Probabilistic Approach to Assessment of Damage Survivability of Cargo Ships

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Abstract: *This paper deals with use of the new SOLAS 2009 probabilistic approach to the assessment of damage survivability of a cargo vessel. Method is used for an existing cargo vessel to assess the level of survivability. Further the influence of height to the center of gravity (or GM) and permeability of cargo spaces are also investigated. The rationality of the approach is demonstrated taking into consideration various possible damage scenarios and their influence on the overall survivability index. The regulation defined the maximum height of the center of gravity to be used as limits given by the intact stability conditions. However in reality KG values of the loaded ship varies significantly and the influence this change to the attained index of subdivision and level of survivability is discussed here.*

I. BACKGROUND

Shortly afterward of the Titanic Disaster in 1912 the need for damage stability regulations and a criteria of assessment have been realized. Subsequently guidelines for subdivision and positioning of watertight transverse bulkheads were developed for passenger ships based on floodable length and factor of subdivision. This approach was known as deterministic method in which survivability is assessed for cases when damage to single compartment, two adjacent compartments etc. depending on length of the ship. In 1973 IMO assembly adopted regulation on subdivision and damage stability of passenger ships based on the probabilistic concepts by resolution A.265(VIII) as an alternative approach. After the Herald of Free Enterprise (Ro-Ro Ferry) disaster in 1987, there had been significant studies and work on flooding and damage survivability of ships. In 1992 a new section to SOLAS Chapter II-1 (part B-1) entered into force as applicable to cargo ships, including Ro-Ro ships, on the subdivision and damage stability based on the probabilistic approach[1]. Initially regulations were adopted for ships over 100m in length. In this criterion, an index called attained index of subdivision (A) is estimated on the basis of the summation of the product of probability of flooding and probability of survival estimated for all single compartment and group of compartments (group of 2 adjacent, or 3 adjacent etc.) for all possible cases of flooding[3].

$$A = \sum_{i=1}^{n} p_i s_i$$

Here p_i represents the probability of flooding of i^{th} compartment or group of compartments disregarding any horizontal subdivision and s_i represent probability of survival after flooding to i^{th} compartment or group of compartments under consideration.

The estimation of factor p_i *is* given in the regulation and based on the statistics of past damage cases and s_i will be estimated from the damage stability calculation using righting lever of the damaged ship.

For the compliance of the regulation the above index *A* should be greater than Required index of subdivision *R* which is based on the length of subdivision for cargo ships. Later in 2005 IMO subcommittee decided to combine cargo ship and passenger ship regulations together and presented as harmonized method in SOLAS 2009.

For Cargo ships, the index *A* has to be calculated for summer load draft (d_s), partial loaded draft(d_p) and light loaded (d_l) conditions and overall *A* is estimated with following weightages. Also different permeability values should be used for cargo spaces depending on the loaded draft. In 1992 regulations index was calculated as average of indexes corresponding to summer load and partial load drafts.

$A = 0.4\ A_s + 0.4A_p + 0.2\ A_l$

The required index of subdivision for cargo ships above 100m in length is given as

$$R = 1 - \frac{128}{L_s + 152}$$

where L_s is length of subdivision.

For ships not greater than 100m but not less than 80m in length, *R* is given by

$$R = 1 - \frac{1}{1 + \frac{L_s}{100}\frac{R_o}{1 - R_o}}$$ where R_o is the value of *R* according to the previous formula.

II. CASE STUDY.

The above regulations are applied for a general cargo vessel built prior to 1992. This was a requirement by the classification society to check that the vessel can attain present probabilistic standards. The vessel has following basic dimensions and capacities.

Length Overall	= 158.87 m
Length between Perpendiculars	= 145.00 m
Breadth	= 22.80 m
Depth	= 13.40 m
Summer load draft (d_s)	= 9.94 m
Displacement at d_s	= 23890 tonne
Maximum allowable KG	= 9.27 m

1) *Light Service Condition:*

Light service condition is defined as the ballast condition of the vessel with 10% consumables

Displacement	= 10388.3 tonne
Mean draft (d_l)	= 4.74 m
Trim (by stern)	= 2.53m
Maximum Allowable KG	= 10.25m

2) *Partial Loaded Condition*:

Partial loaded draft is given by the light draft plus the 60% of the difference between summer loaded draft and light service draft.

Partial Loaded Draft (d_p)	=7.86 m
Displacement at this draft	= 17689.0 tonne
Maximum Allowable KG	= 9.02 m

The center of gravity values given here are the limiting values given in the intact stability booklet of the vessel. However investigations are carried out for different KG values and the sensitivity of KG to the attained index of subdivision is shown below.

The compartments and damage zones definition with compartment boundaries are given in the annex. Total number of watertight spaces are defined in accordance with the subdivision arrangement as 26 and number of single damage zones are taken as 8 as defined in the appendix. A particular single damage zone is selected as the one bounded by two adjacent transverse bulkhead with appropriate bottom tanks.

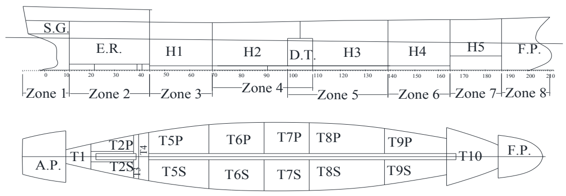


Figure 1. Tanks and Hold Arrangement

When selecting single damage zones both holds below and above tween deck, and relevant tank(s) are considered together assuming damage below tank top does not extends beyond the centerline bulkhead as given in section 3 of appendix. This combination would results in unsymmetrical flooding in the double bottom tanks that may give a worse condition than assuming pure symmetrical flooding.

Any combinations of adjacent zones are considered as summation of such compartments or tanks.

A. *Damage Stability Calculations*

Damage Stability computation is based on the Lost Buoyancy principle considering final equilibrium waterline. The method is being used along with free trim floating condition. The program performs several iterations until displacement and free trim equilibrium conditions are satisfied for a specified angle of heel. Damage vessel is being inclined to set of predefined angles of heel and then midship draft, trim and location of center of buoyancy are estimated once the displacement and free trim conditions are met. Righting lever of the damaged vessel is estimated at such predefined angles of heel using the coordinates of the center of buoyancy considering three dimensional inclination of the vessel. Angle of opening immersion and the damage righting lever is very critical for evaluation of the probability of survival and hence use of free trim inclination of the ship is vital in estimating the status of the damaged ship. The software for damaged stability calculations and use of the regulations is developed by the author some time ago and has been used extensively. Any complicated damage zone can be input to the programme with set of sub compartment in which their boundaries can be defined. Permeability of each subspaces can be given separately. Appendix shows the results of such calculation for a particular damage case.

B. *Influence of Center of gravity KG*

Above loading conditions show the limiting values of center of gravity according to the intact stability requirement. However attained indexes were calculated for different KG values at the different loading conditions and then results are shown in Fig.2. These indexes were calculated based on the recommended permeability values in the regulations.

It was found that vessel attained low indexes at light load conditions because of the very low statical stability lever of the damaged ship. Attained indexes at partial load conditions are comparatively higher than light loaded conditions.

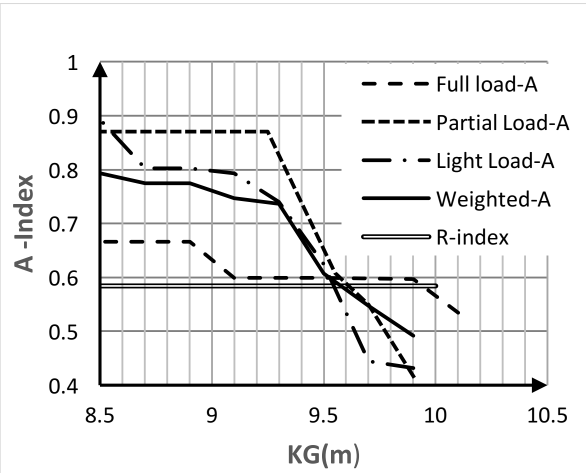


Figure 2. Attained index -A Vs KG(m)

When the center of gravity is above around 9.6m the individual indexes at all loading conditions and the weighted index seems to be falling below the required index. However the above results cannot be generalized as they depend on the vessel and it's intact stability conditions. According to the intact stability requirement light loaded KG is 10.25m but at this KG value the attained index is much lower than the required index and hence light loaded KG has to reduce further to satisfy the damage survivability condition.

Fig.3 shows the limiting values of KG according to intact stability and damage stability requirements.

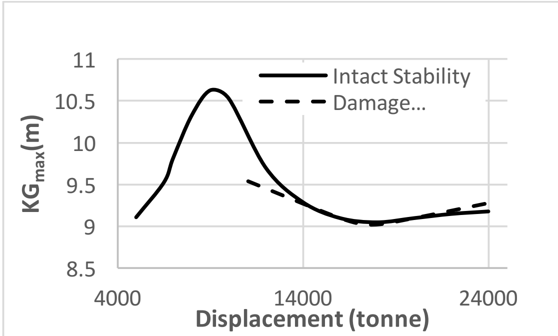


Figure 3. KG_{max} VS Displacement

Except for the light service condition when damage to any 3 adjacent zones, ship is not surviving. The most critical two adjacent case was the zone 5 + 6. When damage to zone 5+6 ship does not survive for almost all cases studied. Then the next critical case become zone 4+5. As the center of gravity rises the attained index start dropping due to the fact that probability of surviving s=0 when damage to firstly for 5+6, secondly for 4+5 and thirdly for 3+4 etc. Although the ship does not survive when damage above three 'two adjacent cases' simultaneously the attained index is greater than the required index of subdivision.

C. *Influence of cargo holds permeability*

Permeability values recommended by the SOLAS 2009 is more optimistic than SOLAS 1992 and hence there is not much room to study the sensitivity of the permeability of cargo hold to the attained index. When permeability of cargo spaces is raised to 0.8 at summer loaded condition there was no change in the index A for the same loading condition. Even for partial loaded condition there was no change in attained index A when the permeability is increased to 0.9. In this consideration, KG values are used as the limiting values given by intact stability requirement.

III. CONCLUSION

Application of the new regulation needs correct study and clear understanding of how to decide on different damage scenarios. Also particulars like locations of opening position and accurate estimation of righting lever of the damaged vessel are very important because level of survivability completely depend on such factors. Maximum values of the height of center of gravity that can be used during loading has to be re-evaluated for all vessels based on the new damage stability regulations and added to the intact stability booklet. Permeability values recommended by the regulations may reflect the worse condition of flooding for three loading conditions and hence seem to be reasonable compared with 1992 version. Further there is significant improvement in safety standards of SOLAS2009 compared with SOLAS1992 for dry cargo ships.

REFERENCES

Stability in damage conditions, SOLAS 74 as amended, chapter II-1, Part B, Regulation, Consolidated edition, International maritime Organization, London, UK 1997.

Papnikolaou.A, Design and safety of ro-ro passenger ships. In Handbuch de Werften Vol XXVI, 2002.

Cargo ships constructed on or after February 1992, SOLAS 74 as amended chapter-II-1, Part B-1, Regulation 25, Consolidated Edition, International maritime organization, London, UK 1997.

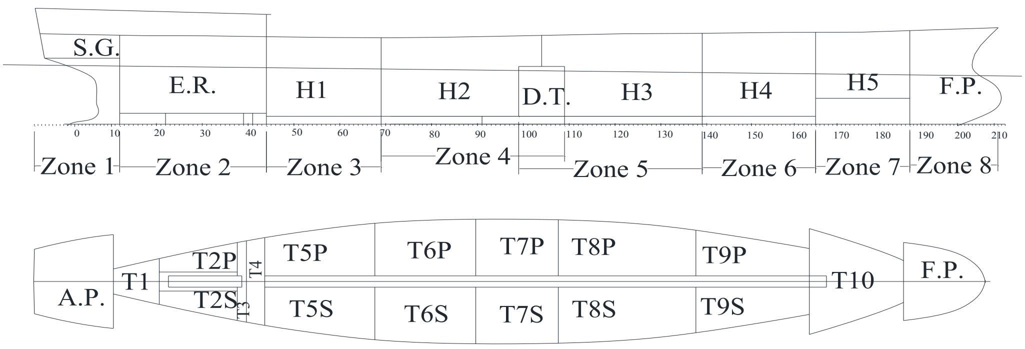
Papanikolaou.A and Eliopoulou.E**,** On development of the new harmonized damage stability regulations for dry cargo and passenger ships. Reliability Engineering System Safety, 2008.

Miguel Palomares**,** IMO development on intact and damage stability The work of the SLF subcommittee. 8th Intentional conference on Stability of Ships and ocean Vehicles,2003.

Herbert J, Koelaman, A new method for probabilistic damage stability. Ship technology Research Vol. 53-2006.

A Francescutto and A D Papanikolaou**.** Buoyancy, stability, and subdivision: from Archimedes to SOLAS 2009 and the way ahead. Proc. IMechE Vol. 225 Part M: J. Engineering for the Maritime Environment 2010

Appendix



Definition of Damage Zones

1.0 Numbering of Tank

Name	Nomenclature	Location	Distance from Aft. Terminal (m) Aft Blkhd		Fwd Blkhd
Aft Peak	A.P.	Fr(-10)- Fr12	0.00	-	13.2
Steering Gear	S.G.	Fr(-10)- Fr12	0.00	-	13.2
Tank 14	T1	Fr12- Fr22	13.2	-	20.7
Tank 15	T2S	Fr22- Fr39	20.7	-	33.45
Tank 16	T2P	Fr22- Fr39	20.7	-	33.45
Tank 7	T3	Fr39- Fr41	33.45	-	34.95
Tank 6	T4	Fr41- Fr44	34.95	-	37.2
Tank 5SB	T5S	Fr44- Fr69	37.2	-	55.95
Tank5P	T5P	Fr44- Fr69	37.2	-	55.95
Tank 4SB	T6S	Fr69- Fr91	55.95	-	72.45
Tank 4P	T6P	Fr69- Fr91	55.95	-	72.45
Deep Tank	D.T.	Fr99- Fr109	78.45	-	85.95
Tank 3ASB	T7S	Fr91- Fr109	72.45	-	85.95
Tank 3AP	T7P	Fr91- Fr109	72.45	-	85.95
Tank 3SB	T8S	Fr109-Fr139	85.95	-	108.45
Tank 3P	T8P	Fr109-Fr139	85.95	-	108.45
Tank 2SB	T9S	Fr139-Fr165	108.45	-	127.00
Tank 2P	T9P	Fr139-Fr165	108.45	-	127.00
Tank 1	T10	Fr165-Fr187	127.0	-	142.4
Fore Peak	F.P.	Fr187-F.E.	142.4	-	156.0
Engine Room	E.R.	Fr12-Fr44	13.2	-	37.2

2.0 Numbering of Cargo Holds

Name	Nomenclature	Location	Distance from Aft. Terminal (m) Aft Blkhd		Fwd Blkhd	Length
Hold 5 + TD 5	H1+ TD5	Fr44- Fr69	37.2	-	55.95	18.75

Hold 4 + TD 4	H2 + TD4	Fr69- Fr104	55.95	-	82.2	26.25
Hold 3 + TD 3	H3 + TD3	Fr104- Fr139	82.2	-	108.45	26.25
Hold 2 + TD 2	H4 + TD2	Fr139- Fr165	108.45	-	127.0	18.55
Hold 1 + TD 1	H5 + TD1	Fr165- Fr187	127.0	-	142.4	15.40

Note : - TD – Tween Deck

3.0 Damage Compartments Boundaries and Flooding Cases

The following Zones are defined to consider as ***single compartment cases*** or floodable space bounded by two adjacent bulkhead. Then the combination of two adjacent and three adjacent are also considered in the same manner as Zone1 +Zone2 , Zone2 + Zone3 etc.

Zone No.	**Location**	**Normalized Blkhd Positions**		**Length (m)**	**Included Compartments**
		Aft Blkhd	**Fwd Blkhd**		
1	Fr(-10) - Fr12	0.00	- 0.0846	13.2	A.P.+S.G.
2	Fr12 - Fr44	0.0846	- 0.2384	24.00	T1+ T2S+ T3+ T4 + E.R.
3	Fr44 - Fr69	0.2384	- 0.3586	18.75	T5S+H1+DK
4	Fr69 - Fr104	0.3586	- 0.5269	26.25	T6S+ T7S+D.T.+ H2
5	Fr104 - Fr139	0.5269	- 0.6952	26.25	T7S+T8S+ D.T.+ H3
6	Fr139 - Fr165	0.6952	- 0.8141	18.55	T9S + H4
7	Fr165 - Fr187	0.8141	- 0.9128	15.4	T10 + H5
8	Fr187 - F.E.	0.9128	- 1.000	13.6	F.P

4.0 Combination of Two adjacent units

Zone No.	**Location**	**Normalized Blkhd Positions**		**Length (m)**	**Included Compartments**
		Aft Blkhd	**Fwd Blkhd**		
1 + 2	Fr-10 - Fr44	0.0000	- 0.2384	37.190	A.P.+S.G.+T1+T2s+T3 +T4+E.R.
2 + 3	Fr12 - Fr69	0.0846	- 0.3586	42.744	T1+T2s+T3 +T4+E.R + T5S+H1 + TD1
3 + 4	Fr44 - Fr104	0.2384	- 0 .5269	45.006	T5S+H1+ T6S+ T7S+D.T.+ H2 + TD2
4 + 5	Fr 69 - Fr139	0.3586	- 0.6952	52.510	T6S+ T7S+D.T.+ H2 + T8S.+ H3 + TD3
5 + 6	Fr104 - Fr165	0.5269	- 0.8141	44.803	T7S+T8S+ D.T.+ H3 + T9S + H4+ TD4
6 + 7	Fr139 - Fr187	0.6952	- 0.9128	33.946	T9S + H4 + T10 + H5 +TD5
7 + 8	Fr165 - F.E.	0.8141	- 1.000	29.00	T10 + H5 + F.P.

5.0 Position of Weathertight and Non-weathertight Openings

The following table shows that coordinates of weathertight and non-weathertight openings

Opening	**Position in meters**		
	Long (X)	**Transverse (Y)**	**Vertical (Z)**
Superstructure door (non-weathertight)	12.6	3.0	22.23
AH1 (weathertight) – No.1	8.4	7.0	18.0
AH2 (weathertight) - No.2	24.6	11.2	14.0
AH3 (weathertight) – No.3	71.1	11.2	14.0
AH4 (weathertight) – No.4	85.4	11.2	14.0
AH5 (weathertight) – No.5	107.1	5.0	14.0
AH6 (weathertight) – No.6	125.8	11.2	14.0
AH6 (weathertight) – No.7	140.4	0.6	15.2

X- Distance from aft perpendicular, Y- Distance from centerline, Z-Height from baseline

6.0 Results of Damage Stability Assessment for a Zone 2

Loading condition

Displacement = 23789.8 t Draft = 9.9400 ,KG= 9.300 LCG = 77.904

Righting lever and damage stability particulars (at the FINAL stage of flooding) when damage to Zone No. 2

BOUNDARY OF ZONE. X1/L = .085 AND X2/L = .238

SUB-COM NO.& TYPE		AFT BLK	FOR BLK	LLT	ULT	PERM
1	0	.085	.133	.000	1.925	.950
2	3	.133	.214	.000	1.925	.950
3	0	.214	.238	.000	1.925	.950
4	0	.085	.238	1.925	0.000	.850

Ang.heel (deg)	Ang.trim (deg)	Tmid (m)	Vol.Displat (m3)	CBx (m)	CBy (m)	CBz (m)	GZ (m)
.000	-2.148	10.909	23209.57	77.761	-.008	5.797	-.008
2.000	-2.003	10.864	23210.34	77.785	.157	5.804	.035
5.000	-1.878	10.813	23207.78	77.791	.387	5.825	.083
10.000	-1.627	10.664	23208.12	77.805	.806	5.900	.204
15.000	-1.591	10.509	23209.61	77.809	1.230	6.025	.340
20.000	-1.883	10.451	23209.64	77.802	1.595	6.174	.430
25.000	-2.257	10.572	23209.85	77.787	1.856	6.300	.414
30.000	-2.649	10.825	23209.74	77.770	2.055	6.413	.336
35.000	-3.099	11.194	23209.57	77.758	2.222	6.526	.229
40.000	-3.699	11.688	23209.58	77.732	2.368	6.651	.112
45.000	-4.399	12.339	23208.24	77.709	2.491	6.774	-.024
50.000	-5.190	13.154	23209.71	77.687	2.599	6.896	-.171

Angle at deck immersion = 0.000deg
Angle at opening immersion = 49.293deg
Angle at closed weathertight immersion = 8.921deg at opening No. 2
Angle at stability vanishes = 44.105deg
Angle of equilibrium = 0.363deg
GM_T at equilibrium = 1.232m
GZmax(m) = 0.116 m