The International Maritime Transport and Logistics Conference
Port & Logistics: "A Vision For Future Integration"
18 - 20 December 2011

Structural Safety of Ships -New Concept

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Abstract

This paper deals with the problem of double oil hull tanker loss due to the reduction of her longitudinal strength following a collision (and not due to lack of buoyancy or a stability which is another problem). For this purpose, the theoretical procedure which was developed by Hegazy [2003] to calculate the residual longitudinal strength of a struck ship after collision, is applied to double hull oil tanker to find out a relation between the extent of damage resulting from collision and the strength of the ship after collision. The residual strength of three double hull oil tankers is studied. The modulus of sections of these ships before and after damage were calculated and were compared with the minimum modulus of section required by the common structural rules. A new concept of structural safety for ship's hull is introduced based on the residual strength of ships after collision. In this way, the problem of collision between ships becomes a factor to be considered in the early stage of ships' design.

Keywords: Collision, Critical Penetration, Double Hull Tanker, Residual Longitudinal Strength, Modulus of section, Structural Safety.

Nomenclature

ABS	American Bureau of Shipping.
CSR	Common Structural Rules.
D	Moulded depth to upper deck. (m)
DHT	Double Hull Tanker.
f_{UD}	Ultimate longitudinal stress in ship deck. (kN/ m^2)
f_{UH}	Ultimate longitudinal stress in ship longitudinal bulkhead. (kN/ m^2)
f_{US}	Ultimate longitudinal stress in shipside. (kN/ m^2)
IACS	International Association of Classification Societies.
MARPOL	The International Conventions for the Prevention of pollution from ships.
VLCC	Very Large Crude Carrier.
$\propto_i$	Inner bottom area factor.
$\propto_o$	Outer bottom area factor.

α_D	Deck area factor.
α_H	Longitudinal bulkhead area factor.
α_s	Side area factor.
β	Ship double bottom height to the moulded depth ratio.
γ	Distance of the plastic neutral axis below the centre of deck area to moulded depth ratio.
$\emptyset_D$	Deck strength factor.
$\emptyset_H$	Longitudinal bulkhead strength factor.
$\emptyset_S$	Side strength factor.

1. Introduction:

The collision accidents continue to occur in spite of continuous efforts to prevent them. With the increasing demand for safety at sea and protection of the environment, it is of great interest to be able to predict an accident, assess its consequences and ultimately minimize the damage of an accident to ships and the environment.

There has been a growing interest in reducing the risk of oil spillage due to accidents involving oil tankers and other vessels which carry potentially polluting and / or hazardous cargo.

Oil spills happen when people make mistakes or are careless and cause an oil tanker to leak oil into the ocean. There are a few more ways an oil spill can occur. Equipment breaking down may cause an oil spill. If the equipment breaks down, the tanker may get stuck on shallow land, when they start to drive the tanker again, they can put a hole in the tanker causing it to leak oil.

Oil spills on the surface of the water are subjected to the weather, waves and currents which can carry the oil spills ashore. Rough seas can split an oil slick apart, carrying some oil in one direction and more in another. In contrast, a near shore oil spill can be totally controlled by currents and wave action that causes the oil to come ashore.

Oil is thick and sticks to everything it touches, while the most visual part of the damage might be the birds and wildlife, consider that the oil covers everything right down to a grain of sand. Every rock, every piece of driftwood, sand, soil and every microscopic habitat is destroyed. [1]

Marine and coastal life can be contaminated in a number of ways, through poison by destruction of habitat and direct contact with oil. Eating or drinking oil can cause any number of problems. Death is the obvious one. However, if an animal eats or drinks oil-saturated food, the effects might be longer reaching that simply making the animal ill.

People are not aware of the immediate impact to an animal's ability to mate and have viable offspring after being exposed to oil contamination. Direct contact with oil harms any animal that comes in contact with the oil. Bird's feathers are designed to repel water to protect the animal from the elements, in addition to allowing many birds to float on the water when resting or searching for food. When oil covers the feathers of a bird, it keeps the feather from repelling water. Oil also weighs down the bird, keeping it from flying. If a bird isn't cleaned of the oil, it's a sure license to death. Many birds ingest deadly amounts of oil trying to clean their feathers. The same

holds true for marine mammals. Marine mammal fur acts as an insulator to keep the animal warm in the coldest waters. When oil saturates the fur, it ruins the ability of the fur to retain heat. [1]
The double hull design concept is one of the effective ways for oil pollution prevention during collision and accidents of oil tankers. However, not all of the design requirements for structural scantlings and arrangements of double hulls are sufficiently well advanced.

Regarding to the concept of critical penetration which were introduced by Hegazy, some definitions which extend the traditional classification of ships' collision "major" and "minor", have been introduced as follows [2]

- **Minor collision**
  This is defined as one in which the cargo tanks remain intact, irrespective of whether the struck vessel in question has single or double skin.
- **Critical minor collision**
  This is the minor collision beyond which rupture of the struck ships' hull in way of a cargo tank occurs with the consequence of cargo spillage.
- **Major collision**
  This is used to describe a collision which causes large inelastic strains and fracture of the struck ship's hull in way of a cargo tank and the striking bow starts to penetrate the hull of the struck ship (i.e. oil spillage occurs).
- **Critical major collision**
  This is used to describe a major collision which causes a critical damage (i.e. critical penetration occurs) and, hence, the residual longitudinal strength of the struck ship will reach its critical value.
- **Back-break collision**
  This is used to describe a major collision which causes a severe damage and, hence, the struck ship will be broken into two due to the loss of her longitudinal strength after collision.
  Consequently, a ship may collapse after a collision because of inadequate longitudinal strength, and it is important to keep the residual strength of damaged ship after collision at a certain level in order to avoid additional catastrophic consequences.
  The main purpose of this study is to develop the theoretical calculations of the residual longitudinal strength of a struck double hull oil tanker after collision and compare it with the minimum requirements of the classification societies.

2. Literature survey:

Minorsky (1959) [3] introduced the most well known empirical approach to collision analysis. His simple formula has been widely used in ship collision analysis because of its simplicity. Minorsky analyzed 26 collision cases of full scale ship accidents and developed an empirical formula indicates that the energy absorption by a ship during a collision is simply proportional to the volume of the destroyed material.

In a series of published works started in 1980 by Hegazy the results of a research project titled “Ship Collision Survivability Assessment” were published. [2, 4, 5, 6, 7, 8]. The program consisted of six parts covering all aspects related to collision between ships. The final goal of this program was to introduce collision between ships as design criteria to be taken into consideration during the early stages of the structural design of the ship.
Hegazy investigated the possibility of a single hull struck ship being broken into two after collision due to the loss of her longitudinal strength. The concept of the ultimate bending strength developed by Caldwell [9] has been used to relate the transverse extent of damage (i.e. penetration) to the struck ship after collision, as well as to develop a procedure to find the critical penetration (and, hence, the corresponding residual strength) beyond which the struck ship might be broken into two if the longitudinal bending moment subsequently exceeds the “design value” [2]. In addition, Hegazy proposed a simple method, which enables the amounts of energy absorbed by different parts of ship structures during a collision to be estimated. His formulae were derived by using theoretical plastic analysis of various structure failure mechanics of different ship’s structural members to evaluate the total absorbed energy by the struck ship and striking vessel’s structures during collision. [8]
Some results based on Hegazy’s works are also represented in a Ph.D. thesis under his supervision [10]

Paik (1998) [12] has been developed a fast and reasonably accurate method for exploring the collapse of the hull girder in the damaged condition. Location and amount of collision damage are defined based on the ABS Safe Hull guide. [11]. The risk of hull collapse is explored by comparing the applied extreme bending moment and the ultimate hull strength which are both estimated by using simplified design oriented methods or formulae. To characterize residual strength an elastic section modulus based residual strength index and an ultimate bending strength based residual strength index are defined.
Paik also in a difference study in 1999 [13] introduced two different modifications for Minorsky formula, which can be used only for a quick estimation of the amount of damage expected in a collided VLCC double hull tanker side structure. The first formula is based on the energy capable of being absorbed until the bow penetrates to the original position of the inner hull without rupture of the inner hull. His second formula is based on the energy capable of being absorbed up to the inner hull rupture.
Wang (2002) [14] produced a method which investigated the longitudinal strength of ships with damages due to grounding or collision accidents. Based on a theoretical analysis, new formulae were derived for dimensionless hull girder strength that was expressed as polynomial equations of dimensionless damage extent up to the cubic terms. These formulae are derived for the residual hull girder strength and verified with direct calculations of sample commercial ships for a broad spectrum of collision accidents. Hull girder ultimate strengths of these sample vessels under sagging and hogging conditions are also calculated, based on which

correlation equations are proposed. These formulae provide very handy tools for predicting the residual strength in seconds, without performing step-by-step detailed calculations, an obvious advantage in cases of emergency or salvage operation.

3. Relation between the extent of damage and the residual longitudinal strength:

Following the same procedure which was developed by Hegazy [2] for single hull ship and apply it to a double hull tanker of mid-ship section such as shown in figure 1. For the purpose of introducing the ultimate strength calculations, the actual structure is represented in the simplified form shown in figure 2, in which A_D is the total cross sectional area of the longitudinally continuous material (plating and longitudinal stiffeners) in the deck before damage at the section considered. Similarly A_S, A_H, A_{IB} and A_{OB} denote the cross sectional areas of one side, one longitudinal bulkhead, inner and outer bottom structure respectively. A_D, A_{IB}, and A_{OB} were assumed to be spread uniformly over the breadth B, while A_S and A_H were assumed to be spread uniformly over the depth D.

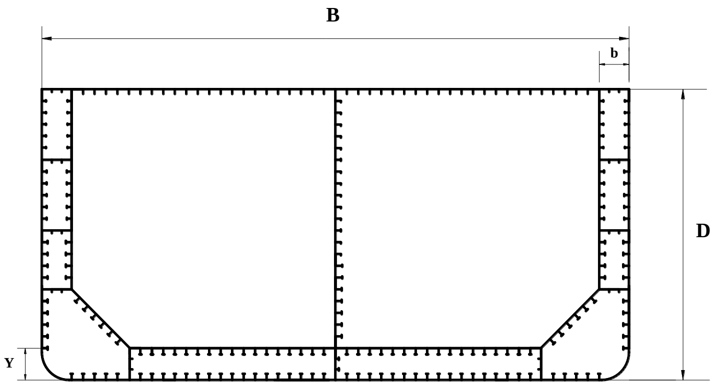

Figure 1: Actual mid-ship section of double hull oil tanker before damage.

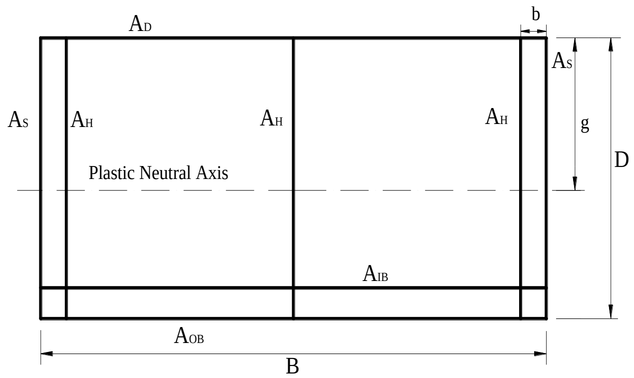

Figure 2: Idealized mid-ship of double hull oil tanker before damage.

The damaged section can be taken at the mid-ship section, where the maximum value of the working bending moment as well as the probability of collision is likely to occur. Assume that after a collision the damage section of the struck ship; one side shell plating, a part of inner, outer bottom and deck plating are lost as shown in the figure 3, but the inner hull longitudinal bulkheads remain intact.
The deck, inner and outer bottom area for the struck ship are reduced after collision to ηA_D, ηA_{IB} and ηA_{OB}.
Where, η is the residual area coefficient for the area after damage to the area before damage and given by;

$$\eta = \frac{B - w}{B} = 1 - w/B \tag{1}$$

Where
w = penetration (i.e. extent of damage in the transverse direction) which is less than or equal to the wing tank width (b) (w ≤ b) as shown in figure 3. (i.e. the inner hull longitudinal bulkhead is intact)

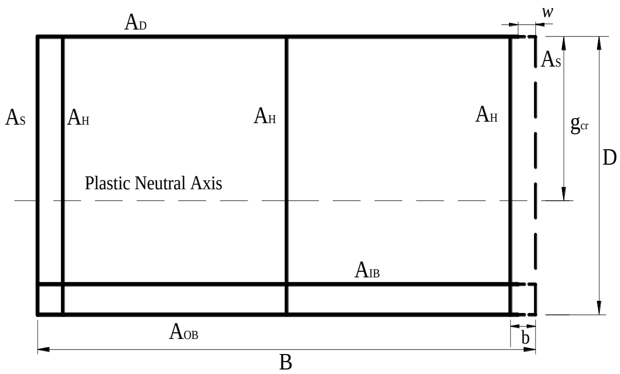

Figure 3: Structural configuration of double hull tanker after damage.

Clearly this is an idealized model, which can be drawn quickly for the given ship section. It would not be difficult in principle to take into account more exactly the actual distribution of area around the cross-section or other damage schemes.
For a ship two situations are to be considered, hogging and sagging and in general the ultimate bending strength will differ between two. Both need to be considered and compared with the predicted maximum applied hogging and sagging moments. In what follows only sagging condition will be treated, although the method equally well apply to the hogging condition. [15]
Figure 4 shows the longitudinal average stress distribution over the cross-section of the struck ship after damage in the limit (or ultimate strength) condition. In the inner, outer bottom structure and in the sides below the neutral axis (whose position is to be determined), the full yield stress in tension side has developed. On compression side, the deck structure and the side above the neutral axis will have reached their ultimate load-carrying

capacities, and because of bulking of plating and / or stiffeners, the effective longitudinal stress at any point in these structures will in general be less than the yield stress of the material. [2]

Caldwell replaced the nearest to the actual distribution of longitudinal stress at collapse by an equivalent average ultimate longitudinal stress in deck f_{UD}, in the side f_{US} and in longitudinal bulkhead f_{UH} by introducing deck, side and bulkhead strength factors given, respectively, [9] as;

$$\emptyset_D = f_{UD}/f_y$$
$$\emptyset_S = f_{US}/f_y$$
$$\emptyset_H = f_{UH}/f_y$$

Where,

f_y= yield stress of the material (assumed to have the same value in tension and compression).

The ultimate strength factors $\emptyset_D$, $\emptyset_S$ and $\emptyset_H$ play an important role in ultimate strength calculation and must be estimated by whatever method seems most appropriate (Faulkner, 1965). [16]

Considering the area for each ship's structural item related to the total mid-ship cross section area in term of "area factor" and called α where,

$\propto_s = A_s/A$, $\propto_i = A_{IB}/A$, $\propto_o = A_{OB}/A$

$\propto_H = A_H/A$, $\propto_D = A_D/A$

Where, A (the total of the cross section before damage)

$$A = A_D + A_{IB} + A_{OB} + 2A_s + 3A_H$$

If (g) is the distance of the plastic neutral axis below the centre of deck area, then using the condition of zero net longitudinal force over the cross section, as shown in figure 4, we get:

$$\gamma = g/D = \frac{\propto_s + 3 \propto_H + \eta(\propto_i + \propto_o - \alpha_D \emptyset_D)}{\propto_s (1 + \emptyset_s) + 3 \propto_H (1 + \emptyset_H)} \tag{2}$$

It must be noticed that equation (2) is derived for the damaged model shown in figure 3, where the number of intact longitudinal bulkheads after collision is 3.

For "n" number of intact longitudinal bulkheads after collision equation (2) will be

$$\gamma = g/D = \frac{\propto_s + n \propto_H + \eta(\propto_i + \propto_o - \alpha_D \emptyset_D)}{\propto_s (1 + \emptyset_s) + n \propto_H (1 + \emptyset_H)} \tag{3}$$

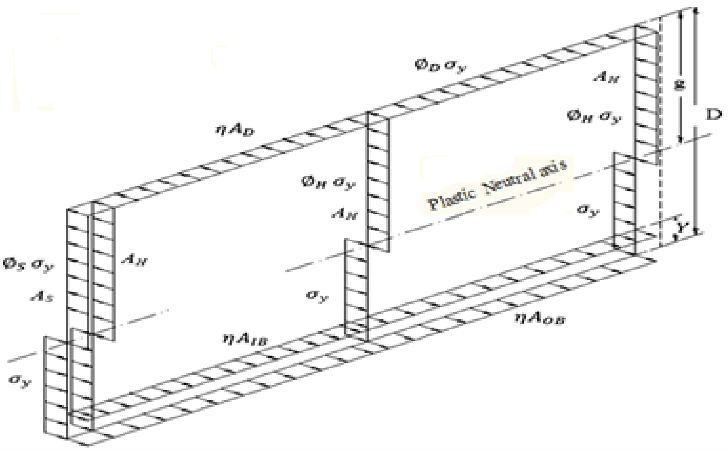

Figure 4: Equivalent average ultimate longitudinal stress distribution over the mid-ship section of an oil tanker in damaged condition.

The internal moment of resistance corresponding to the stress distribution in the limit condition is founded by taking moment about the plastic neutral axis of the forces in deck, side and bottom. Denoting this “Ultimate moment” by (MU) we get:

$$M_U = \frac{f_y A\, D}{2}\left[2\eta(\gamma \emptyset_D \propto_D + \propto_i (1-\gamma-\beta) + \propto_o (1-\gamma)) + \gamma^2(\emptyset_s \propto_s + 3\emptyset_H \propto_H) + (1-\gamma)^2(\propto_s + 3 \propto_H)\right] \qquad (4)$$

For any number of intact longitudinal bulkheads after damage “n” the value of MU will be

$$M_U = \frac{f_y A\, D}{2}\left[2\eta(\gamma \emptyset_D \propto_D + \propto_i (1-\gamma-\beta) + \propto_o (1-\gamma)) + \gamma^2(\emptyset_s \propto_s + n\emptyset_H \propto_H) + (1-\gamma)^2(\propto_s + n \propto_H)\right] \qquad (5)$$

Where,
$\beta = Y/D$
Y is the double bottom height.
Equation (5) was derived for the damaged model shown in figure 3 for w ≤ b (i.e. all longitudinal bulkheads are remained intact after collision)

For w > b, in this case the number of intact bulkhead (*n*) in equation (5) will represent only the number of the remaining intact bulkheads.

For single bottom, single side, without longitudinal bulkheads oil tanker, the ultimate moment can be obtained by putting

$n = 0,\ \propto_i = 0$ and $\beta = 0$ in equation (5), we get:

$$M_U = \frac{f_y A\, D}{2}\left[2\eta\left(\gamma \emptyset_D \propto_D + \propto_o (1-\gamma)\right) + \gamma^2(\emptyset_s \propto_s) + (\propto_s)(1-\gamma)^2\right] \qquad (6)$$

4. Critical penetration:

The introduction of the ultimate bending strength enables the designer to find the true margin of safety, as the ratio between the ultimate bending moment and the working bending moment experienced by the ship among waves (as obtained from wave and loading data). Obviously the ultimate bending strength of the struck ship will be decreased due to the damage resulting from collision (see equation (5)). The value of the working bending moment in the damaged condition can be obtained from longitudinal strength calculation by considering the damaged condition as one among the other condition at which longitudinal bending moment are to be obtained. The damaged section can be taken at the mid-ship section, where the maximum value of the working bending moment as well as the probability of collision is likely to occur.

As explained in ref. [2], if it happens that, after a collision, the transverse penetration is so severe that the ultimate bending moment after damage (as calculated from equation (5)) is equal to the working bending moment (as discussed above); this means that the margin of safety is unity and any increase in the value of the working bending moment would result in the structural collapse of the ship. Following the above discussion Hegazy [2] introduced the term ''critical penetration'' (W_{cr}) to describe the transverse penetration in the struck ship, which results in the equality of the ultimate bending moment of the damaged cross-section and the working one, i.e.,

$$M_U = M \tag{7}$$

Where,

M = the working bending acting at the damaged section of the struck ship obtained as discussed above.

Using *equation* (5) and equation (7), we get:

$$\eta_{cr} = \frac{k - \gamma_{cr}^2(\emptyset_s \propto_s + n\emptyset_H \propto_H) - (1-\gamma_{cr})^2(\propto_s + n \propto_H)}{2\left(\gamma_{cr}\emptyset_D \propto_D + \propto_i (1-\gamma_{cr}-\beta) + \propto_o (1-\gamma_{cr})\right)} \tag{8}$$

Where,

η_{cr} is critical residual area coefficient.

g_{cr} is the distance of the plastic neutral axis below the centre of deck area in the critical major collision.

$\gamma_{cr} = g_{cr}/D$

γ_{cr} is the distance of the plastic neutral axis below the centre of deck area to moulded depth ratio in critical major collision.

k is the bending moment coefficient

Where, $k = \frac{2M}{f_y AD}$

For single bottom, single side tanker (Pre-MARPOL oil tanker), the η_{cr} can be obtained by putting $n = 0$,

$\propto_i = 0$ and $\beta = 0$ in equation (8) to be the following:

$$\eta_{cr} = \frac{k - \gamma_{cr}^2(\emptyset_s \propto_s) - (1-\gamma_{cr})^2(\propto_s)}{2\left(\gamma_{cr}\emptyset_D \propto_D + \propto_o (1-\gamma_{cr})\right)} \tag{9}$$

In this critical condition equation (1) for the residual area coefficient will be

$$\eta_{cr} = \frac{B - w_{cr}}{B} = 1 - w_{cr}/B \tag{10}$$

Where,
w_{cr} is the critical penetration (i.e. critical extent of damage in transverse direction).
By using equations (3) and (8) one can get the following equation for γ_{cr}:

$$\gamma_{cr}^2 + \frac{\mu}{\zeta}\gamma_{cr} + \frac{\psi}{\zeta} = 0 \qquad (11)$$

Solving equation (11) for γ_{cr}, we get:

$$\gamma_{cr} = 0.5\left[\frac{-\mu}{\zeta} \pm \sqrt{\left(\frac{\mu}{\zeta}\right)^2 - \frac{4\psi}{\zeta}}\right]$$

Where, $\zeta = (\alpha_D \emptyset_D - \propto_i - \propto_o)\begin{bmatrix}(2\propto_s(1+\emptyset_s) + 2n\propto_H(1+\emptyset_H)) \\ -(\emptyset_s\propto_s + n\emptyset_H\propto_H) - (\propto_s + n\propto_H)\end{bmatrix}$

$$\mu = (\propto_o + \propto_i(1-\beta))[(2\propto_s(1+\emptyset_s) + 2n\propto_H(1+\emptyset_H))]$$

$$\psi = [(2\propto_s + 2n\propto_H)(\propto_i(\beta-1) - \propto_o)] - [(k - (\propto_s + n\propto_H))(\propto_o + \propto_i - \alpha_D\emptyset_D)]$$

Considering only the logical value of γ_{cr} from equation (11) (which must be less than one), the value of ultimate bending moment M_U can be calculated from equation (5)

5. Critical modulus of section:

After calculating the value of critical penetration (W_{cr}) the value of mid-ship modulus of section in damaged condition can be calculated ($Z_{Critical}$).
Now we have to compare the value of the minimum required modulus of section as calculated by the formula developed by the common structural rules with the value of $Z_{Critical}$ with [15].
The ratio of $Z_{Critical}$ / $Z_{v\text{-}min}$ (less than one) explains that ship's structure is not designed to have adequate structural redundancy to survive in the event the structure is accidently damaged (e.g. subjected to critical major collision).
The factor $Z_{Critical}$ / $Z_{v\text{-}min}$ can be considered as the real structural factor of safety of ship's hull during her life time.

6. Conclusion:

The introduction of the structural factor of safety (ZCritical / Zv-min) represents a new concept of safety, which aims to introduce the problem of collision between ships as a new factor to be considered in the early stage of the design procedure of a ship.

A more detailed investigation about this problem is now going on in order to develop software, which can be used to calculate (ZCritical / Zv-min) for any ship during the early stage of her design. We know that such procedure will lead to increase the steel hull weight of the ship and it will be very useful in some cases where collision may cause very catastrophic results for property, lives and environment. The numerical case study will be a future work.

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