soares 2009, Rizzuto et al. 2010, Rodrigues et al. 2015, Burić et al. 2012). It may be seen that SWBM in sagging may be increased by more than twice in damaged condition compared to the intact SWBM.

However, ship damage may occur in a number of ways, while damage parameters are random quantities. Consequently, probabilistic models may be used to describe random variation of SWBM of the damaged vessel. Not much research has been spent on probabilistic modeling of still water loads of damaged ships.

Applying the probabilistic model suggested by International Maritime Organization IMO (2003), concerning the damage configuration, Rodrigues et al. (2015) simulated progressive flooding and consequently analyzed and compared SWBM for equilibrium position with the limits proposed by the classification rules.

For an Aframax oil tanker, Downes et al. (2007) showed that in the full load condition 10% of the damage cases lead to an increase in sagging SWBM of 25% or more of the allowable SWBM.

IMO damage parameters probabilistic model is used in Bužančić Primorac et al. (2015) studying statistical properties of SWBM for an Aframax oil tanker damaged by collision and grounding. The same procedure is adopted herein to study the same characteristics for the Suezmax tanker, generating the random damage scenarios by Monte Carlo simulation using IMO probability distributions of damage parameters (IMO 2003). Such probabilistic model may have application in structural reliability assessment of damaged ship (Prestileo et al. 2013).

Description of the studied ship and methodology used to simulate damage size and location are described in Section 2 of the paper. After that, results of damage stability calculations are presented with focus on relative increase of SWBM with respect to the SWBM of the intact ship. Probabilistic description of relative SWBM and the comparison with the results for an Aframax tanker are then provided in Section 4. Finally, some consideration is given to the accuracy of the approach and corresponding conclusions are drawn.

2. DESCRIPTION OF SHIP AND DAMAGE CASES

The case study ship is Suezmax oil tanker with main particulars presented in Table 1.

Table 1. Main particulars of the case study Suezmax oil tanker

Main particulars of oil tanker		
Length between perpendiculars, L_{PP}	m	260
Breadth, *B*	m	46
Depth, *D*	m	22
Draught, *T*	m	16
Deadweight, *DWT*	dwt	160000

Cargo hold area consists of 6 pairs of cargo tanks (hereinafter CT) and 6 corresponding pairs of water ballast tanks (hereinafter WBT) in double bottom and side. WBTs are divided into portside and starboard tanks by center line girder in the double bottom. Full loading condition on scantling draught is used in the analysis with cargo density of 0.89 t/m^3.

As ship damage may occur in a number of ways, damage parameters are in general random quantities that may be described by probability distributions. Such probability distributions of damage size and location, for cases of the collision and grounding damages are proposed by International Maritime Organization (IMO 2003).

In order to define credible damage scenarios, Monte Carlo (MC) simulation according to IMO probabilistic models is performed. 1000 random numbers are drawn according to IMO models and number of events resulting in damage of certain number of compartments is presented in Tables 2-5 for collision and grounding respectively.

According to Bužančić Primorac et al. (2015), the collision damage is naturally assumed asymmetrical, while for grounding damage simplification is introduced as the assumption that grounding damage is always symmetrical. Also, the probabilities of certain damage obtained according to Tables 2-5, do not distinguish between damage of only WBTs or WBT and CTs. It means that damage probabilities from Tables 2-5 relate the specified numbered area between the transverse bulkheads (i.e. FP is area of fore peak, T1 is area of cargo and water ballast tanks 1P&S,…, ER is area of engine room). Therefore these probabilities should be multiplied with probabilities that double hull/double bottom is or isn't breached (0.257/0.743 for inner shell and 0.210/0.790 for double bottom).

In total, 54 damage cases are analyzed for collision, while 60 damage cases are included to cover all reasonably possible grounding damages. The reason for larger number of grounding damage cases is that there is about 10% probability of damage of 5 or more tanks in longitudinal way, while that probability for collision is almost negligible. Sum of probabilities of occurrence of all damage cases for collision reads 1 as well as sum of probabilities of all grounding damage cases.

Table 2. Frequencies of occurrence of damages if one tank is damaged

Damage	**FP**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**ER**
Collision	24	74	50	56	60	60	58	143
Grounding	20	43	29	19	6	6	6	30

Table 3. Frequencies of occurrence of damages if two tanks are damaged

Damage	**FP-T1**	**T1-T2**	**T2-T3**	**T3-T4**	**T4-T5**	**T5-T6**	**T6-ER**
Collision	63	47	53	55	70	55	77
Grounding	119	73	52	52	17	13	44

Table 4. Frequencies of occurrence of damages if three tanks are damaged

Damage	**FP-T1-T2**	**T1-T2-T3**	**T2-T3-T4**	**T3-T4-T5**	**T4-T5-T6**	**T5-T6-ER**
Collision	10	6	9	7	12	9
Grounding	124	30	34	18	17	28

Table 5. Frequencies of occurrence of damages if four tanks are damaged

Damage	**FP-T1-T2-T3**	**T1-T2-T3-T4**	**T2-T3-T4-T5**	**T3-T4-T5-T6**	**T4-T5-T6-ER**
Collision	1	0	0	1	0
Grounding	60	15	16	3	10

Some of the most important damage cases, inducing largest SWBM or having high probability, for collision and grounding damages are specified in Tables 6 and 7 respectively, together with corresponding probabilities of occurrence and SWBM as relative value. Relative SWBM is obtained by dividing SWBM in damage condition with SWBM for intact ship.
It may be seen that all important cases covered in Tables 6 and 7 include only damage of WBTs. It is found that damage of corresponding cargo tanks leads to the lower values of SWBM. One explanation for this finding can be that full loading condition on scantling draught is used in the analysis. In such condition, density of cargo is rather high (0.89 t/m^3) and it could be that outflow of the cargo is larger than weight of the flooding water. Consequently, increase in SWBM is lower when cargo tanks are damaged. The same phenomenon is highlighted and thoroughly discussed by Rodrigues et al. (2015). Based on the progressive flooding analysis, they concluded that more energetic collisions that would damage inner hull and cause cargo leakage, lead to less severe increase of SWBM.

Table 6. Probability and relative SWBM for collision damage cases

Dam. case No.	**Damaged tanks**	**Probability (%)**	**SWBM$_d$/SWBM$_i$ (overall)**	**SWBM$_d$/SWBM$_i$ (damaged area)**
4	WBT 3S	4.12	1.25	1.25
5	WBT 4S	4.42	1.43	1.43
6	WBT 5S	4.42	1.35	1.35
11	WBT 2-3S	3.90	1.20	1.20
12	WBT 3-4S	4.05	1.66	1.66
13	WBT 4-5S	5.16	1.75	1.75
14	WBT 5-6S	4.05	1.42	1.42
19	WBT 3-5S	0.52	1.94	1.94
20	WBT 4-6S	0.88	1.78	1.78
25	WBT 3-6S	0.07	1.95	1.95

Table 7. Probability and relative SWBM for grounding damage cases

Dam. case No.	**Damaged tanks**	**Probability (%)**	**SWBM$_d$/SWBM$_i$ (overall)**	**SWBM$_d$/SWBM$_i$ (damaged area)**
5	WBT 4P&S	0.47	1.83	1.83
10	WBT 1-2P&S	5.76	0.37	0.37
11	WBT 2-3P&S	4.11	1.49	1.49
12	WBT 3-4P&S	4.11	2.27	2.27
13	WBT 4-5P&S	1.34	2.42	2.42
14	WBT 5-6P&S	1.03	1.85	1.85
16	WBT 1-2P&S, FP	9.79	-0.74	-0.55
18	WBT 2-4P&S	2.68	2.12	2.12
19	WBT 3-5P&S	1.42	2.75	2.75
25	WBT 3-6P&S	0.24	2.72	2.72

3. RESULTS OF THE ANALYSIS

Hydrostatic analysis of damaged ship is performed using VeriSTAR Stability software (Bureau Veritas 2009). For each of damage cases, static equilibrium position is found and also distribution of SWBM along the ship. Only full load condition on the scantling draught is considered in the present analysis. SWBM at midship for that load condition reads -2200 MNm (sagging).

SWBM in damaged condition is presented in Tables 6 and 7 for collision and grounding respectively, as relative value, i.e. as ratio of $SWBM_d$ in damaged condition and $SWBM_i$ in intact condition. Also, distinguish is made between maximum $SWBM_d$ along whole ship and maximum value in the region of damaged tanks only.

Histograms of relative SWBM in damaged condition are presented in Figure 1 for collision and grounding damages respectively. Histograms are obtained by relating relative SWBM with probabilities of occurrence of such damage presented in Tables 6 and 7. For collision damage relative SWBM are classified into 12 classes of width 0.2 represented by their mean values in the range from -0.3 to 0.9 and for grounding damage the number of groups is increased to 19 in the range from -0.9 to 2.7. It should be emphasized that relative SWBM for all 52 cases for collision and 51 cases for grounding damage are included in histograms, because some conditions, which didn't satisfy all the requirements i.e. the equilibrium condition could not be calculated, are excluded from the consideration. Also, relative SWBM overall and for region of damaged tanks only are presented separately.

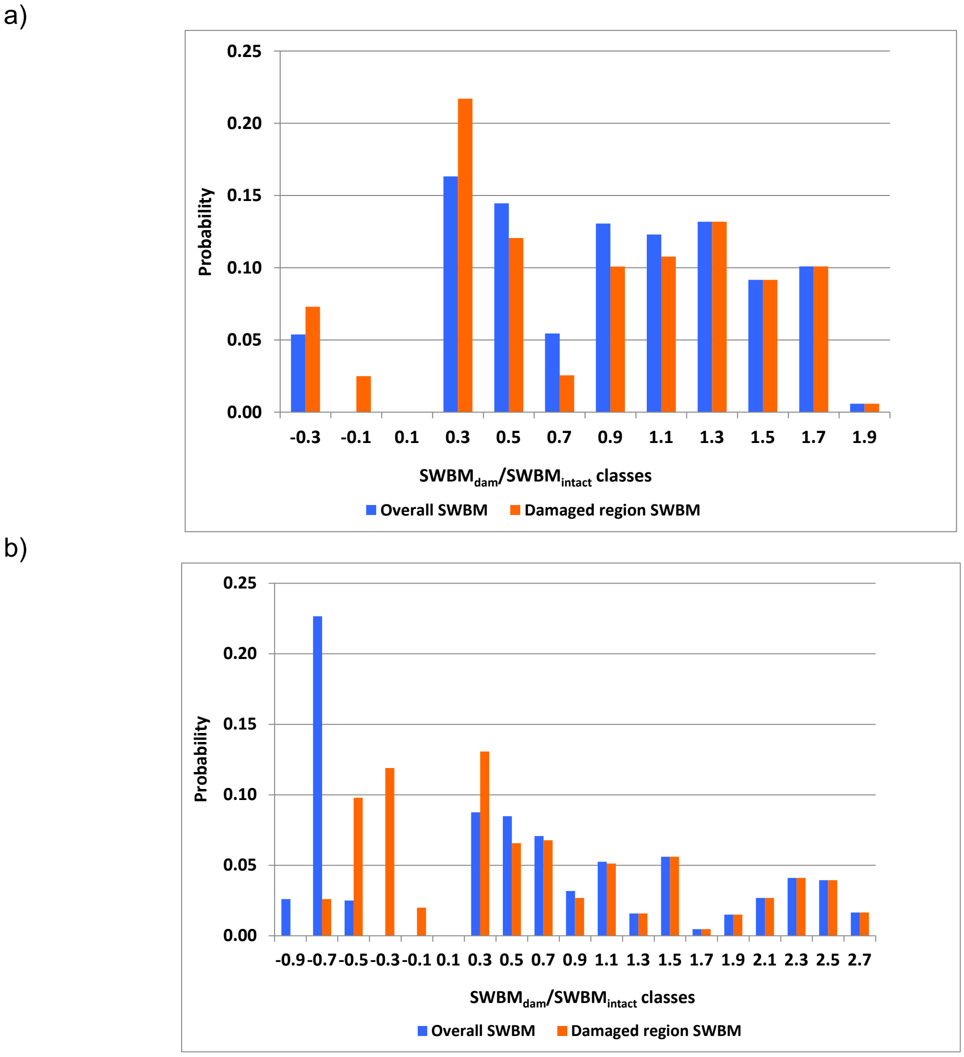


Figure 1. Histograms of SWBM for a) collision and b) grounding damage

Expected values of relative SWBM in case of collision damage read 0.88 and 0.82 for overall maximum SWBM and for maximum value in damaged tanks region respectively. Analogous expected values of relative SWBM in case of grounding damage read 0.46 and 0.53 It may be seen that for grounding damage expected maximum value for damaged area is larger compared to the expected overall maximum values, while for the collision damage the situation is opposite.

Standard deviation of relative SWBM in case of collision damage reads 0.54 and 0.57 for overall maximum SWBM and for damaged tanks area respectively. Standard deviation of relative SWBM in case of grounding damage reads 0.99 and 0.90 for overall and for damaged tanks area respectively. Therefore, dispersion of relative SWBM is much larger for grounding damage compared to the collision.

For collision damage, maximum relative SWBM is achieved for damage case when 4 consecutive WBTs in midship area are damaged (WBT 3-6 (SB)). The maximum value of 1.95 is achieved in the region of damaged tanks. Such damage case, however, has rather low occurrence probability (0.07%). The most important damage case regarding contribution to the expected relative SWBM is the damage of WBTs 4 and 5 (SB). The measure of the importance is the product of relative SWBM and probability of such damage case. The maximum relative SWBM for that damage case reads 1.75, and it is achieved in the region of damaged tanks. The probability of occurrence of such damage case reads about 5%. For collision damage, probability of exceeding SWBM for intact condition read 45% and 44% for overall distribution and in the area of damaged tanks respectively.

For grounding damage, maximum relative SWBM is achieved for damage case when 3 consecutive WBTs in midship area are damaged (WBT 3-5 (PS & SB)). The maximum value of 2.75 is achieved in the region of damaged tanks. The occurrence probability of such damage reads 1.42%. The most important damage case regarding contribution to the expected relative SWBM is damage of WBTs 3 and 4 (SB & PS). The maximum relative SWBM for that damage case reads 2.27, and it is achieved in the region of damaged tanks. The probability of occurrence of such damage reads about 4%. For grounding damage, probability of exceeding SWBM for intact condition reads 45%, both for overall distribution and in the area of damaged tanks.

Another interesting conclusion that may be drawn from Figure 1 is that for the most dangerous damage cases overall maximum SWBM occurs in the area of damaged tanks. It may be clearly seen as columns in histogram 9-12 for collision and 12–19 for grounding are of the same height for overall SWBM and for SWBM in damaged region.

4. PROBABILITY DISTRIBUTIONS OF SWBM OF DAMAGED SHIP

Factor of increase of SWBM (K_{US} in Equation 1) is obviously random variable that preferably should be defined by appropriate probability density function. It is found that normal distributions represent relatively good fit to the histograms.

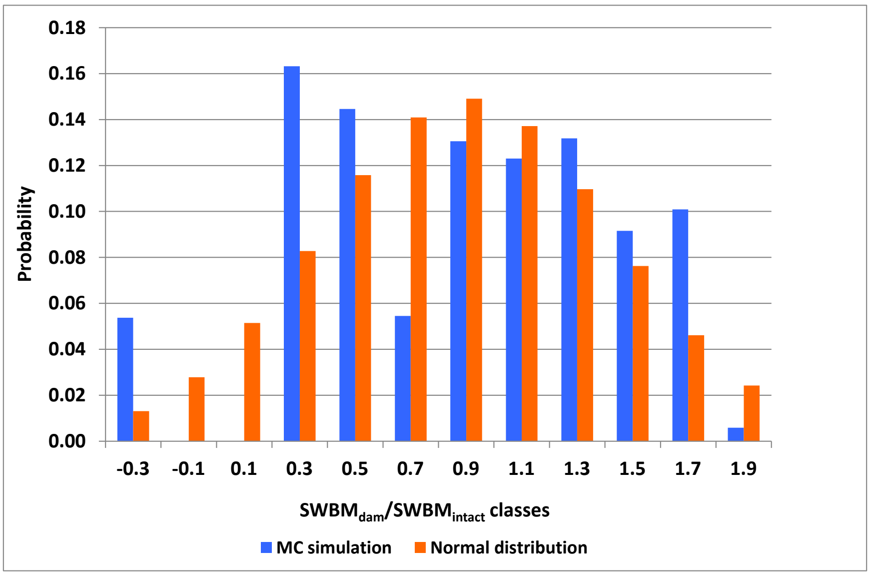
Comparison of normal distribution with histograms in case of collision and grounding damage is presented in Figures 2 and 3 respectively. In both figures, comparison is performed a) for overall maximum and b) for maximum in the area of damaged tanks only. Parameters of normal distributions used in Figures 2 and 3 are presented in Table 8.

It is obvious from Figures 2 and 3 that the normal distribution is not perfect-fitting to calculated histograms. The first reason is that normal distribution is unlimited on both ends, while histograms are limited at maximum values. Secondly, histograms are not symmetric with respect to the mode, while normal distribution implies symmetry.

Applying of some other distributions, such as truncated normal distribution or beta distribution, may improve the fitting. It is questionable, however, if using some other distribution type will improve noticeably accuracy of the reliability analysis as the normal distribution is usually employed in probabilistic SWBM modeling, despite the same problems as those described herein.

The statistical parameters of SWBM of the damaged Aframax oil tanker are presented in Table 9 (Bužančić Primorac et al. 2015). We can conclude from Tables 8 and 9 that in the case of collision damage, statistical properties for Aframax and Suezmax tanker are fairly similar. For grounding damage, mean value for overall maximum SWBM is lower and standard deviation is higher for Suezmax comparing to Aframax values, while the changes of SWBM for damaged area are quite similar. Possible explanation for differences in grounding between two ship types could be that although Suezmax tanker is about 30 meters longer, ballast and cargo tanks arrangement is the same, i.e. cargo hold area consists of 6 pairs of cargo tanks (CT) and 6 corresponding pairs of WBTs in double bottom and side. Suezmax cargo tanks are about 40-50% and ballast tanks about 30-40% larger than the same tanks of Aframax tanker. Therefore, the influence of increased weights in the middle part or at the end of the Suezmax oil tanker is visible as higher values of SWBM in sagging or hogging comparing to Aframax tanker for the same damage cases. In the case of grounding, the influence of higher hogging values is more significant, resulting in decreasing of the mean values of SWBM.

a)



b)

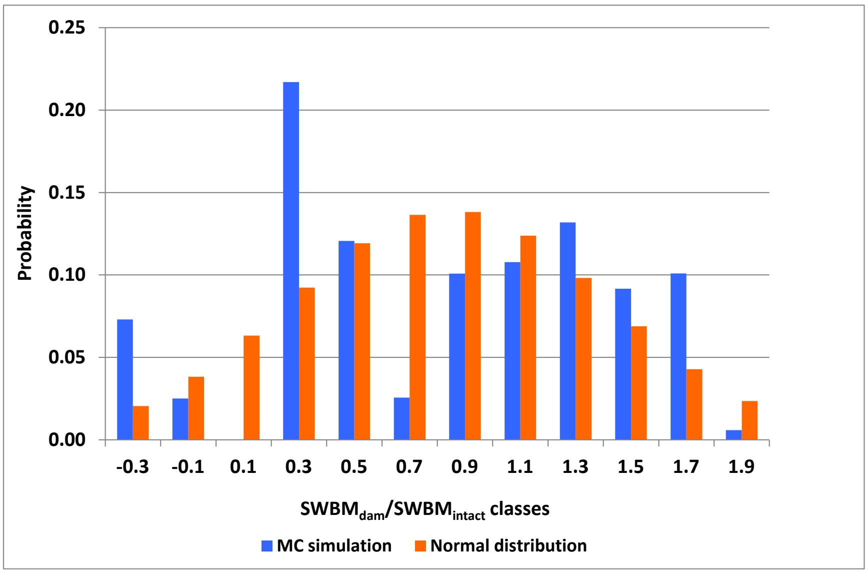


Figure 2. Fitting of normal distribution to SWBM histograms for collision damage a) overall maximum; b) maximum in damaged area

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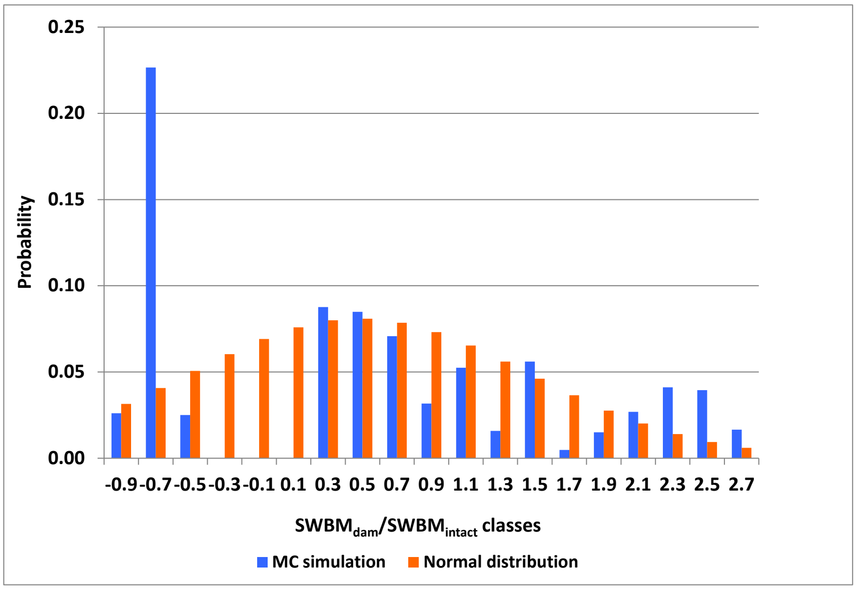
Table 8. Parameters of normal distributions of relative SWBM of damaged Suezmax oil tanker

Damage condition	**mean value**	**stand. deviation**
Collision (overall)	0.88	0.53
Collision (damaged area)	0.82	0.57
Grounding (overall)	0.46	0.99
Grounding (damaged area)	0.53	0.90

Table 9. Parameters of normal distributions of relative SWBM of damaged Aframax oil tanker

Damage condition	**mean value**	**stand. deviation**
Collision (overall)	0.88	0.45
Collision (damaged area)	0.76	0.55
Grounding (overall)	0.60	0.86
Grounding (damaged area)	0.58	0.85

a)



b)

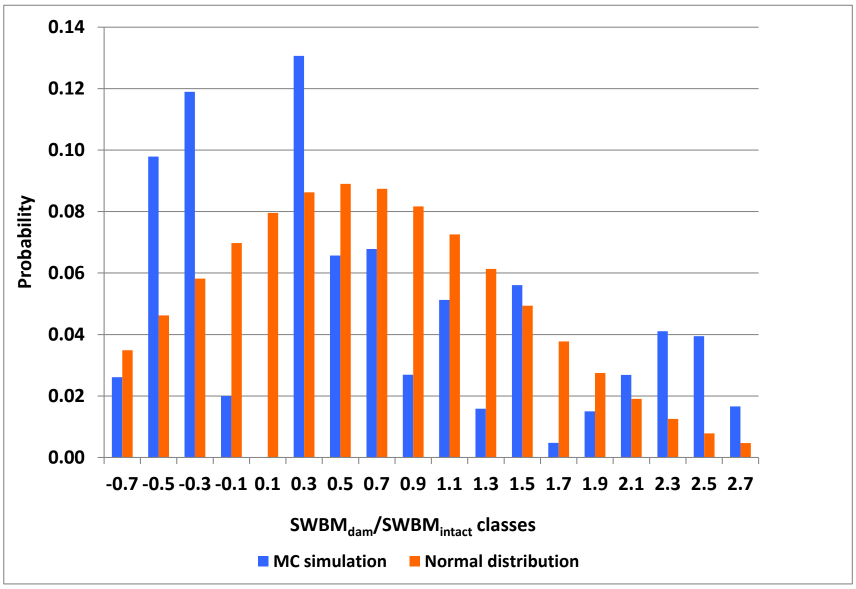


Figure 3. Fitting of normal distribution to SWBM histograms for grounding damage a) overall maximum; b) maximum in damaged area

5. CONCLUSION

The purpose of the paper is to study statistical properties of still water bending moment of double hull oil tanker damaged in collision or grounding accidents. Plausible damage scenarios are generated by MC simulation using IMO (2003) probabilistic models of damage parameters. Only full load condition on scantling draught is analyzed.

It was found that mean value of maximum relative SWBM reads 0.88 and 0.46 for collision and grounding damage respectively. Corresponding standard deviation reads 0.53 and 0.99. If only damaged region is considered, mean value of maximum relative SWBM is reduced for about 7% in collision and increased for about 6% in grounding.

Concerning the probability of exceeding the seagoing SWBM limit value for sagging in the midship area (-3600 MNm), it reads about 11% for collision damage and 32% for grounding, both for overall distribution and in the area of damaged tanks. As the grounding damages resulting in much higher relative SWBM values, the probability of exceeding the limit SWBM is almost three times higher than for collison damages. For aframax tanker, these probabilities were equal and read about 24%.

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