Residual strength of ships after grounding

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In some grounding accidents, the real injury to the ship and the environment may occur after a period of time or even during salvage procedures. This would be as a result of the loss of stability or insufficient longitudinal strength of the ship, which may break in two. This paper is concerned with the problem of the reduction in the ship's longitudinal strength after grounding. New formulae and computer programs are proposed to predict the sectional moduli and the residual hull girder ultimate bending moments that are necessary to evaluate the residual strength index. A typical single hull tanker is analyzed for grounding accident scenarios, to attain relations between the transverse extent and location of bottom damage and the loss in residual strength. This will be useful not only in the design stages, but also for the analysis of a specified situation and to determine the critical damage scenario.

فى بعض حوادث جنوح السفن، قد يظهر الخطر الحقيقي بعد فترة من استقرار السفينة على القاع أو أثناء عملية الإنقاذ. يحدث هذا إما نتيجة فقدان اتزان السفينة، أو عدم كفاية المتانة الطولية لها، حيث تتكسر عندئذ إلى جزأين. يتناول هذا البحث مشكلة النقص في المتانة الطولية للسفينة بعد تعرضها للحادث، حيث تستعرض الدراسة معادلات جديدة و برامج لحساب معامل المقطع وعزوم الانحناء القصوى اللازمة لتقدير المتانة المتبقية ومؤشرها. و يتناول البحث بالتحليل ناقلة بترول نمطية تتعرض لنماذج مختلفة من عورية القاع، حتى يمكن إيجاد علاقات بين الموقع و المدى العرضي للتلف و النقص فى المتانة المتبقية. تفيد هذه العلاقات ليس فقط في مراحل التصميم و إنما أيضاً في تحليل حالات محددة ومعرفة المدى الحرج لعورية القاع.

Keywords: Residual strength, Grounding of ships, Ultimate bending strength, Critical bottom damage

1. Introduction

Grounding accidents may be classified into soft grounding and rigid grounding. A soft grounding is that which occurs as the ship runs aground on a soft yielding surface such as underwater shelf, beach or a channel bank. In this case, the local damage due to initial impulse may be limited to plastic deformation of the affected part, most probably with no plate tearing or hull rupture. Rigid grounding is the situation of a ship striking an underwater hard object such as rocks, coral reeves, or hard shelves. The initial impact may lead to immediate hull rupture, tearing or cutting of the bottom plating.

The hull rupture may be of minimum danger in itself, especially if the vessel has a double bottom and/or a double hull. However, grounding may be become a disaster if the ultimate longitudinal bending strength of the stranded ship is reached due to bad salvage operation or due to other factors like weather or progress of plastic deformation. From this point of view, the residual strength of the ship after grounding is as important as the hull behavior during the event. The residual strength may be considered as a synonymous of the accidental limit state; this had been widely attempted in order to attain safe standard forms or codes [1]. The cornerstone in this field is to define a damage scenario and then estimate the ultimate bending strength of the damaged hull girder. The risk of hull collapse is then explored by comparing the applied extreme bending moment and the ultimate hull strength. This design criterion may be required for ships that threaten the environment by pollution disasters, or for ships subjected to high grounding risk.

This paper approaches the main tools that are required to judge the residual longitudinal strength of ships after grounding by means of the residual strength index. These are the section modulus and the ultimate bending moment in hogging and sagging conditions. The effect of a simplification adopted by Paik et al. [2] in his residual strength assessment,

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is investigated throughout the application of the analysis to a single hull tanker.

The residual strength index is used here to estimate the critical transverse extent of bottom damage that may cause the back-breaking of the ship.

2. Residual strength index

To assess the residual strength of a grounded ship, it is firstly important to define the location and extent of bottom damage. To predict damage due to a grounding accident, a realistic scenario which specifies ship type, size, speed, ...etc., should be established in advance. The extent and location of bottom damage caused by grounding of a ship may be defined by using statistical analysis of grounding data extracted from past casualties. The grounding damage levels are defined in design guides such as ABS SafeHull [3]. In this code, the following members are assumed to be damaged and excluded from the calculation of the hull-girder section:

- Bottom shell plating for a width of 4 meters or B/6, whichever is greater.
- Double-bottom girders attached to the damaged shell plating are assumed ineffective up to the following percentage of the girder's depth:
  - 25% for girders situated within 1 meter marginal zones of the damaged plating,
  - 75% for girders situated between the marginal zones.
- All of the bottom longitudinals within the damaged bottom shell and the longitudinal stiffeners within the damaged parts of girder.

Collapse of the defined damaged hull girder can then be assessed using the residual strength index. The hull-girder residual strength after damage is determined according to the reduced section modulus and the reduced ultimate strength.

The residual strength index may be based on the section modulus as given by :

$$F_S = \frac{Z}{Z_r}\,. \tag{1}$$

The ABS SafeHull guide specifies the required section modulus for the damaged hulls as follows:

$$Z_r = 0.9M_{ts}/F_p \quad \text{(cm}^2\text{.m) at deck ,} \tag{2}$$

$$Z_r = 0.9M_{th}/F_p \quad \text{(cm}^2\text{.m) at bottom,} \tag{3}$$

and

$$F_p = 1.784/Q \quad \text{(tonf/cm}^2\text{),} \tag{4}$$

where:

Q = 1.0 for ordinary mild steel ,

= 0.78 for grade H32 high tensile steel.

If the section modulus based residual strength index F_s is less than a specified value (taken as 1.0 [3]), then the hull would not have the required level of residual strength.

Another residual strength index is based on the ultimate bending strength and is given by:

$$F_u = \frac{M_u}{M_t}\,, \tag{5}$$

where M_u and M_t are the ultimate bending strength and the total bending moment, respectively, appropriate to the actual hull girder bending condition, whether hogging or sagging. This also should not be less than 1.0.

The present study uses the IACS guidance formula [4] for estimating the design stillwater and wave-induced bending moment, given by:

$$M_{sw} = -6.63C_1L^2B(C_B+0.7)\times 10^{-3} \quad \text{tonf.m for sagging,} \tag{6}$$

$$= +1.53C_1L^2B(8.167-C_B)\times 10^{-3} \quad \text{tonf.m for hogging ,} \tag{7}$$

$C_1 = 10.75-[(300-L)/100]^{1.5}$ for 90≤L≤300m,

C_1=10.75 for 300<L<350m,

$C_1 = 10.75-[(L-350)/150]^{1.5}$ for 350≤L≤500m

$$M_w = -11.22C_1L^2B(C_B+0.7)\times 10^{-3} \quad \text{tonf.m for sagging,} \tag{8}$$

$$= +19.37C_1L^2BC_B\times 10^{-3} \quad \text{tonf.m for hogging,} \tag{9}$$

These design components calculated from intact design bases are then combined as suggested by the ABS SafeHull guide for the grounding condition:

$$M_{th}= 1.1\ M_{sw} + 0.5\ M_w\ , \tag{10}$$

$$M_{ts}= 0.9\ M_{sw} + 0.5\ M_w\ . \tag{11}$$

In this study, it is aimed to assess the residual strength index for different values of transverse extent of damage. This is more than a design value; it may help in the analysis of a specified or estimated damaged condition of a grounded ship. The required value for the residual strength index may be used to define the critical damage for the considered ship structural configuration.

3. Elastic section modulus

The midship section modulus as used in the simple beam theory is the mean for the evaluation of the hull-girder primary strength. In basic ship design, it is recognized that a ship should have its section modulus larger than the established required minimum value given by the Rules. A computer program has been prepared to calculate the exact hull sectional properties amidship for the intact vessel or for a defined damage scenario. In some situations the use of such a program may be impractical. It is important to have a simple formula for calculating the position of the neutral axis and the hull girder moduli. The midship section idealization used here is shown in fig. 1. It may represent a typical single or double-hull tanker configuration, since the sectional area A_S may include the inner and outer sides and the longitudinal bulkheads (if any). The difference between this idealization and that used by Paik [2], is that it considers the area of the bottom girders separately and not as a part of A_B. In fact, in case of single hull tankers, the bottom girders are of considerable depth and the simplification considering that the centroid of their sectional area is located at the bottom, may be not fair enough. The expressions obtained for the position of the neutral axis and for the sectional moduli are then:

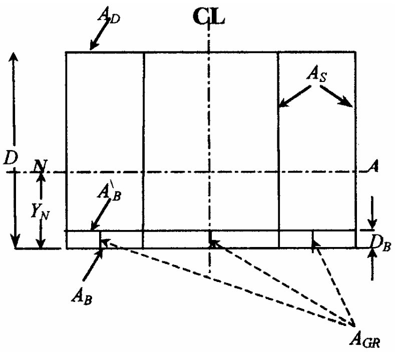


Fig. 1. Midship section idealization.

$$Y_{NA} = \frac{D(A_S + A_D) + \frac{D_B}{2}(2A'_B + A_{GR})}{(A_D + A_B + A'_B + 2A_S + A_{GR})}, \tag{12}$$

$$Z_B = \frac{I_{NA}}{Y_{NA}} \text{ and } Z_D = \frac{I_{NA}}{D - Y_{NA}}.$$

Where;

$$\begin{aligned} I_{NA} = \Big[& A_D(D-Y_{NA})^2 + A'_B(Y_{NA} - D_B)^2 \\ & + A_B * Y_{NA}^2 + \frac{2A_S D}{3}\left(D - 3Y_{NA} + \frac{3Y_{NA}^2}{D}\right) \\ & + \frac{A_{GR} D_B}{3}\left(D_B - 3Y_{NA} + \frac{3Y_{NA}^2}{D_B}\right)\Big]. \end{aligned} \tag{13}$$

The damaged area at bottom, side, and longitudinal bottom girders or longitudinal bulkheads should be excluded from the corresponding original area.

4. Ultimate bending strength

The backbreaking of the ship will occur if the ultimate bending moment of the damaged hull girder is reached. Some simplified design oriented methods or formulae (e.g. [2,5]) had been established to estimate the ultimate bending moment starting from a suggested longitudinal stress distribution at the hull girder ultimate limit state. The pioneering suggestion for this distribution was that of Caldwell [6]. Hegazy [5] used this distribution to assess the residual strength of a collided single hull tanker. This approach has been extended and applied to damaged ships due to grounding [7]. Recently, more refined suggestions have been made and supported by non-linear finite element methods dealing with the progressive collapse analysis of ship's hull structures [2]. The assumed distribution of longitudinal stresses in a hull cross-section at the overall collapse state is shown in fig. 2.

In the present study, the formulae derived by Paik [2] to evaluate the ultimate sagging and hogging bending moments for a single or double-hull ship are modified to involve the bottom center and side girders.

The calculation of ultimate bending moment depends on the cross-sectional area. The reductions on the ultimate strength are expected to be more marked for the hogging condition than for sagging condition, because the damages are located in the bottom which is then in compression, inducing a reduction on the ultimate strength [8].

4.1. Sagging condition

The position of the stress distribution neutral axis measured from the base line is then:

$$g = \frac{C_1 D + \sqrt{C_1^2 D^2 + 4C_2 D}}{2\left(\sigma_{us} + \sigma_{ys}\right)} * \sigma_{ys}\,, \tag{14}$$

where,

$$C_1 = \frac{A_D \sigma_{uD} + 2A_S \sigma_{us} - A_B \sigma_{yB} - A'_B\, \sigma_{ys} - A_{GR} \sigma_{ys}}{A_S\left(\sigma_{us} + \sigma_{ys}\right)}\,, \tag{15}$$

$$C_2 = \frac{D_B}{2A_S}\left(2A'_B + A_{GR}\right), \tag{16}$$

but

$$H = g\left(\frac{\sigma_{us} + \sigma_{ys}}{\sigma_{ys}}\right),$$

then:

$$H = \frac{C_1 D + \sqrt{C_1^2 D^2 + 4C_2 D}}{2}\,. \tag{17}$$

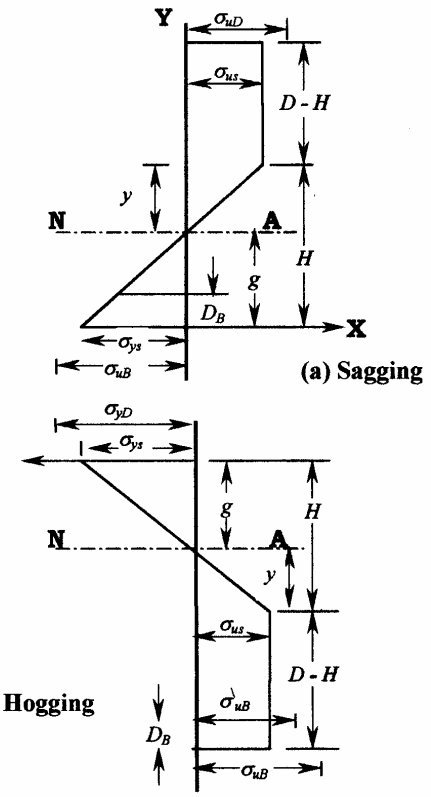


Fig. 2. Assumed stress distribution.

The ultimate sagging bending moment M_{us} may be written as:

$$\begin{aligned} M_{us} &= -A_D\left(D - g\right)\sigma_{uD} \\ &\quad - \frac{A_S}{D}\left(D - H\right)\left(D + H - 2g\right) * \sigma_{us} \\ &\quad - \frac{A_S H}{3D}\left[\sigma_{us}\left(2H - 4g\right) + 2g\sigma_{ys}\right] \\ &\quad - \frac{A_{GR}\sigma_{ys}}{4g}\left(2g - D_B\right)^2 . \end{aligned} \tag{18}$$

4.2. Hogging condition

The position of stress distribution neutral axis measured from deck will be:

$$\frac{g}{D} = \frac{A_B \sigma_{uB} + A'_B\, \sigma'_{uB} + 2A_S \sigma_{us} + A_{GR} \sigma_{us} - A_D \sigma_{yD}}{A_S\left(\sigma_{us} + \sigma_{ys}\right)^2} . \sigma_{ys}\,, \tag{19}$$

and H will be:

$$\frac{H}{D} = \frac{A_B \sigma_{uB} + A'_B\, \sigma'_{uB} + 2A_S \sigma_{us} + A_{GR} \sigma_{us} - A_D \sigma_{yD}}{A_S\left(\sigma_{us} + \sigma_{ys}\right)}\,. \tag{20}$$

Then, the ultimate hogging bending moment M_{uh} may be written as:

$$\begin{aligned} M_{uh} &= A_D\sigma_{yD}g + A_B\sigma_{uB}(D-g) \\ &+ A'_B\,\sigma'_{uB}\,(D-g-D_B) \\ &+ \frac{A_S H}{3D}\left[\sigma_{us}(2H-4g)+2g\sigma_{ys}\right] \\ &+ \frac{A_S}{D}(D-H)(D+H-2g)\sigma_{us} \\ &+ \frac{A_{GR}}{2}(2D-2g-D_B)\sigma_{us}\,. \end{aligned} \tag{21}$$

The essential step is then to determine the ultimate strength of the compression flange (σ_{uD} or σ_{uB} and σ'_{uB}) and the side structure in the vicinity of the compression flange (σ_{us}), which are stiffened panels.

In this study, the approach followed and carried out by the calculation program is that adopted by Rutherford [9]. Among the possible collapse modes of a stiffened panel, two main predictions of the ultimate strength are assessed:

- the plate collapse mode , which is the simple buckling of the plate between stiffeners, and
- the stiffener collapse mode which consists of the compression failure of the stiffener under the combination of in-plane compression and negative bending.

The lowest of these defines the ultimate condition and identifies the mode to be used in the evaluation of M_{uh} and M_{us}.

5. A case study

The world single hull tanker fleet (including chemical carriers) consists of 5,243 vessels, i.e. 71% of the total tanker fleet (in August 2002) [10]. All these vessels require more attention and stricter safety requirements during this decade to avoid any pollution disaster caused by these aging ships. The candidate ship is a typical single hull oil tanker having the structural configuration shown in fig. 3. This existing vessel has the following characteristics:

Length overall	265.0	m
Length BP	253.0	m
Breadth, moulded	40.0	m
Depth, moulded	19.62	m
Summer draft	14.93	m
Dead weight	111,460	t

This tanker has one cargo central tank of 16.0m breadth and two side tanks 12.0m wide each. The deck and bottom panels are made of high tensile steel (AH and EH); the full scantlings are given in [7]. The required minimum value of the section modulus as given by the Rules [4] is:

$Z_{min} = 25.7$ m^3.

For the intact midship section it has been found that:

$Z_{deck} = 33.12$ m^3,

$Z_{bottom} = 33.7$ m^3.

The smaller modulus has then a margin of 29% exceeding the minimum standard.

Two damaged scenarios are investigated. In the first scenario, the omitted part of the bottom plating begins at the bilge at a point 2.187m above the base line, and extends gradually towards the ship's center girder as shown in fig. 4. The omitted part is incremented gradually by a value equal to the spacing between bottom longitudinals (840mm).

In the second scenario, the omitted part starts at the centerline of the ship and is incremented gradually towards port and starboard directions until it reaches the longitudinal bulkheads, as shown in fig. 5. The complete evaluation of the residual strength in terms of residual section modulus at bottom and deck, and the ultimate bending moment under sagging and hogging conditions has been carried out in [7].

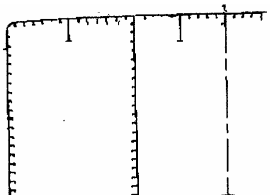


Fig. 3. Structural configuration of the case study.

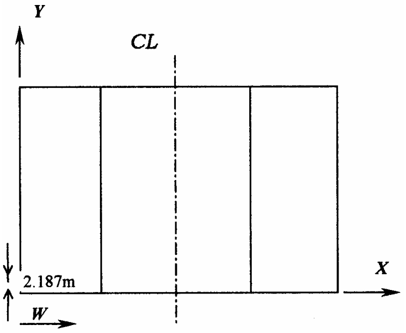


Fig. 4. Damage scenario 1.

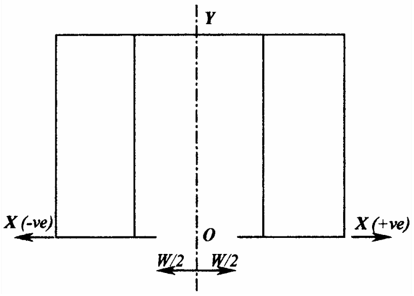
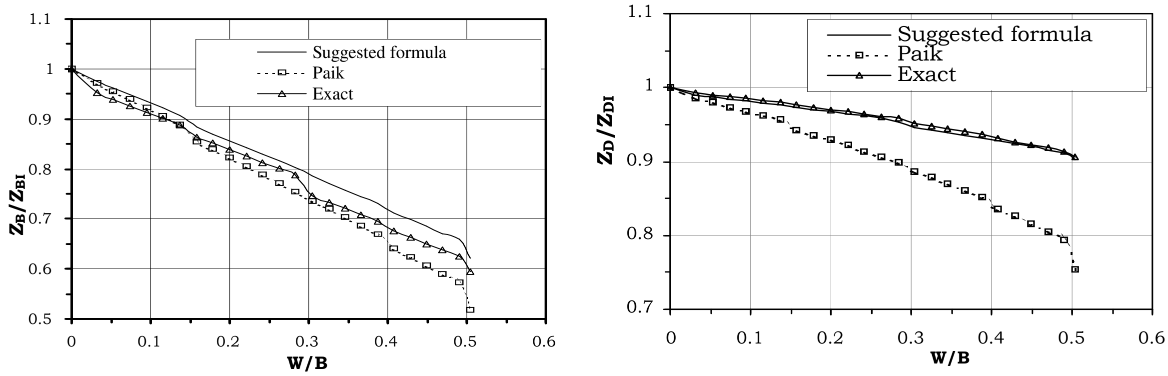
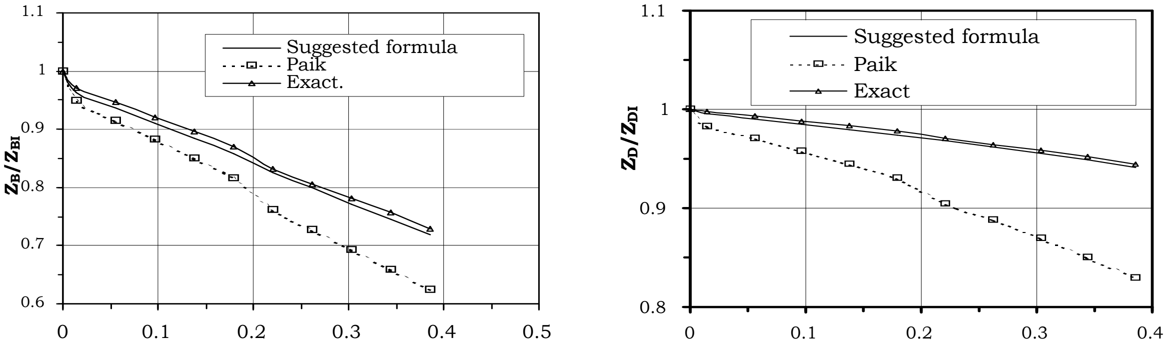


Fig. 5. Damage scenario 2.

Section modulus: The properties of the midship section are examined after omitting a part of the bottom plating with the stiffeners and girders(if any). For each damaged condition, i.e., for each step of the assumed scenarios, the loss in section modulus is evaluated accurately by means of a computer program in order to judge the accuracy of the suggested formula (12) and (13). The good agreement between both calculation methods shows the advantage of treating the bottom girders separately, as shown in fig. 6. The loss in section modulus at bottom is more important than the loss in section modulus at deck. A transverse bottom damage of 40% (scenario 1) has resulted in a reduction of 32% in bottom modulus of section.



(a) Damage scenario 1



(b) Damage scenario 2

Fig. 6. Loss in section modulus.

Ultimate bending strength: The proper consideration of the bottom girders has resulted in smaller values for the ultimate bending moment in hogging and sagging conditions as shown in fig. 7. In both scenarios, the reduction in ultimate bending moment in hogging is much larger than the reduction in sagging, as expected.

The values necessary for the application of the residual strength index concept have been calculated by means of the aforementioned formulae, as follows:

$(Z_r)_{deck} = 18.925$ m^3,

$(Z_r)_{bottom} = 23.102$ m^3.

(MN.m)	hogging	sagging
M_{sw}	2929.5	-2701.7
M_w	5072.9	-4572.2
M_t (grounding)	5758.9	-4717.7
M_u (intact)	7328.4	-4939.6

The critical extent of transverse bottom is obtained by setting the indices F_s and F_u equal to 1.0, and using each of the above values with the corresponding chart from fig. 6 and fig. 7. The results are given in table 1 and table 2.

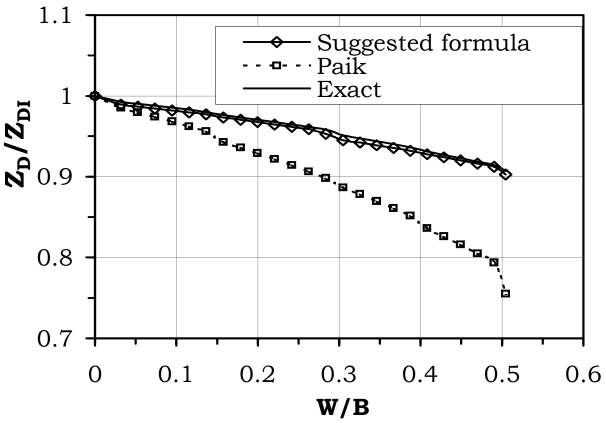
The critical extent of bottom damage is the lowest of the values given above. For both scenarios, this value is obtained in the sagging condition from F_u; it is 6.4m for scenario 1 and 8.8m for scenario 2. It is to be noted that the extent of bottom damage as required for the assessment of the ABS SafeHull guide is of 6.66m (B/6). The residual strength index based on the elastic section modulus seems to be highly optimistic and is not a good measure for this case study.

Table 1
Damage scenario 1

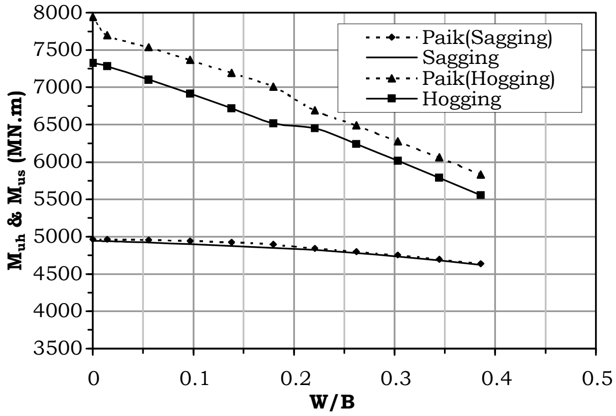
Index	State	$(W/B)_{critical}$	Critical extent (m)
F_s	deck	>0.5	>20
	bottom	0.39	15.6
F_u	hogging	0.3	12
	sagging	0.16	6.4

Table 2
Damage scenario 2

Index	State	$(W/B)_{critical}$	Critical extent (m)
F_s	deck	>0.5	>20
	bottom	>0.4	>16
F_u	hogging	0.34	13.6
	sagging	0.22	8.8



(a) Damage scenario 1



(b) Damage scenario 2

Fig. 7. Loss in ultimate bending moment (absolute value).

6. Conclusions

- Many valuable attempts have been carried out to formulate simple methods for the assessment of the residual strength of ships after damage. This study contributes to the assumptions made for these methods and suggests an algorithm, as summarized in fig.8, to determine the critical transverse extent of bottom damage that occurs if either of the

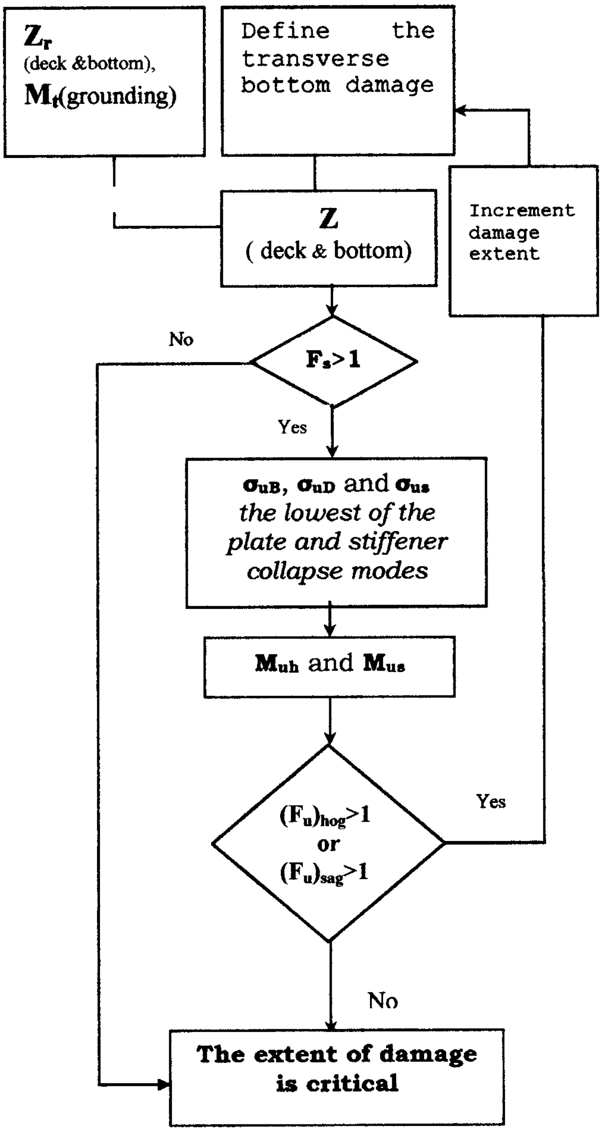


Fig. 8. Procedure to asses the critical bottom damage.

residual strength indices has a value less than one. This critical extent of damage would be useful in the design stage, if an acceptance criterion of the ship's performance in grounding is considered. It would also be useful for a salvage engineer to define a specific grounding situation and an adequate salvage plan.

- The established computer program has been applied to a single hull tanker. For this vessel configuration, the separate consideration of the bottom girders will avoid any underestimation of the section modulus, and overestimation of the ultimate bending moment.
- The residual strength index based on the ultimate bending moment of the hull girder after damage seems to be much more realistic than the index based on the section modulus. In fact, the elastic section modulus does certainly not reflect the behavior of a structure under progressive collapse.
- The ultimate hogging bending moment should be carefully regarded in damaged hull due to grounding, since it suffers from considerable loss due to bottom damage. However, this does not guarantee that the sagging ultimate moment would not be reached. A complete assessment of the situation is necessary for the vessel under consideration.

Nomenclature

A_B, A'_B	are the area of outer or inner bottom,
A_D	is the area of deck,
A_S	is the a half of the area of side shell and longitudinal bulkheads,
A_{GR}	is the area of all the bottom girders,
B	is the ship breadth,
C_B	is the Block coefficient,
D	is the ship depth,
D_B	is the height of double bottom,
I_{NA}	is the second moment of sectional area about neutral axis ,
L	is the ship length,
M_{sw}	is the stillwater bending moment,
M_t	is the total bending moment,
M_w	is the wave bending moment,
M_u	is the ultimate bending moment,
W	is the transverse extent of bottom damage,
Y_{NA}	is the distance between elastic neutral axis and bottom,
Z	is the elastic section modulus,
Z_B, Z_D	are the elastic section modulus at bottom or deck,
Z_{BI}, Z_{DI}	are the initial section modulus at bottom or deck,
σ_{uB}	is the ultimate buckling strength at outer bottom,
σ'_{uB}	is the ultimate buckling strength at inner bottom,
σ_{uD}	is the ultimate buckling strength at deck,

σ_{us}	is the ultimate buckling strength at side,
σ_{yB}	is the mean yield strength at outer bottom,
σ_{yD}	is the mean yield strength at deck,
σ_{ys}	is the mean yield strength at side,,

- For all moments "h" in the subscript is denoted for hogging and "s" for sagging.

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