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on Ship Stability

by

Prof. Dr. M. A. Shama

1- Shama, M. A., (UK-1968) "A Method for Calculating Ship Stability Curves", Shipbuilding and Shipping Record, Aug.
2- Shama, M. A., (UK-1969) "A Computer Program for Ship Stability Curves", Shipbuilding and Shipping Record, May.
3- Shama, M. A., (UK-1975) "The Risk of Losing Stability", Shipping World and Ship, Oct.
4- Shama, M. A., (Germany-1976) "On the Probability of Ship Capsizing", Schiff und Hafen, Sept.
5- Shama, M. A., (Egypt-1989) "Safety Requirements for Nile Tourist Vessels", Seminar on Future of Nile Tourism in Egypt, (In Arabic), Alex., Eng. Journal, Vol.28, No.2, April.
6- Shama, M. A., (Egypt-1993) "Ship Stability Assessment, Criteria & Risk", AEJ, July.
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SHIP STABILITY, ASSESSMENT, CRITERIA AND RISK*

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SUMMARY

The various approaches to the assessment of ship stability are presented. The main components of heeling moments are given. The heeling moments affecting certain types of ships are indicated. Both deterministic and probabilistic approaches are considered. The different stability criteria currently used for intact and damage conditions are given. Special attention is given to the modern approach based on risk analysis. The intact and damage stability problems of Ro/Ro ferries are identified. It is concluded that efforts should be directed to develop our National Stability Criteria for ships operating in the River Nile and in our coastal waters. These criteria should be based on probabilistic concepts and should take account of our environmental and operational conditions.

INTRODUCTION

The phenomenon of stability of any system, in general, could be represented and explained by the state of equilibrium of forces acting on the system. The state of equilibrium of the system of forces could be either stable or unstable. When finite small deviations occur, after subjecting a system of forces to a small disturbing force, the state of equilibrium is considered stable. Conversely, when large deviations occur, the state of equilibrium is unstable. This definition could easily explain the problem of intact stability of ships and any floating structure.

Ship stability is considered as one of the major seagoing properties of a ship. It has a direct impact on ship and passenger safety. Inadequate ship stability or ignorance of the impact of its deficiency on ship safety has caused many ships to capsize with loss of thousands of passenger lives [1,2]. At small angles of inclination, the stability of displacement vessels is measured by the metacentric height, GM. At large angles of inclination, the statical stability curve is normally used.

The magnitude of GM depends on cargo distribution, form and geometry of vessel, sea condition and speed of vessel. On a wave crest and in a following sea, GM may be seriously affected. The carriage of deck cargo also has an adverse effect on GM. The presence of slack tanks induces free surface effect which has an impairing effect on GM. Consequently, GM should be treated as a random variable since the main parameters affecting its magnitude are not deterministic quantities. This necessitates relating the assigned values of GM with the probability of losing it.

Under dynamic conditions, ship stability is measured by the area under the statical stability curve. The latter is normally obtained from the cross curves of stability. Various methods are available for the calculation of these curves. These methods, however, are based on the assumption that inertia forces and hydrodynamic pressure are neglected. Therefore, experimental and theoretical methods are proposed to determine ship stability among waves. Because of the random variation of the main parameters affecting the shape and area of the statical stability curve, the characteristics of the latter are subjected to elements of uncertainties and therefore should be treated as random variables. Consequently, the reserve of dynamical stability should be associated with the risk of capsizing since the external forces acting on a ship among waves are random in nature.

In this paper, the basic concepts of rational stability

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criteria are presented so as to give proper foundations for the establishment of our National Stability Criteria for Inland Passenger Ships and for ships operating in our coastal waters.

1. SHIP SURVIVAL CAPABILITY

Ship survival capability could be measured by the following basic items of ship stability:

1.1 Initial Stability

Initial stability of displacement vessels is defined by the distance between ships' C.G. and the metacenter M_o. A floating ship has a stable equilibrium, at small angles of inclination, when:

$$GM > 0$$

However, GM cannot be used solely as a measure of ship stability. A ship having a high GM value and a deficient statical stability curve is inferior to a ship with a lower GM value and superior statical stability curve, see Figure (1).

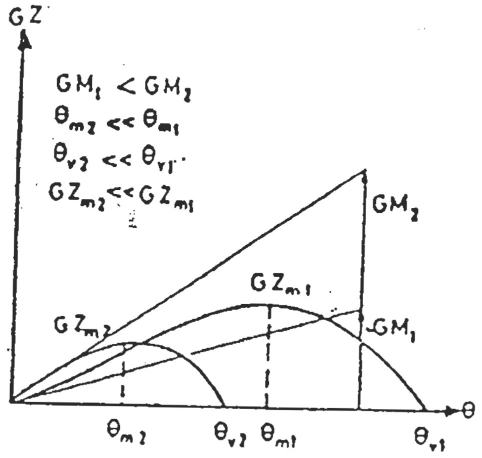


Figure 1. Effect of GM.

The minimum GM should satisfy the following relation:

$$GM_{min} = GM_o - GM_R > 0$$

where:

GM_o = intact initial value of GM

GM_R = residual GM after flooding > 0

The initial stability GM_o is generally given by:

$$GM_o = KM - KG > 0$$

$$\text{i.e. } KM/KG > 1.0$$

Both KM and KG are random variables dependent on several parameters. Therefore, GM_o is also a random variable, see Figure (2).

Assuming statistical independence, the risk of losing GM_o could be calculated as follows [3]:

$$\text{Risk} = P\,(GM_o \le 0) = \int_{-\infty}^{0} p\,(GM_o)\,dGM_o$$

where $p\,(GM_o)$ = p.d.f. of GM_o

It should be indicated here that losing initial stability does not necessarily lead to capsizing but may cause the ship to attain a list whose magnitude depends on the shape of the statical stability curve.

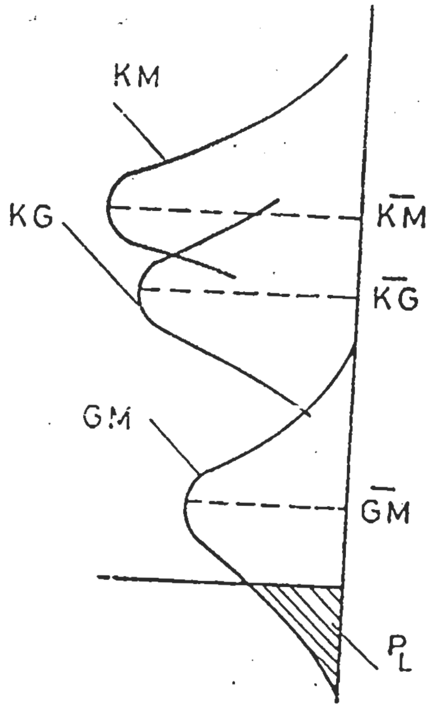


Figure 2. Demand and capability.

1.2 Dynamical Stability

It represents the work done by the righting moment to inclining the ship through an angle "θ" and is given by:

$$M_d = \int_0^{\theta} \Delta . GZ . d\theta$$

where: Δ = ship displacement

The variation in the positions of the centres of buoyancy and gravity (B and G) during ship inclination play the principal role in the calculation of dynamical stability.

This definition, however, does not take into account inertia, hydrodynamic and friction forces. The calculations, therefore, are based on quasi-static conditions. The errors inherent in this assumption has not yet been fully identified [3].

1.3 Reserve of dynamical Stability (D_R)

The reserve of dynamical stability is given by [4]:

$$D_R = D_S - D_H > 0$$

where: D_S = Dynamical stability

D_H = Work done by an arbitrary heeling moment, see Figure (3).

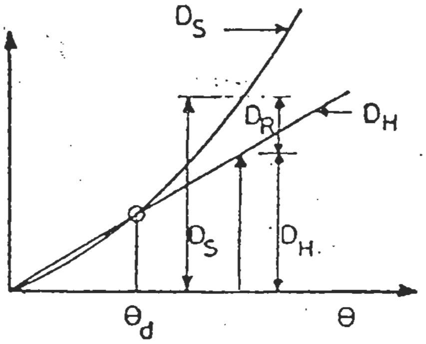


Figure 3. Dynamic angle of heel and margin of safety.

2. RISK OF CAPSIZING (R)

The risk of capsizing could be calculated from the p.d.f. of the Reserve of Dynamical Stability "D_R", as follows [4]:

$$R = P(D_R \le 0) = \int_{-\infty}^{0} p(D_R)\, d D_R$$

The p.d.f. of "D_R" could be obtained from the p.d.f. of the various parameters affecting D_R, such as:

- initial stability, GM_o
- magnitude of maximum righting arm, GZ_m
- angle at which GZ_m occurs
- angle of vanishing stability, θ_v

Let, $D_R = N(\bar{D}_R, \sigma_{D_R})$

$$\beta = \bar{D}_R / \sigma_{D_R}$$

Then: $\bar{D}_R = \bar{D}_S - \bar{D}_H$

$$\sigma_{D_R} = \left\{\sigma^2_{D_S} + \sigma^2_{D_H}\right\}^{1/2}$$

$$R = 1 - \phi(\beta)$$

where: β = safety index

$\phi(\beta)$ = cumulative distribution function of the standard normal p.d.f.

The variation of "R" with β is shown in Figure (3). The effect of the assumed shape of the p.d.f. of both D_s and D_H on the value of the Risk is shown in Figure (4).

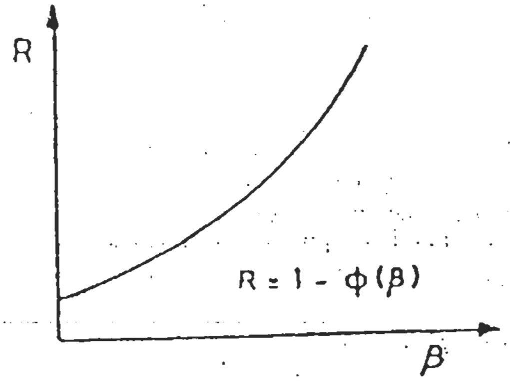


Figure 4. Variation of R with β.

3. DYNAMIC HEELING MOMENT "D_H"

There are several hazards affecting ship stability. The impact of one or more of these hazards may cause the ship to lose her stability and even capsize. The main types of these hazards are:

- Wind and Gust
- Waves
- Excessively high C.G.
- Shipping green water
- Towing
- Collision
- Grounding
- Growding of passengers
- Crowding of livestock
- High speed turning
- Excessive free surface in tanks
- Shifting of grain cargo
- Misuse of nozzle propellers
- Excessively high GM-Excessive Rolling
- Structural failure causing ingress of water
- Etc.

These hazards may induce static and dynamic heeling moments.

The total dynamic heeling moment is calculated from the various components of heeling moments acting on the ship. These heeling moments depend on ship type, size, trade, environment, zone of operation, etc.

3.1 Wind and Gust Heeling Moments

Although ship motions are usually associated with the effect of waves, it is often the additional effect of wind that determines whether or not the vessel will capsize. It is therefore vital that studies of extreme behaviour of vessels properly take account of wind loading.

3.2 *Wind Heeling Moment*

The wind heeling moment is given by [5]

$$M_w = \tfrac{1}{2} . \rho . C_D . A_p . H . \nu^2_w$$

where:

ρ = air density

C_D = drag coefficient

A_p = lateral projected area of vessel above operating waterline

H = vertical distance between centre of A_p and centre of underwater area

ν = wind velocity

3.3 *Angle of Heel Due to Wind Loading*

The angle of heel is given by:

$$\theta = M_w/GM. \Delta \leq \theta_w$$

Where: θ_w = maximum allowable angle

The variation of wind pressure with wind speed is given by:

ν_w (m/s)	15.5	26.5	34.8
p (kg/m^2)	20	50	70

4. HEELING MOMENT DUE TO TURNING OF SHIP

The heeling moment due to turning of ship is given by [6]:

$$M_t = 0.02 . \nu_s^2 . \Delta (KG - T/2)/ L \qquad \text{t.m.}$$

where

ν_s = service speed, m/s

Δ = ship displacement, tonnes

KG = height of C.G. of ship, m

T = ship draught, m

L = ship length, m

Angle of heel due to turning is given by:

$$\theta = M_t/GM. \Delta \leq \theta_T$$

where: θ_T = maximum allowable angle

5. HEELING MOMENT DUE TO CROWDING OF PASSENGERS

For passenger ships, an additional heeling moment due to crowding of passengers should be taken into account [6]. This heeling moment is given by:

$$M_p = W \left(\frac{B}{2} - a\right) \qquad \text{t.m}$$

where: W = weight of all passengers

The angle of heel due to crowding of passengers is given by:

$$\theta = M_p/GM.\ \Delta \le \theta_p$$

where: θ_p = maximum allowable angle

6. OTHER HEELING MOMENTS

There are additional heeling moments dependent on ship type and trade. The following are some examples:

- For Fishing Vessels, heeling moments due to net towing and shipping green water on deck should be taken into account, see Figure (5).

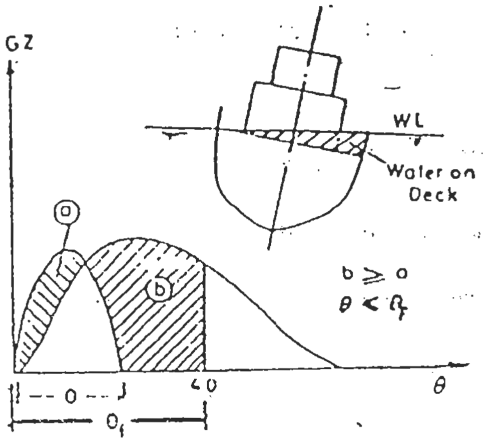
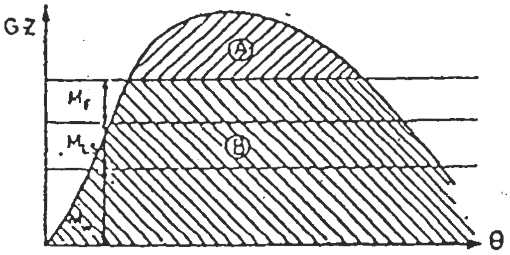


Figure 5. presence of water on deck.

- For Livestock Carriers, heeling moments due to shift of livestock and shift of fodder should be taken into account, see Figure (6).
- For Bulk Carriers, heeling moments due to grain shift should be taken into account, see Figure (7).



M_f = Moment Due to shift of Fodder.
M_{ls} = Moment Due to shift of Live stock.
M_w = Moment Due to wind.

Figure 6. Heeling moments for livestock carriers.

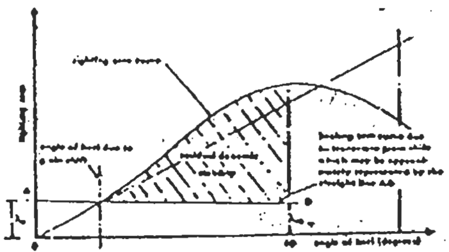


Figure 7. Heeling moment due to grain shift.

7. STABILITY CRITERIA

Compliance with stability criteria does not ensure immunity against capsizing. Masters should, therefore exercise good seamanship with regard to:

- season of the year
- weather forecasts
- navigational zone
- ship speed
- ship course
- competency of the crew
- etc.

7.1 Intact Stability Criteria

i. Initial GM

$$GM_0 > a$$

a is a value dependent on ship type and should depend on ship size and operational environment.

- Excessive GM_0 is to be avoided for seagoing ships since it may produce large accelerations which cause adverse effects on hull construction, crew, cargo, etc. The variation of period of rolling with GM_0 is shown in Figure (8).

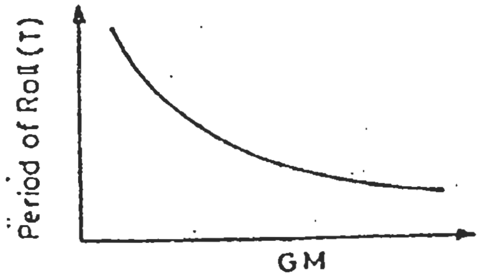


Figure 8. Variation of GM_0 with T.

- GM_0 should be corrected for free surface effects of slack tanks.

The (FSM) free surface moment could be estimated as follows: [6]

$$FSM = \nu . b\, \rho .\, k .\, \sqrt{\delta}$$

where:

ν = tank volume, m^3
l.b.h = tank maximum length, maximum breadth and maximum height
k = a dimensionless coefficient dependent on b/h

b/h	5	2	1	0.5	0.2
k	0.11	0.09	0.05	0.02	0.01

GM_o could be estimated by a Rolling Period Test and is given by:

$$GM_o = \left(\frac{f.B}{T_r}\right)^2$$

where

B = ship breadth, m
T_r = rolling period, seconds
f = a rolling period factor
= 0.88 for empty ship
= 0.78 for fully loaded ship with + 20% of total load liquids in tanks
= 0.73 for fully loaded ship with 5% of total load liquids in tanks

Curves of Minimum GM/Maximum KG should be provided to give the upper limit of KG for each loading condition.

ii. Statical Stability Curve

The IMO intact stability criteria is given by, see Figure (9):

$GZ\ max \geq \alpha$
ϕ at $GZ\ max \not< 30°$
$GM_o \geq \delta$
$\phi_\nu \geq \theta^*$, θ^* depends on ship type

where: ϕ_ν angle of vanishing stability

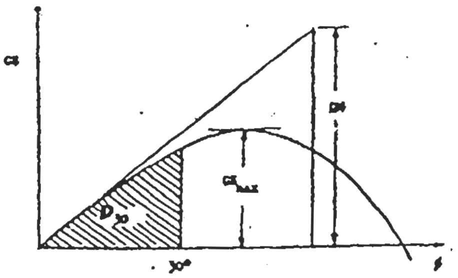


Figure 9. Intact IMO stability criteria.

iii. Dynamic Stability

IMO dynamic stability criteria are given by [6]:

$D_{\phi=30} \geq 0.055$ m. rad.
$D_{\phi=40/\theta f} \geq 0.09$ m. rad.
$D_{\phi=30\text{-}40} \geq 0.03$ m. rad.

iv. *Damage Stability Criteria*

The damage stability criteria is given by:

$GM_{residual} \geq b_1$

$(GM_m)_{residual} \geq b_2$

v- *Weather Criteria*

Several wind and rolling criteria, indicated by IMO Resolution, ensure the ability of a vessel to withstand the effect of beam winds and rolling, see Figure (10).

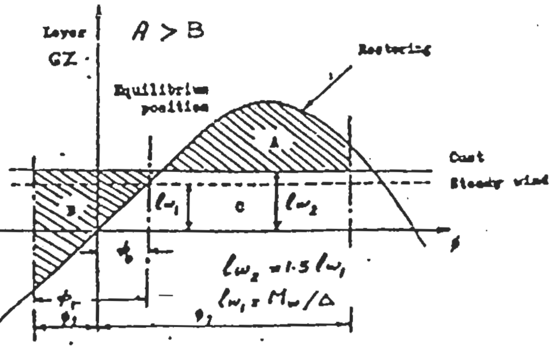


Figure 10. IMO weather criteria.

vi. *Probabilistic Criteria*

The risk of losing stability depends on [7]:

- Ship Capability (Survival Capability)
  - Initial Stability
  - Intact Stability
  - Damage Stability
- Demand
  - Various commponents of heeling moments
  - Uncertainties of all heeling moment parameters

-Various probabilities of collision, damage and survival. Figure (11) shows the probability of damage of a length "1" in a certain collision scenario.

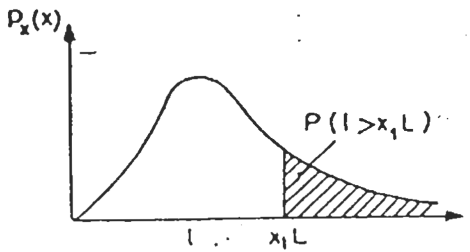


Figure 11. PDF of "l".

8. SUBDIVISION AND DAMAGE STABILITY

- On February 1st, 1992, all cargo ships, including Ro-RO vessels, should comply to IMO requirements for the subdivision and damage stability.
- The requirements apply to ships of 100m and more in length. This will have a major effect on the watertight compartmentation and the positions of bulkheads.
- These new requirements are based on probabilistic concepts instead of the deterministic procedures specified in existing codes and conventions.
- The method of assessing damage stability and the probability of survival of a proposed design is based on calculating the degree of subdivision required by calculating the Required Subdivision Index "R". The computation of the Subdivision Index involves calculations and analysis of "Residual Stability" in a large number of unique damage scenarios.

The subdivision Index is given by [8]

$$R = (C_1 + C_2 L_s)^{1/3}$$

where: $C_1 = 0.002$, $C_2 = 0.0009$

L_s = subdivision length

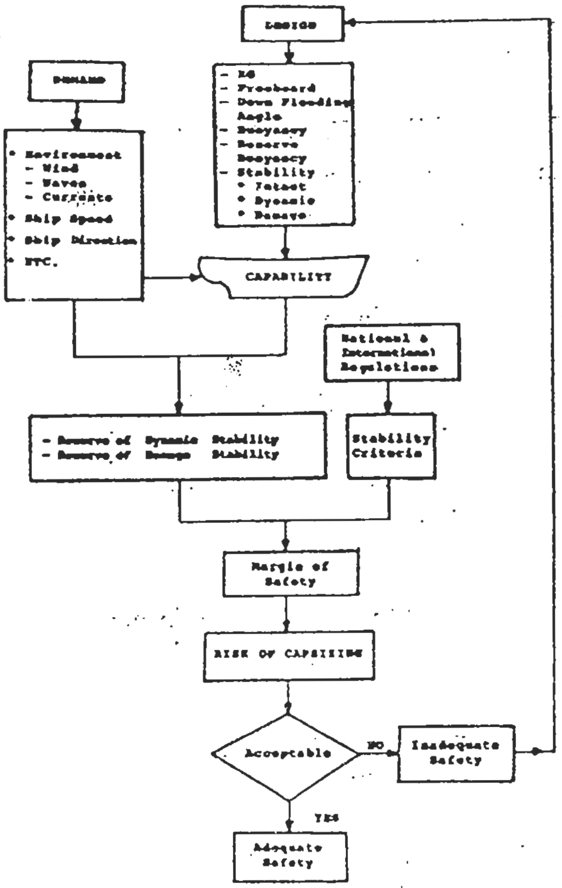


Figure 12. Demand, capability and risk.

The acceptable degree of survival could be attained when:

$$A \geq R$$

where

A = Attained Index = $\sum p_i s_i$, see Figure (13)
i = indicates flooding configuration
p_i = corresponding probability of accurance
s_i = corresponding probability of survival

- The degree of subdivision provided in ships to meet the new regulations will be affected by the Required Subdivision Index.
- The likelyhood of unacceptable damage occuring can be determined from ship structural configuration and the p.d.f. of: position of damage, length of damage, penetration of damage, permeability of damaged zone, occurence of accident, crew competence.

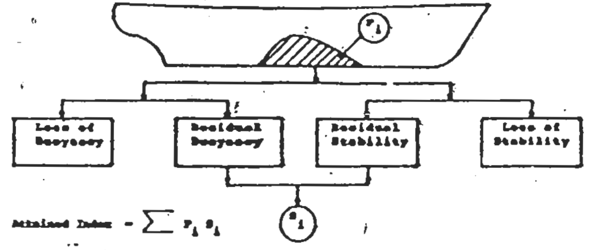


Figure 13. Attained index.

- An important aspect of safety in the event of damage is the existence of a damage control plan. This plan should give information on the possible consequences of flooding and instructions on how to control it. Figure (14) shows the consequences of damage and flooding of one or more compartments of a ship.
- The probability of survival of any ship after damage depends entirely on the degree of subdivision of the ship.
- It is evident that many bulkheads does not mean good watertight subdivision. The more bulkheads in a ship the higher the risk of breaching one of them in case of damage by collision. Different parts of the ship are exposed to different risk levels.

9. PROBABILISTIC APPROACH

- The probabilistic approach is based on the estimation of Risk.
- For general cairo ships, container ships, bulk carriers, etc., the Risk of foundering, as a result of hull damage or flooding of internal spaces was accepted. Crew protection was assumed to be provided by the compulsory life saving equipment.
- In the deterministic method, the dimensions and location of damage, as well as flooding configurations, are defined beforehand, and the residual stability of the ship is calculated for these assumptions.
- The floodable length procedure used to assess passenger ship subdivision, assume symmetrical flooding to an imaginary margin line and actually neglects actual loss of stability. The ship may lose her stability and capsize before she loses her reserve buoyancy.

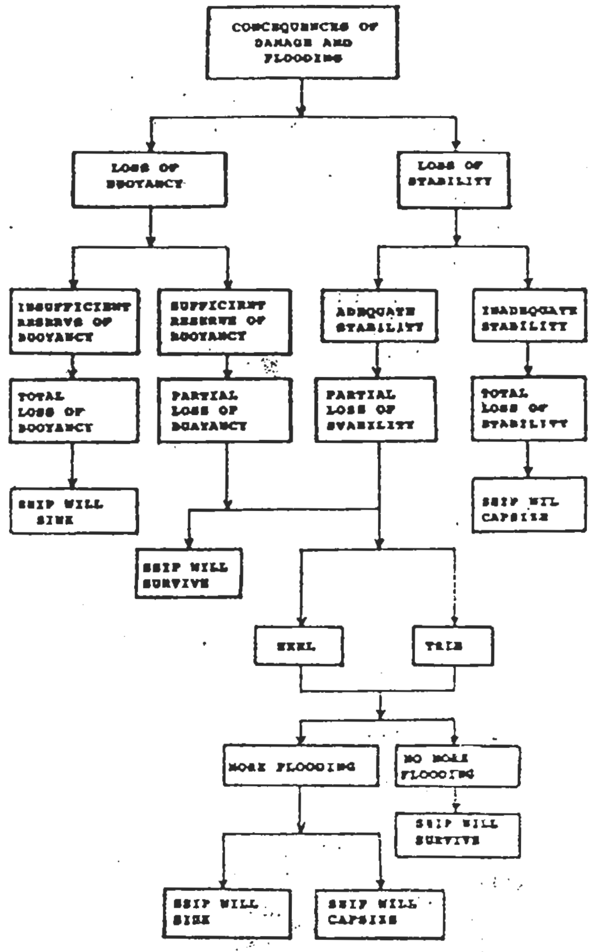


Figure 14. Consequences of damage and flooding.

- The probabilistic concept adopts a more rational approach by considering the likelyhood of collision resulting in the flooding of anyone compartment, or any number of adjacent compartments either transversely, longitudinally or vertically.
- The designer has to obtain an "Attained Index" for the ship which should not be less than the "Required Index", which expresses the minimum acceptable degree of survival. This approach allows for any possible flooding configuration.
- The probability of a ship having sufficient residual buoyancy and stability to survive each flooding configuration is assessed. The summation of all positive probabilities of survival gives the "Attained Subdivision Index".
- Risk analysis study could be based on:

- Casualty reports and records
- Identification of hazards involved, corresponding risks, methods to reduce those risks, i.e. effects of design parameters [8].
- Reduction of the extent of damage due to collision by examining the amount of energy which could be absorbed in a typical collision. This may require changes in the structural configuration and design of ships.
- Improving ship stability in a damaged condition for various scenarios of general arrangements.
- Evaluation of intact and damage stability using model tests of typical ship types such a RO/RO vessels.

10. STABILITY OF RO/RO SHIPS

- The standards of intact stability currently adopted for RO/RO ferries are adequate.
- RO/RO ships are more likely to capsize after events involving collision, stricking a fixed object, cargo shift or foundering than general cargo ships because of the entery of flood water to large open vehicle decks or engine room.
- It is important to identify the main factors involved in damage stability calculations, flooding mechanism, intermediate stages of flooding and the mechanism of capsizing.
- Residual stability standard should provide adequate values against capsizing under certain conditions.
- RO/RO vessels should comply with a higher damage stability requirements. Minimum amount of residual stability after damage to be ascertained and specified.
- RO/RO vessels should be designed to survive a prescribed extent of damage. If the actual damage is greater than the prescribed one, the vessel will not survive. The extent of damage is prescribed by the length, depth of penetration and height of the damaged part.
- Present measures to improve RO/RO safety are:
  - Indicator lights for bow/stern doors
  - T.V. cameras for bow/stern doors
  - physical and positive reporting system to ensure the closure of loading doors.
- No RO/RO or passenger vessel could be designed to withstand unlimited damage. Therefore, a degree of Risk is inevitable, which should be acceptable by all parties concerned as well as the public.

11. CONCLUSIONS

From the foregoing presentation, it is concluded that:

1- Initial stability cannot be solely used as a general measure of stability of displacement vessels.
2- The rational approach for assessing ship safety against capsizing should be based on probabilistic methods for both intact and damage conditions. A degree of Risk is inevitable which should be acceptable by all parties concerned as well as the public.
3- There is evident lack of knowledge on the variabilities of the various components of heeling moments affecting different ship types.
4- Compliance with currently used stability criteria does not ensure immunity against capsizing.
5- The degree of subdivision of new ships should comply with the Required Subdivision Index.
6- The risk of capsizing could be greatly improved by the provision of Damage Control Plan.
7- The increase in number of bulkheads does not mean good watertight subdivision.
8- No RO/RO or Passenger vessel could be designed to withstand unlimited extent of damage.
9- There is a definite need for developing our National Stability Criteria for the various types of ships operating in the River Nile and in our Coastal Waters. These criteria should take account of our environmental and operating conditions, among several other factors affecting ship safety.

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