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INFLUENCE OF THE HEELING ANGLE ON ULTIMATE BENDING CAPACITY OF DAMAGED SHIP

Abstract

When a ship is damaged, the operators need to decide on immediate repair actions by evaluating the effects of the damage on the safety of the ship using residual strength assessment procedures. Safety assessments are usually performed with respect to the ultimate vertical bending moment capacity assuming upright position of damaged ship. However, floating conditions of damaged ship could be changed dramatically resulting in change of the draught and trim and also inducing the important heeling angle. In case of the ship heeling the bending moment can be decomposed in two components, one perpendicular and other one aligned to the neutral axis of the intact ship. The problem is equivalent as considering upright damaged section loaded by combined vertical and horizontal bending moments. Such problem is commonly approached by nonlinear interaction equation between vertical and horizontal bending moments. The aims of the present paper are firstly to review literature with such interaction equations published and then to apply one of them on the example of damaged tanker loaded by combined bending moments caused by the heeling angle. The purpose is to evaluate importance of the heel on the structural safety of damaged ship.

Key words: damaged tanker, ultimate strength, heeling angle

UTJECAJ BOČNOG NAGIBA NA GRANIČNI MOMENT SAVIJANJA OŠTEĆENOG BRODA

Sažetak

U slučaju oštećenja brodske konstrukcije, potrebno je donositi brze odluke, koje se zasnivaju na procjeni utjecaja oštećenja na sigurnost broda, koristeći pritom metode proračuna granične čvrstoće. Uobičajeno je da se procjena sigurnosti oštećenog broda u uspravnom položaju provodi u odnosu na granični vertikalni moment savijanja. Međutim, stanje ravnoteže oštećenog broda može se značajno promijeniti, pri čemu dolazi do promjene gaza, trima i bočnog naginjanja broda. Kod bočnog nagiba, moment savijanja se može razložiti na dvije komponente, jednu okomitu na i drugu paralelnu s neutralnom linijom neoštećenog trupa. Isti problem možemo također razmatrati na način da opterećenje uspravnog broda složenim momentom savijanja razložimo na vertikalnu i horizontalnu komponentu. Ovakvim problemima obično se pristupa koristeći nelinearnu jednadžbu sa spregnutim vertikalnim i horizontalnim momentom savijanja. Cilj ovog članka je dati pregled objavljenih radova koji sadržavaju takve spregnute jednadžbe i jednu od njih primijeniti na oštećeni tanker opterećen složenim momentom savijanja uslijed bočnog nagiba broda. Svrha rada je procjena utjecaja bočnog nagiba broda na sigurnost oštećene brodske konstrukcije.

Ključne riječi: oštećeni tanker, granična čvrstoća, bočni nagib

1. Introduction

The structural failure of the tanker may occur due to ship collision, grounding or some other type of human mistake. In case of such an accident, the ship strength could be significantly reduced while still water loads increase and could become considerable cause of the structural overloading. The well known accident of a single hull oil tanker „Prestige" in 2002. clearly showed that such a scenario can result in the ultimate structural failure and the sinking of the ship as the most unfavourable outcome with the spillage of a large amount of oil into the environment.

A damaged ship may collapse after a collision or grounding if she does not have adequate longitudinal strength. Such collapse can occur when the hull's maximum load-carrying capacity (or ultimate hull girder strength) is insufficient to sustain the corresponding hull girder loads applied [1]. Calculating the ultimate strength after damage is important to determine the options for recovery of the vessel [1], [3].

The results presented in this paper are related to the ultimate strength assessment of the ship damaged by collision. As some investigations show, accidents caused by collision contribute more than 50 percent of the ship accidents at sea [4].

In the present study, for collision damage defined by [5], the ultimate strength calculation of intact and damaged tanker is performed by modified Paik-Mansour formula [7]. As the angle of heel is possible consequence of the unsymmetrical (collision) damage, combined effect of the vertical and the horizontal bending moments becomes important [6]. Therefore, this paper deals with the ship hull collapse under the combined load effect and the strength is represented by an interaction equation for vertical and horizontal bending moments [4],[9] . Values of interactive coefficients for intact and damaged ship are considered from available researches [4],[9],[10]. Eventually, the interaction equations proposed in [4] are used in numerical calculations, as these equations are obtained for tanker very similar to one analysed in the present study. The aim of numerical calculations is to evaluate influence of heeling angle on ship safety. The only load component considered in the present paper is still water bending moment, as it can be dramatically increased in the case of flooding of some compartments.

2. Description of damage

Main particulars of double-hull oil tanker analysed in the present study are shown in Table 1.

Table 1. Main particulars of oil tanker

Dimension	Unit (m, dwt)
Length between perp., Lpp	234
Breadth, B	40
Depth, D	20
Draught, T	14
Deadweight, DWT	105000

Damage extent is presented in Table 2 for collision damage [5]. Collision damage represents damage of the main deck at side and upper part of the side shell (Figure 1).

Table 2. Extent of collision damage

Dimension	Collision (m)
Breadth	2.05
Height	5.30

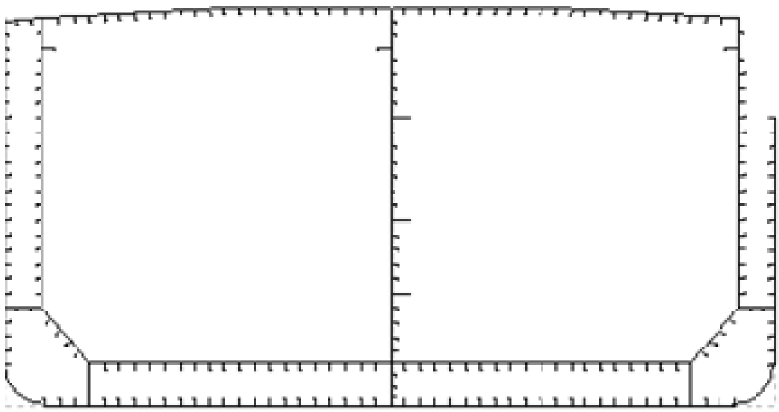

Fig. 1. Location and extent of collision damage

3. Ultimate strength of damaged ship structure

As applied hull girder loads increase, the most highly stressed structural components of the ship's hull buckle in compression or yield in tension. A ship can withstand further hull girder loading even after the buckling or yielding of a few structural components, whose internal stress will be redistributed to adjacent intact members. The most highly compressed member will collapse first and the overall stiffness of the hull decreases gradually. Buckling and collapse of structural members will occur progressively until the ultimate limit state is reached. To prevent collapse of the ship hull, evaluation of the ultimate overall hull strength has become unavoidable in the ship structural design.

In the conceptual study of ultimate bending strength, as the present one, it is practical to use some of rapid methods for ultimate strength prediction. Such methods are based on presumed stress distribution at ultimate limit state. Paik and Mansour [11] developed an advanced analytical method based on assumed stress distribution over the hull cross section at the ultimate limit state. Compression and tension regions between yielded (σ_x^Y) and buckled (σ_x^U) elements, still remain in a linear elastic or unfailed state, reaching an elastic stress of σ_x^E.The height of buckled elements region (h_C) is assigned on the basis of the geometrical and material properties of the ship's hull structure. Under a vertical or horizontal bending moment, the summation of axial forces over the entire cross-section of the hull becomes zero, i. e.

$$\int \sigma_x dA = 0 \qquad (1)$$

The height of buckled elements region is defined by solving Equation 1. Modified Paik-Mansour method [7] involves two unknowns, i.e. height of the buckled elements region (h_C) and height of the yielded elements region (h_Y). Equation 1 is insufficient to determine two unknowns, and thus the iteration process is required to determine heights h_C and h_Y. The distance of the neutral axis of the cross-section of the ship's hull at the ultimate limit state from the ship's baseline (g_{uv}) or centerline (g_{uh}), can be calculated as the sum of the first moments of the bending stresses of all structural elements for the baseline or centerline divided by the sum of the bending stresses. The ultimate vertical bending moment M_{uv} is calculated as the first moment of the bending stresses around the horizontal neutral axes and the ultimate horizontal bending moment M_{uv} is calculated as the first moment of the bending stresses around the vertical neutral axes.

Following described procedure, the ultimate vertical bending moments, M_{uv} and the ultimate horizontal bending moment, M_{uh} for intact and damaged tanker analyzed in this paper are given in Table 3. The vertical bending moment for the sagging condition M_{uv}, denoted by M_{uvs}, is negative and the horizontal bending moment M_{uh} is defined negative when damaged side is in compression.

Table 3. Ultimate strength of intact and damaged ship

Ship condition	Ultimate strength	
	VBM (sagg) (MNm)	HBM (MNm)
intact	-8763	-16192
ABS collision damage	-7866	-14570

4. Ultimate strength of heeled ship

As the angle of heel is possible consequence of the unsymmetrical (collision) damage, combined effect of the vertical and the horizontal bending moments becomes important. Therefore, this paper deals with the ship hull collapse under the combined load effect and the strength is represented by an interaction equation for vertical and horizontal bending moments expressed as follows [4],[9]:

$$\left(\frac{M_v}{M_{uv}}\right)^{\alpha} + \left(\frac{M_h}{M_{uh}}\right)^{\beta} = 1 \quad (2)$$

Review of interaction coefficients proposed by different authors is given in Tables 4 and 5, for intact and damaged ship respectively. Interaction coefficients for damaged ship are valid for the case when damaged side is in compression. When damaged side is in tension, different interaction coefficients are obtained. Also, it should be mentioned that values in Tables 4 and 5 are for sagging bending moments, while interaction coefficients for hogging bending moments may generally be different. Comparison of interaction equations obtained using different coefficients is presented in Figures 2 and 3, for intact and damaged section respectively.

Table 4. Review of the interactive coefficients for intact section according to different authors

Authors	α	β
Paik et al.[11]	1.85	1
Gordo and Guedes Soares [9]	1.5-1.66	1.5-1.66
Jia and Moan [4]	1.52	1.96
Khan and Das [10]	1.806	1.806

Table 5. Review of the interactive coefficients for damaged section according to different authors

Authors	α	β
Jia and Moan [4]	1.43	2.06
Khan and Das [10]	1.76	1.76

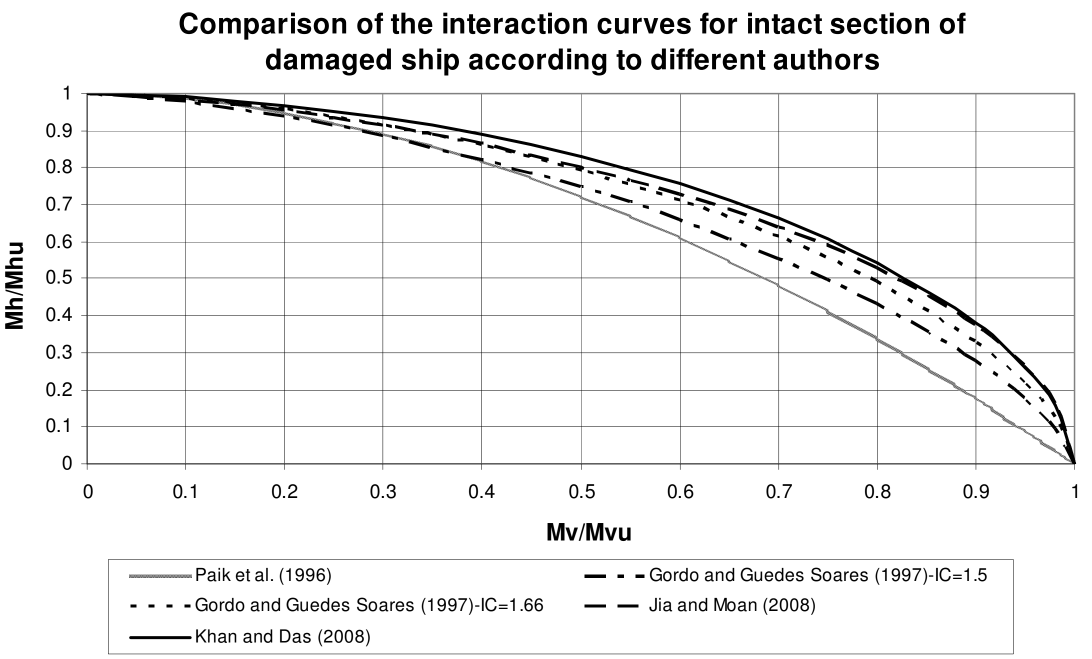

Fig. 2. Comparison of the interaction curves for intact section of damaged ship according to different authors

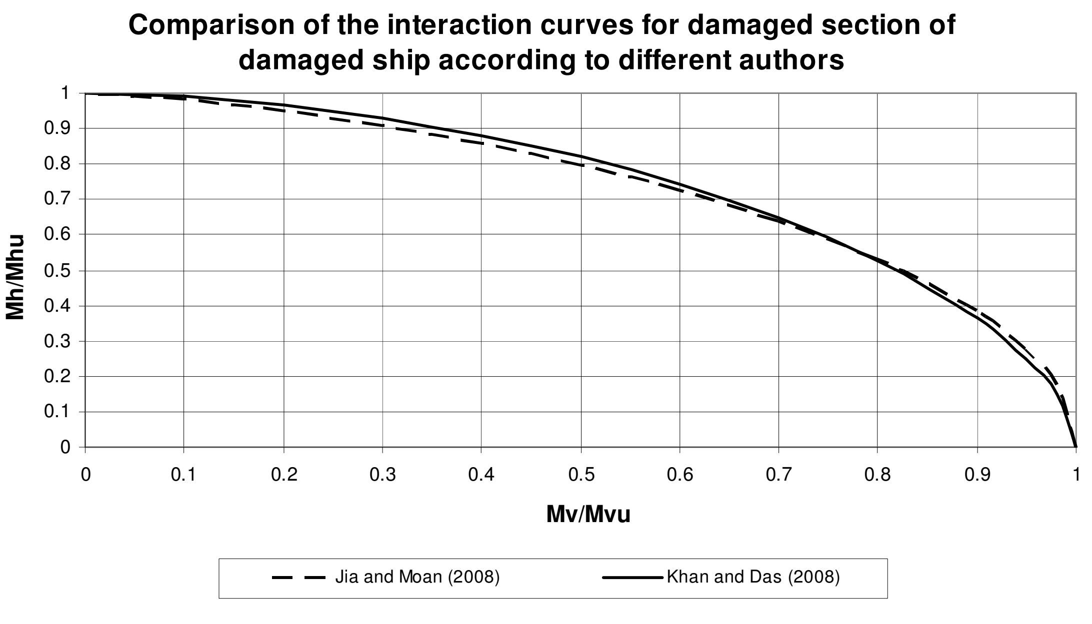

Fig. 3. Comparison of the interaction curves for damaged section according to different authors

Maximum sagging still water bending moment (SWBM) for studied ship in intact condition reads 1962000 kNm. For the worst case of SWBM in damaged condition, sagging SWBM could attain value 2.38 x 1962000 kNm = 4669560 kNm [3]. SWBM may for heeled ship be decomposed in two components, one perpendicular and other one aligned to the neutral axis of the intact ship cross section. Former component actually represents horizontal bending moment *(M_h* in equation 2) while the latter represents vertical component (M_v in equation 2). Decomposition of SWBM in two perpendicular components is shown in Figure 4.

For the intact ship, we adopted α =1.52 and β =1.96 according to [3]. For the ship damaged by collision, values of interaction coefficients are taken as α =1.43 and β =2.06 [3]. Results of the interactive formula (2) calculation are presented in Figures 5 & 6 for intact and damaged ship sections of the damaged ship respectively, for different heeling angles φ. It should be clarified that intact section of damaged ship means section outside damaged area. Only interaction coefficients provided in [4] are considered in the numerical analysis. The reason is that those interaction coefficients are obtained for aframax tanker very similar to the one analysed in the present study.

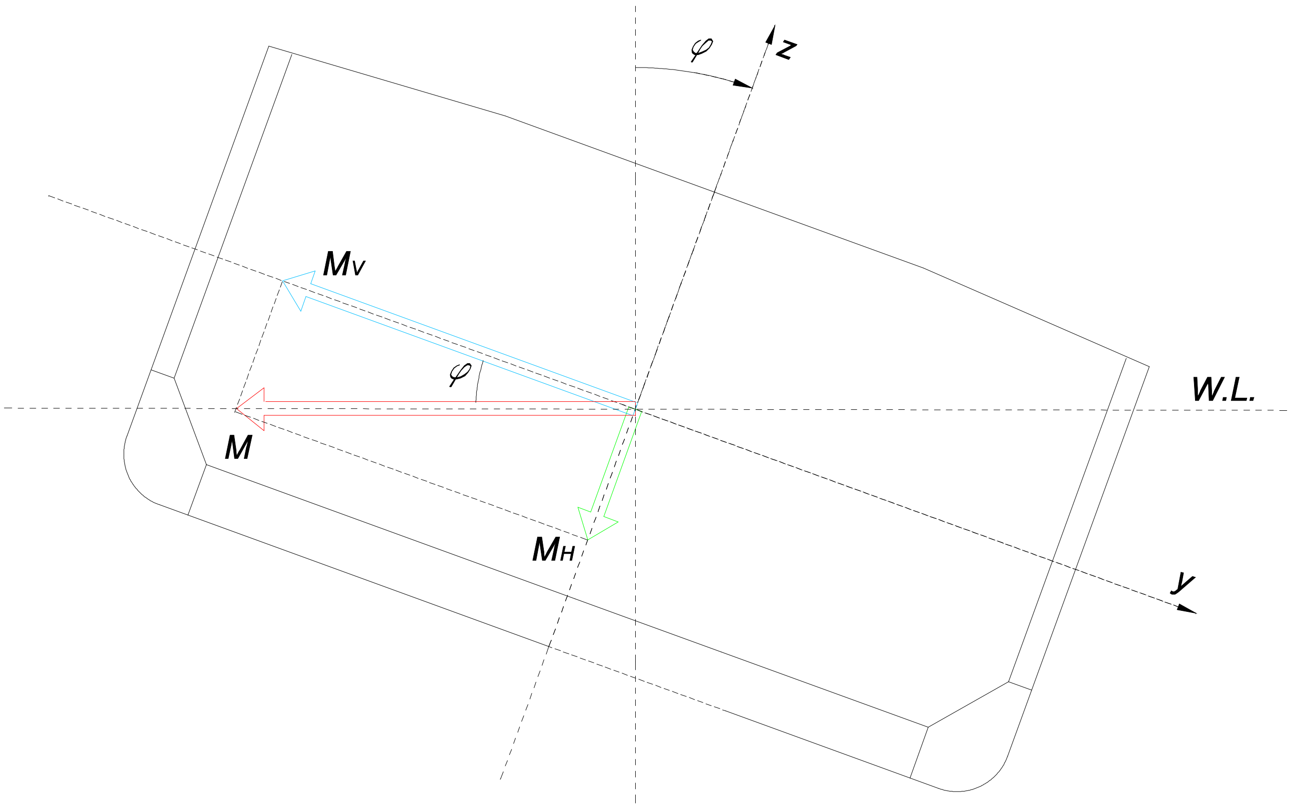

Fig. 4. Combined bending of hull girder

Figures 5 and 6 present outcome of the application of the interaction equation (2) for different heeling angles. Inner curve represents load for different heeling angles and it is obtained by simple trigonometric relations using Figure 2. Outer curve represents interaction collapse equation. Straight lines represent paths from load to the collapse curves for different heeling angles (5, 20 and 45 deg). Heeling angles along each of straight lines are the same, which means that the ratio of the horizontal and vertical bending moments is constant.

If distances between inner and outer curves are expressed in terms of bending moments, then additional increase of bending moment to cause collapse is presented in Table 6. Obviously, for both intact and damaged sections, distances from load curve to the collapse interaction curves are increasing with increasing heeling angle and it can be concluded that the heeling angle has positive influence on the residual strength of a damaged oil tanker.

Table 6. Increase of bending moment to cause hull girder coallapse for intact and damaged sections

Heeling angle (°)	BM increase for intact section (MNm)	BM increase for damaged section (MNm)
5	4112	3216
20	4412	3512
45	5872	4464

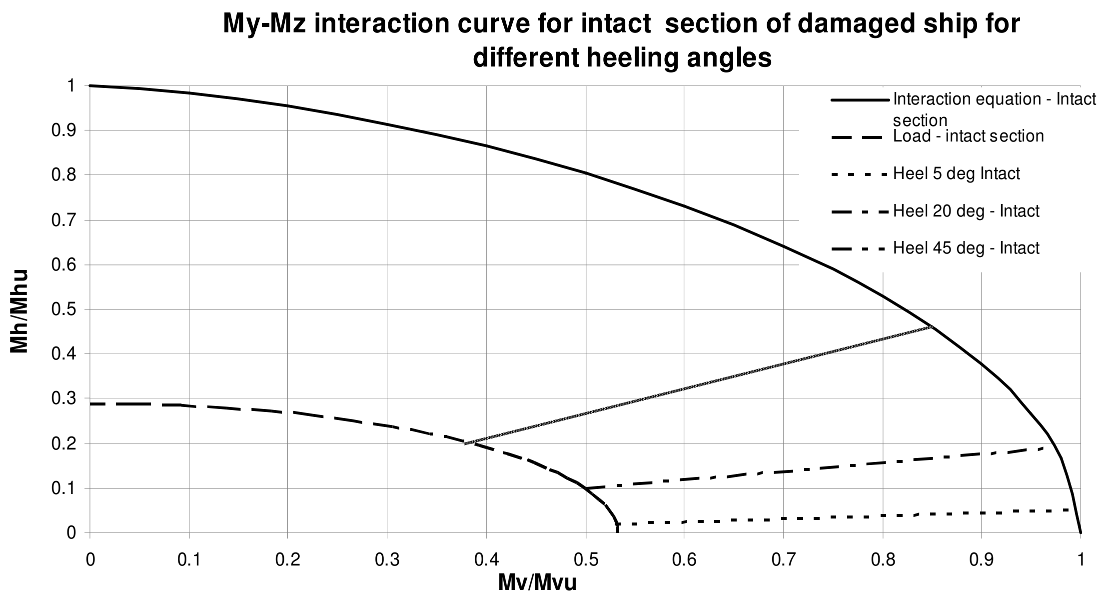

Fig. 5. Graphical representation of the results of interaction formula for intact section of damaged ship for different heeling angles

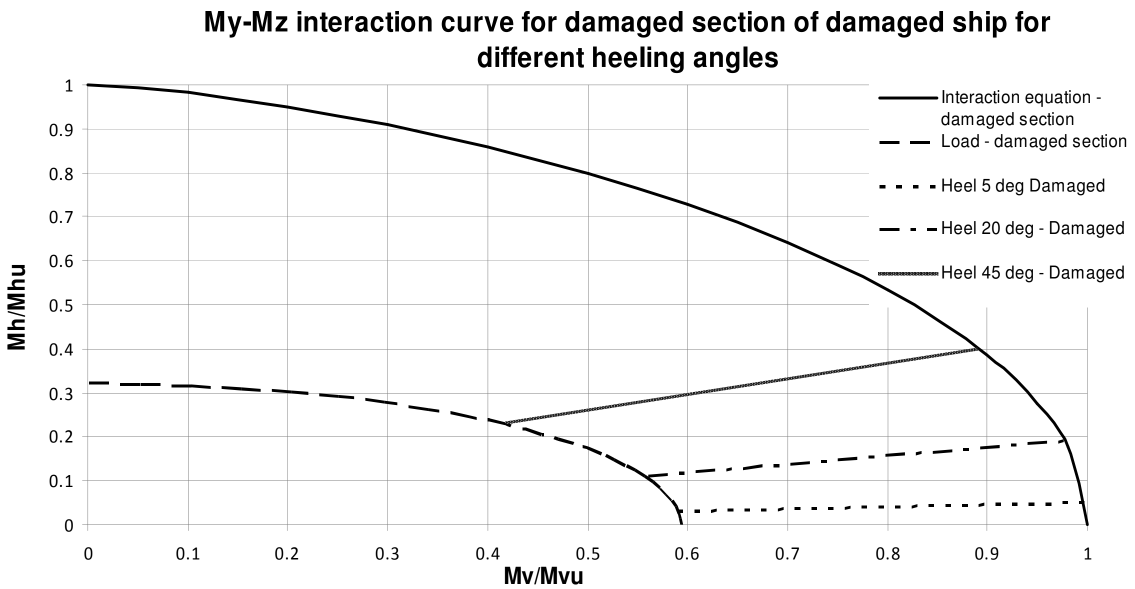

Fig. 6. Graphical representation of the results of interaction formula for damaged section of damaged ship for different heeling angles

5. Conclusion

The aim of this study is to evaluate influence of heeling angle on ship safety concerning ship ultimate strength. If damaged ship is heeled because of unsymmetrical (collision) damage, combined effect of the vertical and the horizontal bending moments becomes important. Therefore, for the purpose of conceptual analysis in this paper, the modified Paik-Mansour method was applied for the vertical (M_{uv}) and horizontal (M_{uh}) ultimate bending moment calculation. Then, the strength is represented by an interaction equation for vertical and horizontal bending moments.

The influence of the heeling angle on the safety of the ship is positive, as the distance of the load interaction curve to the ultimate strength limit curve increases with increasing heel angle (Figures 5 and 6). That is verified by calculation of the interaction equation values for different heeling angles of the damaged ship, loaded by SWBM for the worst damage case (Table 6).

The influence of the rotation of the neutral axis on the ultimate strength is not included in this calculation, because it is almost negligible for double-hull oil tankers having outer shell damage [12].

The wave loading component is not included in this calculation, because dominant load component considered in the present study is SWBM, which, for the worst damage case, could be more than twice compared to the SWBM of the intact ship. Neglecting wave loads is possible for closed seas, with low wave activity, as it is the Adriatic Sea. However, for wave environments with high waves, vertical and horizontal bending moments are to be considered as well. The calculation methodology is in principle similar to the one presented herein.

The paper provides results at conceptual level, enabling identification of needs for more detailed research, where more accurate methods for ultimate strength calculation, as the progressive collapse method, may be applied. Eventually, presented study could be further explored and considered within the risk-based framework using structural reliability analysis for evaluation of safety of damaged oil tanker [10].

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