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Recent Advances in Damage Stability Assessment with Application on a Container Vessel

Abstract

The paper reviews the design procedure and recent work published on the topic of the damage stability and the safety assessment criteria that is established accordingly. The available damage scenarios must be designed prior to the safety assessment of a damaged ship.
Another aspect of the discussions is an opinion on some problematic aspects of the damage stability regulations with practical aspects presented in literature very sparse and the fact that different computer programs may give divers outcomes. A little review on the damage stability requirements with its new regulations is given.
Stability assessment is performed on a selected container ship using the Maxsurf software for both the intact and damage condition of the vessel, while the parameters related to damage stability are identified and categorized when developing deterministic and probabilistic damage scenarios.

Key words: damage stability, regulations, deterministic, probabilistic

1. Introduction

The damage stability calculation methods for ships can be calculated by way of deterministic damage stability and probabilistic damage stability. The method chosen depends on the type of the ship. No matter which method is chosen a safety of ships against sinking/capsize in case of loss of their watertight integrity is the main concern to society, regulatory bodies, and the industry itself.

Ever since the 1960's when Kurt Wendel [1] presented a concept for a probabilistic method for designing ship subdivision recognizing that ship survival after damage is affected by numerous uncertainties such as damage extent, damage location, loading condition, permeability and wave and wind conditions at the time of the incident this has nowadays became the prevailing tendency. It is based on damage statistics in terms of the longitudinal extent of the damage, the penetration of the damage, the height of the damage and consequently analysed to find relations between damage parameters and main particulars of struck vessel. Additionally analysed data included vertical position of the lowest point of the damage sealed by ship depth and damage location in terms of port and starboard.

However the development of probabilistic regulations started slowly in the late 60s, and only in 1973 the International Maritime Organization (IMO) introduces the probabilistic method of subdivision for passenger ships, through resolution A.265(VIII) [2] but only an alternative to the deterministic procedure.

In 1990 the Maritime Safety Committee (MSC) of IMO adopts resolution MSC.19(58) [3] while in 1996 Resolution MSC.47(66) [4] extended the application of the probabilistic method to dry cargo ships exceeding 80 m in length.

There were two distinct problems which stemmed from those regulations.

1. Engineer's often complained about the complexity of the method. The stability calculations were difficult and required specialist software and oversight in the design process.
2. Through a lot of examples it was found that for the same ships using the same proposed methodology with different software's yielded results which were all „over the place" [5].

To address those issues a project called 'Harmonization of Rules and Design Rationale' (HARDER)' [5] with main objective to account to lacking knowledge by performing a systematic fundamental and practical research and to clearly identify the problems stated above which resulted in so called harmonisation work. It meant re-evaluating and proposing new formulations to the existing regulations. It can be found in SOLAS Chapter II-1, Part B-1 [6] based on MSC.216(82) [7], denoted as 'Regulation E' in the table which will be debriefed further below.

To give a brief overview of the current state of regulations a table systemized in [8] is given.

Table 1: Current damage stability regulations.

A	Passenger vessels pre-2009	Deterministic
B	The Stockholm Agreement	Probabilistic
C	Safe return to port regulations	Deterministic
D	Damaged stability requirements - 'Type A/B' vessels (pre-2009)	Deterministic
E	SOLAS damaged stability rules post-2009	Probabilistic

'Regulation A' is described in MSN 1698M (MCA, 1998) [9]. A key element in this regulation is the margin line, which is related to the freeboard requirements.

In 1995 IMO opened the possibility for certain groups of countries to sign regional agreements on damage stability standards. Northern European countries set up the so-called Stockholm Agreement [10] systemised as 'Regulation B'. This regional agreement applies to passenger ro-ro ships and specifies that ships must comply SOLAS90 criterion with a certain amount of water on deck.

'Regulation C' "Safe Return to Port" [11] means new SOLAS regulations are applicable to new passenger ships having their keel laid on or after 1st July 2010, and having a length of 120m or more, or having 3 or more Main Vertical Zones.

'Regulation D' for a type A (carrying liquid cargo in bulk) and B (all other ships) were mandatory with predetermined amount of damage and longitudinal extent of one or of any two adjacent compartments depending of the type of the vessel.

2. Theoretical background

The aim of this section is to review the new probabilistic damage stability assessment concept and to explain the technical and scientific background of the new probabilistic rules with the comparison to the deterministic approach.

The most dangerous flooding corresponds to open damaged compartment (freely connected to the sea) which is partially filled as the water can then flow in and out of the compartment and moves as the ship rolls. The exact evaluation of the probability of survival of a ship is very difficult since all factors that contribute to it are complex and interdependent. This approach, the so-called probabilistic method is therefore applied resulting in an estimate of ship's probability of survival to flooding hazard.

As for similarities with old deterministic regulation, harmonized regulations include consideration of the different heeling moments which can act on the ship.

Permeability of each general compartment or part of a compartment shall of course be explicitly taken into account. However, in harmonized regulations cargo space permeability is set to a value dependent on the draught of the ship, but which is always equal or larger than 0.70. The permeability takes into account that the tanks are not completely filled with water in case of damage, since some of the spaces will always be occupied by for example, machinery components, piping, etc.

2.1. Deterministic damage stability

The effect of flooding of a ship depends on numerous factors or uncertainties such as which compartment or group of compartments are flooded, on draught and intact stability of the ship, permeability of flooded compartments, sea state during the accident and consequent steady heel angle as well as possible transient asymmetric flooding. There are several ways to evaluate the trim and stability of a ship after flooding, using the deterministic methods such as "Added Mass Method" and "Lost Buoyancy Method". The floodable length method is a way to ensure that the ship has some capacity to resist flooding. The most common method which is adopted by IMO is 'Lost Buoyancy Method' where the margin line represent the key element as a line in the ship's side located at least 76mm below the upper surface of the bulkhead deck which cannot touch the water. This method is also known as constant displacement method and is used in the new harmonized probabilistic method. The procedure includes calculating the ship's draught after flooding, without heel and trim. The centre of buoyancy after flooding is recalculated followed by the heel and trim from the new transverse and longitudinal positions of the centre of buoyancy and the position of the centre of gravity. The ship's draughts taking into account all three effects and the metacentric heights for these draughts are evaluated. The underwater volume gained through sinkage is now equal to overall underwater volume lost through flooding.

2.2. Probabilistic damage stability

The probabilistic methodology for the development of the new harmonised regulations and the way of modelling of ship's survivability and the risk for capsize/sinking in case of damage consists of probability that the buoyancy after flooding is sufficient for survival and the probability that stability after flooding is sufficient to prevent capsizing or dangerous heeling due to loss of stability or heeling moment. A summation over all possible damage cases indicates whether that the probability of survival is sufficient once a compartment (or group of adjacent compartments) is flooded denoted *A*.

$$A=A(p,v,r,s) \tag{1}$$

p - Probability that only the compartment or the group of compartments under consideration may be flooded, disregarding any horizontal subdivision.
v - Probability that the damage will not exceed a given height above the waterline.
r - Reduction factor, which represents the probability that inboard spaces will not be flooded.
s - Probability of survival after flooding the compartment or the group of compartments under consideration.

Probability of flooding with its main factors that affect the three-dimensional damage extent of a ship with a given watertight subdivision are related to transverse, horizontal and longitudinal subdivision. Transverse subdivision is the simplest case where only the location and length of damage in the longitudinal direction is considered. In case the ship has also a horizontal subdivision above the waterline, vertical extent of damage may be limited to the depth of that subdivision, while vertical extent of damage is subject to uncertainty with the probability of not damaging that horizontal subdivision denoted v_i. Maximum vertical extent of damage above a given waterline has changed from 7 m to 12.5 m in new regulations, thus providing an increased safety level.

With longitudinal subdivision uncertainty related to damage penetration is evaluated with the probability that a side compartment is opened expressed as $p_i r$ or $p_i\,(1\text{-}r)$ for a probability that an inner compartment is opened in addition to the side compartment.

The current probabilistic damage stability regulations are based on damage statistics from Lutzen [12]. Database has been analysed to find relations between damage parameters and main particulars of the struck vessel. Damage parameters, such as longitudinal location, damage length, vertical extent damage and damage penetration are four uncertainties under consideration used to derive probability distributions for the variables which characterise damage.

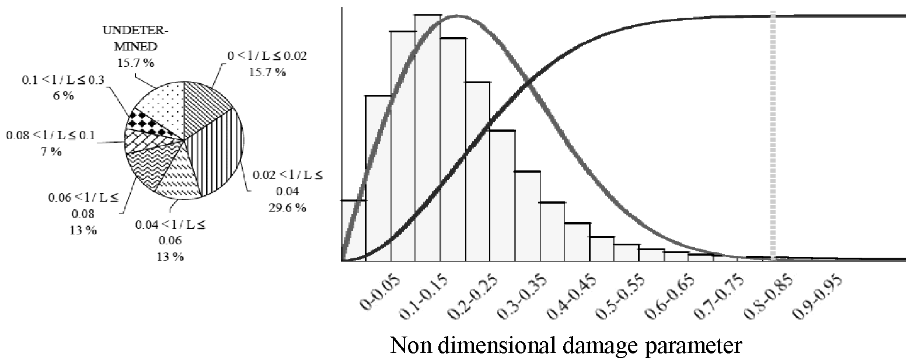

Figure 1: Damage statistics [12]/Probability distributions for damage variables.

All statistical models start with measurements from the real world, which are used to construct a histogram. To get an indication which ship type is most vulnerable to different forms of accident and to provide some explanation of the likely characteristics of the incurred damage the extracted statistics are used. It is done by using cumulative distribution for each of the damage parameters. This step will result in probability density functions (or classes of PDFs) which are then included in legislation or standards. For instance, from all recorded incidents only 5% of penetrations were greater than $0.5B$ and the largest damage length in statistics observed was $0.48L$. In new harmonised regulations maximum damage length changed from 48 m to 60 m, damages of $B/2$ should be assumed (allowing penetration of longitudinal centre line bulkheads).

In the case of transverse subdivision, the joint probability function for the p-factor is a function of the non-dimensional damage location and the non-dimensional damage length as independent parameters.

Factor p_i can be calculated for one damaged zone only or if there are more adjacent damaged zones. For a one damaged zone the formula becomes,

$$p_i \;=\; p(x1_j,x2_j)\cdot[r(x1_j,x2_j,b_k) - r(x1_j,x2_j,b_{k\text{-}1})] \qquad (2)$$

or for instance three adjacent damage zones

$$p_i = p(x1_j,x2_{j+n-1}) \cdot [r(x1_j,x2_{j+n-1},b_k) - r(x1_j,x2_{j+n-1},b_{k-1})]$$
$$-p(x1_j,x2_{j+n-2}) \cdot [r(x1_j,x2_{j+n-2},b_k) - r(x1_j,x2_{j+n-2},b_{k-1})]$$
$$-p(x1_{j+1},x2_{j+n-1}) \cdot [r(x1_{j+1},x2_{j+n-1},b_k) -r(x1_{j+1},x2_{j+n1},b_{k1})]$$
$$+ p(x1_{j+1},x2_{j+n-2}) \cdot [r(x1_{j+1},x2_{j+n-2},b_k) - r(x1_{j+1},x2_{j+n2},b_{k1})] \quad (3)$$

where

$$r(x1, x2, b_0) = 0 \quad (4)$$

while the symbols denoted represent:

j - the aft most damage zone number involved in the accident, starting with number 1 at the stern.

k - the number of a particular longitudinal bulkhead functioning as a barrier for transverse penetration, counted from the shell towards the centre line (k = 0 for the shell).

x_1 - distance from the aft end (terminal) of the ship to the aft end of the zone in question.

x_2 - distance from the aft end (terminal) of the ship to the forward end of the zone in question.

b - mean transverse distance in metres measured from the shell to the longitudinal barrier in question.

$p(x1,x2)$ - accounts for the probability of the considered longitudinal damage extent.

$r(x1,x2,b)$ - a probability factor accounting for the transverse damage extent. IMO, 2006).

Further cases for more adjacent zones are not given in this sub-section, due to their complexity.

The reduction factor *r* was determined by the following formulae:

$$r(x1,x2,b) = 1-(1-C)\cdot\left[1-\frac{G}{p(x1,x2)}\right] \quad (5)$$

where:

$$C = 12\cdot J_b\cdot(-45\cdot J_b+4) \quad (6)$$

$$J_b = \frac{b}{15\cdot B} \quad (7)$$

G value varies from cases whether the compartment is extending over the entire ship length, for inside compartments and for forward/aft compartment.

The probability of survival, *s*, was constructed based on the results of all model tests conducted for the three mechanisms of capsize in waves which were observed in damage condition. Again, the cumulative probability of survival for a damaged *GM* was constructed and superimposed with the IMCO statistics on sea state at moment of collision thus yielding resulting probability of survival *s* as a function of damage *GM* and damage freeboard. That enabled development of the Static Equivalent Method (SEM). It was found that SEM was too complicated to be applied in practice and were not significantly more accurate. Using a traditional *GZ* based formulation that were used instead, for conventional ships, a good correlation to the probability of survival from the model tests was obtained.

The proposed probability of survival which corresponds to factor s_i, is given as

$$s_i = \text{minimum} \; \{ s_{\text{intermediate},i} \text{ or } s_{\text{final},i} \cdot s_{\text{mom},i} \} \tag{8}$$

where:

$s_{\text{intermediate},i}$ represents the probability of survival in all intermediate phases of flooding and $s_{\text{mom},i}$ represents the probability of survival to inclining moments but both apply to passenger ships only and thus will be omitted, while,

$s_{\text{final},i}$ – probability of survival for a final equilibrium state after flooding is given

$$s_{\text{final},i} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}} \tag{9}$$

where GZ_{max} need not to exceed 0.12m and Range of positive stability need not to exceed 16°.

Factor *K* is dependent on the equilibrium angle determined by:

$$K = \sqrt{\frac{\theta_{maks} - \theta_e}{\theta_{maks} - \theta_{min}}} \tag{10}$$

where those angles represent the angles of heel during intermediate stage of flooding. The method based on a traditional *GZ* formulation needs to have a correction if GZ_{max} is not located at the peak of the curve when one or more openings are submerged and the *GZ* curve is consequently cut at this point, because the righting lever becomes negative by definition. A common design strategy to avoid this problem is to place all openings at a certain distance above the bulkhead deck [13].

The probability of survival s_i is to be taken as zero (no survivability) if the lower edge of unprotected or weathertight openings through which progressive flooding may take place immerses.

Finally *A*-index is determined by summarizing and weighing the results from the three loading conditions. The weighting accounts for the corresponding percentual time (40% time spent on *ds*, 40% time spent on *dl* and 20% time spent on *dp*) in operation. The loading conditions are defined by their trim, *GM* value and the mean draught d. Attained subdivision index, *A*, should be calculated as:

$$A = 0.4As + 0.4Ap + 0.2Al \tag{11}$$

- *ds* – Deepest subdivision draught
- *dp* – Partial subdivision draught
- *dl* – Light service draught

The probabilistic concept is based on the calculation of the attained index A and its evaluation for the assessment of ships' damage stability compared to the required index, regulatory one, R, [14] such that

$$A \geq R \tag{12}$$

Equally, each partial index is a sum of the contribution of all damage cases.

$$A = \sum p_i s_i \tag{13}$$

Minimum values of the attained subdivision index at specific draughts are set in the harmonized rules. For cargo ships, required subdivision index is now 0.47-0.74. The partial indices *As*, *Ap* and *Al* are to be not less than 0.9*R* for passenger ships and 0.5*R* for cargo ships.

The *R*-index for passenger ships was established based on sample ship calculations from the HARDER project. Actually, the detailed information on the development of the *R*-index is difficult to obtain. Hjort [15] reported that the value of the *R*-index declined with increasing values of ship length and number of passengers which was totally unacceptable for IMO as it was argued that it would give an unbalanced picture of the safety level of large existing passenger ships. In consequence, a compromise was agreed upon and a new, but not necessarily scientific 'correct' formula for the *R*-index was developed [16].

Thus, the calculation of the new Required Index was based on the "equivalence of safety" principle meaning that the ratio between the attained and required index (*A/R*) for the existing and new rules should be similar. It meant to say that if the ratio was very different, one would suggest that all the ships constructed before were unsafe. Therefore, a satisfactory level of safety was assumed for the existing regulations and the levels of safety for the new ones on the average remained unchanged.

Main aspects taken in consideration in determination of *R* were satisfactory number of ships per type, the robustness of formulae at ship type level that may vary with ship type and that the level of safety should be uniform.

In the case of cargo ships greater than 100 m in length (Ls) MSC.194(80) [17]:

$$R = 1 - \frac{128}{L_S + 152} \tag{14}$$

3. Case study

The ship taken as an example (based on "Jean Bosco" container ship) has following principal dimensions.

L_{oa} = 201.41 m, L_{pp} = 189 m, B = 32.24 m, D = 18.692 m, T = 11.017 m,
DWT = 30 887 t, v = 19.33 kn.

All functions within Maxsurf Stability are performed using a graphical multi-window environment consistent with all other Maxsurf modules. Data is displayed in form of tables and figure. Additionally, the permeability of the different compartments used in this study are pre-set by Maxsurf, but of course in accordance with the rules.

3.1. Deterministic damage stability

The stability of the ship in the damaged condition was calculated for the case of fully loaded ship at full load draught. In order to simplify the procedure and to reduce the time of calculation, only the damage of those tanks and storage areas considered to have the most negative impact on the ship's stability were taken into account. Regarding damage stability, the requirements are purely deterministic, i.e. the damage extent is predetermined. In other words, no damage to individual spaces has been considered, but only a group of compartments distributed along the length of the ship starting from the engine room, tank groups (NO°1 to NO°5) and forepeak is taken into account. The one group of compartments consist either of heavy fuel tank or water ballast double bottom or wing tank along with the cargo tank at a designated longitudinal position.

However using deterministic method a realistic scenarios are hard to predict even though the method is suitable when modelling a range of scenarios. The regulation is conservative in the sense that it always assumes the worst-case scenario, therefore a simulated damage consisting of compartment groups NO°2, NO°1 and forepeak is taken as an example. Ships must be designed in a way that margin line does not submerge if one, two or three compartments are flooded. Usually this is achieved by designing the compartments that are smaller and by using both the double bottom or wing tanks in order to minimise parallel sinkage in the case of flooding.

In this case as already stated the damage depth was taken as such that the penetration was large enough to flood whole group of compartments yet it did not exceed half breadth of the ship.

The damage zone is presented highlighted on figure 2.

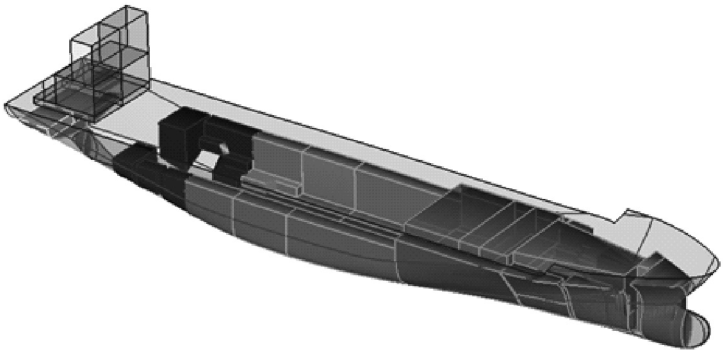

Figure 2: Simulated damage consisting of compartment groups NO°2, NO°1 and forepeak.

The main consequences of flooding for the ship's equilibrium position are increase in draught and decrease in mean freeboard until equilibrium is reached. The change in trim and heel angle until the longitudinal and transverse positions of the centre of buoyancy and centre of gravity are in the same vertical is also calculated.

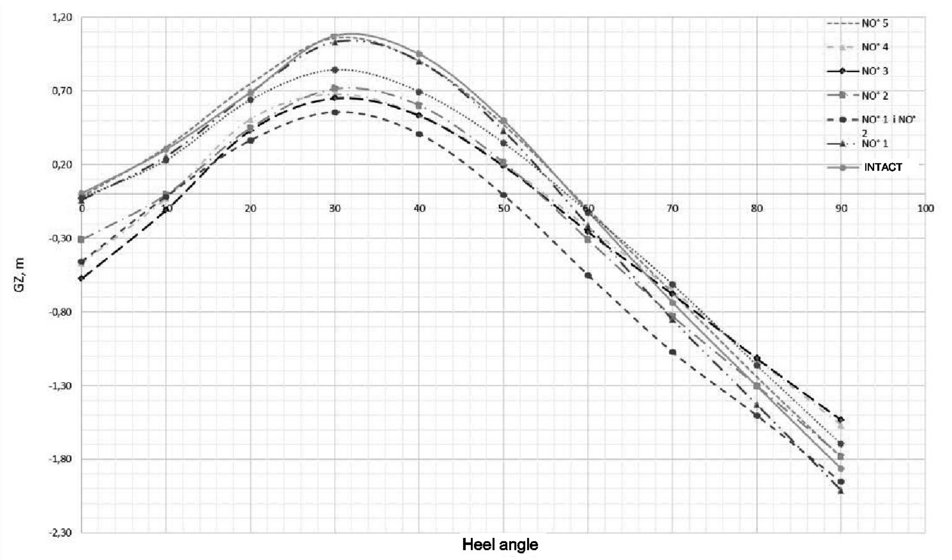

Figure 3: Comparison of GZ curves for the intact and various damaged cases.

For all the cases including the most severe ones the rules were satisfactory meaning that:

1. GM > 0.05 m
2. Heel angle ≤ 7° for one compartment flooding, or 12° for two or more adjacent compartments.
3. Specific minimum requirements related to the area under the GZ curve
4. Range of stability ≥ 15°. This requirement may be reduced from 15° to 10° if the area under the GZ curve increases by a certain ratio.

For any type of vessel, the margin line must not be submerged in the final equilibrium position. However, as evident from table 2, the criteria Margin line immersion – Equilibrium based was surpassed by 1,367 m above the margin line which indicates deck immersion as seen on figure 4. Only part of the rules requirement were given in following table 2, regarding margin line.

Table 2: Margin line immersion criteria according to SOLAS, II-1/8 [6]

CODE	CRITERIA	VALUE	UNITS	ACTUAL	STATUS
SOLAS, II-1/8	8.6.3: Margin line immersion - Equil based				Fail
	the min. freeboard of the	Marginline			
	shall be greater than (>)	0	m	-1,367	Fail

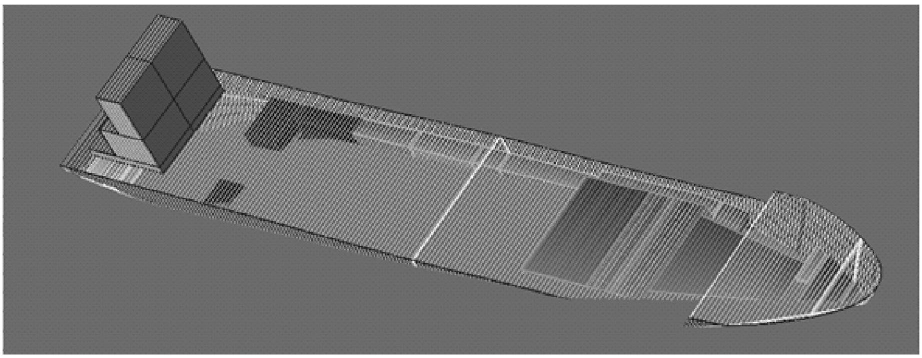

Figure 4: Equilibrium based position for simulated damage consisting of compartment groups NO°2, NO°1 and forepeak.

3.2. Probabilistic damage stability

As already stated in section before, the probabilistic calculation will deliver *A*-index with the aim to be as high as possible, but only after suitable fixed discretization in a number of zones, in longitudinal, transverse and vertical direction is prepared as seen in figures.

Since each zone and all combinations of adjacent zones contribute to the *A*-index it important how the zones are set. In general more zones will yield higher *A*-index.

In this case, since the vessel taken as an example was already built, the zones were divided according to the actual watertight subdivision of the ship. The subdivision was conducted bearing in mind that the subdivision length L_S defines the extremes for the hull in longitudinal direction (Figure 5 and 6). When there is double bottom, probability of flooding should be split in:

- Probability of flooding the double bottom only.
- Probability of flooding the compartment above the double bottom only.
- Probability of flooding both spaces.
- Each case will present different probabilities of survival, s_i.
- In MSC.19(58) [3] the approach was to assume that the most unfavourable vertical extent of damage occurs with total probability *p*.

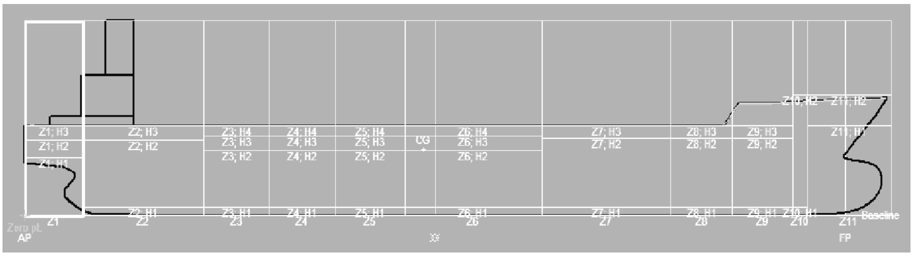

Figure 5: Transverse and vertical subdivision zones.

A double bottom shall be fitted extending from the collision bulkhead to the aft peak bulkhead.

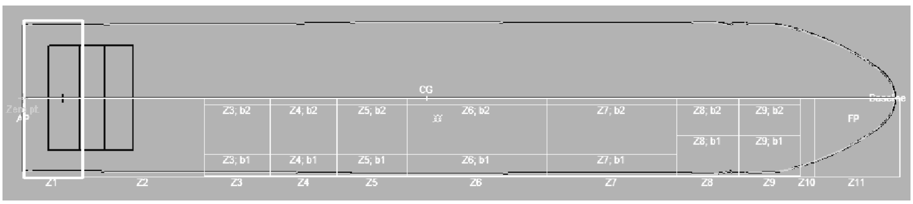

Figure 6: Longitudinal subdivision zones.

As evident from the figure the longitudinal bulkhead is more distant from the side in the fore region then in middle part while in the engine room area there isn't one. For practical reasons the number of zones should be limited to some extent but in accordance with the rules. The eleven-zone division of a ship where the bottom line triangles indicate single-zone damages, while the parallelograms indicate multi-zone damages is illustrated in figure 7.

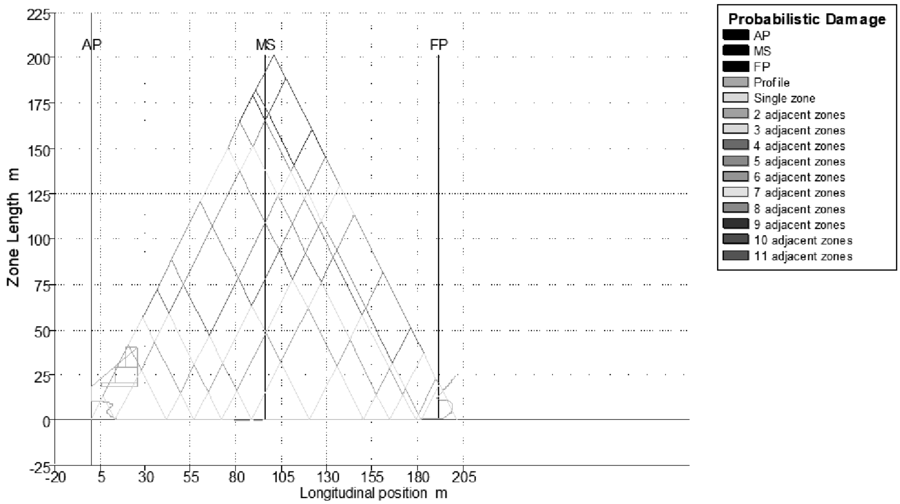

Figure 7: Possible single- and multi zone damages for a ship with 11 zones.

The calculation is preformed up to the 5 adjacent zones and part of the results for p_i, v_i, r_i is given in the following table 3.

Table 3: Selected partial output of the results for p_i, v_i, r_i

Zones	x1(aft end of damage from aft terminal of Ls), m	x2(fwd end of damage from aft terminal of Ls), m	J	Min. Damage lenght, m	Combined zone lenght, m	MSC.216(82) p (single zone)	MSC.216(82) p (multiple zone)	Test (Y/N)
1 adjacent zone								
Zone 1, 1	0	13,55	0,06708	0	13,55	0,04427	0,04427	Yes
Zone 2, 1	13,55	41,8	0,13985	0	28,25	0,077784	0,077784	Yes
Zone 3, 1	41,8	56,999	0,07524	0	15,199	0,026499	0,026499	Yes
Zone 4, 1	56,999	72,34	0,07595	0	15,341	0,026952	0,026952	Yes
Zone 5, 1	72,34	88,599	0,08049	0	16,259	0,029954	0,029954	Yes
Zone 6, 1	88,599	120,599	0,15842	0	32	0,094735	0,094735	Yes
Zone 7, 1	120,599	150,599	0,14851	0	30	0,085639	0,085639	Yes
Zone 8, 1	150,599	164,999	0,07129	0	14,4	0,024005	0,024005	Yes
Zone 9, 1	164,999	178,999	0,06931	0	14	0,022794	0,022794	Yes
Zone 10, 1	178,999	182,399	0,01683	0	3,4	0,001506	0,001506	Yes
Zone 11, 1	182,399	202	0,09703	0	19,601	0,069436	0,069436	Yes
						sub total	0,503574	
						cumulative total	0,503574	

Zones	Total r	r 1	r 2	r 3	r 4
1 adjacent zone					
Zone 1, 1	1				
Zone 2, 1	1				
Zone 3, 1	1	0,519625	0,453304	0,027071	
Zone 4, 1	1	0,518536	0,454102	0,027362	
Zone 5, 1	1	0,511943	0,458906	0,029151	
Zone 6, 1	1	0,459271	0,495839	0,044889	
Zone 7, 1	1	0,462555	0,493601	0,043845	
Zone 8, 1	1	0,792287	0,182361	0,025352	
Zone 9, 1	1	0,795619	0,179942	0,024439	
Zone 10, 1	1				
Zone 11, 1	1				
2 adjacent zones					
Zone 1, 2	1				
Zone 2, 2	1	0,447328	0,50393	0,048742	
Zone 3, 2	1	0,461613	0,494243	0,044144	
Zone 4, 2	1	0,459885	0,495421	0,044693	
Zone 5, 2	1	0,444237	0,506008	0,049755	
Zone 6, 2	1	0,438396	0,509918	0,051687	
Zone 7, 2	1	0,446656	0,267378	0,237005	0,048961
Zone 8, 2	1	0,733189	0,223934	0,042876	
Zone 9, 2	1	0,771784	0,197051	0,031164	
Zone 10, 2	1	1			

Zones	Total v	v 1	v 2	v 3	v 4	v 5	v 6	v 7
1 adjacent zone								
Zone 1, 1	1	0,018909	0,369231	0,317128	0,294732			
Zone 2, 1	1		0,38814	0,317128	0,294732			
Zone 3, 1	1		0,167627	0,307692	0,229949	0,294732		
Zone 4, 1	1		0,167627	0,307692	0,229949	0,294732		
Zone 5, 1	1		0,167627	0,307692	0,229949	0,294732		
Zone 6, 1	1		0,167627	0,307692	0,229949	0,294732		
Zone 7, 1	1		0,429166	0,276103	0,294732			
Zone 8, 1	1		0,429166	0,276103	0,294732			
Zone 9, 1	1		0,429166	0,276103	0,294732			
Zone 10, 1	1			1				
Zone 11, 1	1	0,705268		1				
2 adjacent zones								
Zone 1, 2	1		0,018909	0,369231	0,317128	0,294732		
Zone 2, 2	1		0,167627	0,220513	0,087179	0,229949	0,294732	
Zone 3, 2	1		0,167627	0,307692	0,229949	0,294732		
Zone 4, 2	1		0,167627	0,307692	0,229949	0,294732		
Zone 5, 2	1		0,167627	0,307692	0,229949	0,294732		
Zone 6, 2	1		0,167627	0,261538	0,046154	0,229949	0,294732	
Zone 7, 2	1		0,429166	0,276103	0,294732			
Zone 8, 2	1		0,429166	0,276103	0,294732			
Zone 9, 2	1		0,429166	0,276103		1		
Zone 10, 2	1		0,705268		1			

Results for each damage case which contributes to the index *A* include the draught, trim, heel, *GM* in damaged condition. Probabilistic values *p* and *v* with the dimension of the damage and righting lever curve (incl. GZ_{max} and range) with factor of survivability s is calculated as well.

According to the MSC.216(82) [7] each calculation is conducted for the partial attained index *A* in the various draughts which likewise have to exceed the partial required index *R*.

For each loading condition the obtained results were:

ds - *As* = 0,6995, which exceeds the required partial index *Rs* = 0,32
dp - *Ap* = 0,9238, which exceeds the required partial index *Rp* = 0,32
dl - *Al* = 0,974 , which exceeds the required partial index *Rl* = 0,32

The total attained index using eq. (11) is then,

$A = 0.4 \cdot 0{,}6995 + 0.4 \cdot 0{,}9238 + 0.2 \cdot 0{,}974 = 0{,}838$

Since $R = 0{,}64$,

$0{,}838 > 0{,}64$

which leads to conclusion that the subdivision is performed properly. The same configuration has been updated using a more detailed model. An attained index of *A* = 0.821 was obtained. A fully detailed structure and its effect on the attained index is not the aim of this paper but based on this some preliminary findings it can be observed that the differences between the simplified and more complex model are rather small and comply very well to the results reported in [17] for a container ship. Normally, the differences are slightly larger for the exact subdivision of the ship usually caused by slightly different interpretations of *b* and *r*.

The more detailed subdivision generally has lower attained index than the simplified subdivision [18]. But overall even for a limited and only preliminary research a tendency that simplified modelling of subdivision can give an indication of the attained index, is very useful for preliminary stage of design.

To check compliance based on the *GM* or *KG* limiting curves obtained from damage stability calculations of each trim, an envelope curve covering all calculated trim values should be developed. The limiting envelope curve presents minimum operational metacentric heights (or *KG* values) which meet all stability criteria for draught range from lightship draught to maximum draught. Resulting values were acceptable for all three draughts.

4. Discussion of the results

The fact is that the container ship is chosen randomly because the structural arrangement was at our disposal. It is therefore even more interesting that a comparison between deterministic and probabilistic method yielded different outcomes. However, for a reasoning one has to come back to the new harmonised regulations. There, it states that all weathertight and unprotected openings have to be taken into account as they can have a large effect on the attained index instead of the margin line.

The margin line definition is therefore no longer in the regulations while for instance evacuation routes have been included instead. Margin line which is replaced by watertight hatches, horizontal escape routes on bulkhead deck for probabilistic method produced a different outcome as compared to deterministic method. The very reason probabilistic method complied with the rules is the absence of margin line requirement. Even if there is a problem like that for the probabilistic method (not in our case) shifting these vulnerable points as near to the centre-line as possible means that considerable areas of the main deck can now be flooded after damage.

However as reported in [18] for a similar container ship the calculations showed that at the full load draught *ds*, damage to either of the two forward container holds or to the foremost of the after holds (which is similar as in predetermine deterministic case) would result in capsize. Same was reported for a 2-compartment damage to the after container hold and the engine room and most of the cargo holds. It may indicate that new regulations can be a somewhat poor survivability standard. Of course, different subdivision arrangement alters the *A*-index so we cannot draw a direct parallel to the ship examined in [18].

On the other hand, the probability of damage to two or more adjacent compartments involves the subtraction of the probabilities of the smaller damages. It's not as much that there aren't many accidents documented that lie near the aft and fore of the vessel's hull but based on the damage statistics most of these damages are smaller in extent. In the forward and aft regions of a ship, where the waterlines are narrowing, this may lead to very small probabilities. The software itself omits cases where the probability of damage is lower than a certain threshold which could explain the above.

Something similar was reported in [19] but to the damage cases which can occur, according to the system of regulations, which lie outside the vessel's hull (stem regions).

Loading conditions comply with both probabilistic and Two Compartment standard deterministic even though new harmonised rules no longer give any reference to One or Two compartment standard. Two compartment standard is more onerous since the damage extent has to be predetermined.

Probabilistic analysis requires more damage cases on top of which the modelling of the ship in Maxsurf is very detailed. There is one big benefit of the probabilistic model and that is that simplifications in subdivision can be made and yet still the resulting *A*-index value is close to the actual one for the ship in question. This approach requires a less amount of computational power which would normally take for a fully detailed ship. Probabilistic approach is thus less rigid in the positioning of bulkheads, so one can use a simplified compartment arrangement that could accelerate the optimization procedure of the ship subdivision.

Finally, quite recently Koelman [20] proposed an update to the probabilistic assessment of container ship stability. The main idea is that the stability assessment is not based on two sharp values of ship weight and KG, but on probability distributions of weight and KG instead. Given the two probability distribution functions (for ship weight and KG) and the accepted capsize probabilities, upper and lower limits of weight and KG can be determined resulting in more sufficient stability criteria.

5. Conclusion and further work

The paper presented state of the art methods and trends with respect to damage stability, especially concerning regulations. Truth to be told “golden age” of this research was about a decade ago upon which new harmonised rules were installed. Even though this paper confirmed most of already known which were backed up by references there still are some issues that were raised by this research. Mostly it concerned uneven results from the deterministic and probabilistic methods for a bow region damage scenarios but also for some case studies already reported.

There is a tendency from deterministic to probabilistic methods, to tackle container ship stability problem in a fully probabilistic way. Since realistic scenarios are hard to predict with deterministic method they are slowly being replaced with probabilistic methods [8]. As an individual study with only one ship and one subdivision (modelled based on the existing ship) there are still uncertainties related to the results because of limitations, simplifications and assumptions made. In order to give full clarity of the questions raised this study should be broadened to:

- Investigating different types of ship
- Optimisation of the subdivision knowing that even simplified results yield satisfactory attained index
- Using a different software (such as in-house) Foran as a benchmark study

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Pregled najnovijih trendova u procjeni stabiliteta u oštećenom stanju s primjenom na kontejnerski brod

Sažetak

Ovaj rad daje pregled postupaka projektiranja i osvrt na recentne radove objavljene na temu stabiliteta u oštećenom stanju i kriterijima procjene sigurnosti koji se u skladu s tim utvrđuju. Drugi aspekt rada čini rasprava o nekim problematičnim aspektima propisa vezanih uz praktične primjere provjere stabiliteta u oštećenom stanju koji su literaturi vrlo rijetki i činjenicom da različiti računalni programi mogu dati drugačije ishode.
Prikazan je i osvrt na kriterije stabiliteta u oštećenom stanju. Provjera stabiliteta izvedena je na odabranom kontejnerskom brodu koristeći Maxsurf softver gdje su identificirani i kategorizirani parametri vezani uz simuliranje oštećenje trupa za deterministički i vjerojatnosni pristup kod stabiliteta u oštećenom stanju.

Ključne riječi: stabilitet, oštećeno stanje, pravila, deterministički, vjerojatnosni