TRACING THE ULTIMATE LONGITUDINAL STRENGTH OF A DAMAGED SHIP HULL GIRDER

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ABSTRACT: This technical note suggests the use of constant, residual strength contours of a damaged hull girder section to enhance assessment of a ship's survival ability when exposed to longitudinal vertical bending after an accident. Following a general discussion on a ship's hull girder longitudinal load carrying capacity based on elasticity theory, on fully plastic resistance moment theory and on ultimate bending moment approach, the investigation focuses on the effects of different damage modes of a hull section on the residual longitudinal strength of an impaired ship. The practical application of the computational link between the residual strength contours and a ship's survival is further clarified in given examples.

Key words: ship, ship construction, strength of ship, longitudinal strength, theory of plasticity, load-end shortening method, ship's survival ability, residual strength, ultimate strength, buckling strength, collision, tanker, bulk carrier.

1. Introduction

The defect of longitudinal members of a ship's cross-section in the amidships area of a hull girder may occur during collisions, explosions or in the event of exceedingly high, single or repeated, static or dynamic overloading [1, 2, 3, 4, 5]. The vertical longitudinal bending may lead to yielding, buckling, fatigue, cracking and fracture of ship's longitudinal structural members [6]. In the standard semi-empirical longitudinal strength check procedure based on yield bending or buckling, the ultimate strength check was not a required procedure [7]. The ultimate strength check was earlier rather a desired theoretical option, considering the ultimate longitudinal strength of the intact and damaged hull girder as the vertical, fully plastic resistance moment [8], corrected for effects of high tensile steel, buckling, shear forces and axial forces [9], for ship in upright and in inclined position 10].
In the recent approach of Classification Societies e.g. [11], the hull girder ultimate check is required for ships equal to or greater than *150 m* in length only for intact hull in an upright position. The ultimate bending capacity has to be assessed according the rule requirements by the extreme values of the curve of bending moment capacity versus the curvature of the transverse section in hogging and sagging conditions of an intact ship by using beam theory [12]. The strength of the hull beam is additionally affected by large amount of uncertainties related to fabrication imperfections, yield stresses, modulus of elasticity, initial deflections, residual stresses, corrosion, as well as to modeling uncertainties [13]. The Idealized Structural Unit Method (ISUM) of first generation [14] and of second generation [15] is considered as prospective.
By an iterative numerical procedure presented in this technical note, in addition to the ultimate strength check of an intact ship recognized as an important aspect of safety of ships at sea [16], different assumed damage shapes in the amidships area of a hull girder are investigated in order to provide contours of constant values of a residual strength of the ship's damaged cross-section. The constant strength contours obtained by the presented procedure may facilitate urgent decisions about further actions after an accident and may provide a better comprehension of the damaged ship strength in structural design.

2. The elastic and fully plastic resistance moment of the ship's hull girder

According to the commonly adopted longitudinal strength standards for oceangoing steel ships [7], the hull elastic section modulus within 0.4L amidships is based on allowable working stress amounting to $R_d = \frac{175}{k}\ N/mm^2$. The material coefficient k is defined with respect to the upper yielding stress R_e^h, as $k = \frac{295}{(R_e^h + 60)}$ and presented for commonly used mild and high tensile shipbuilding steels in Table 1.

The safety factor against yielding is defined as a ratio between the yielding and the working stress:

$$f = \frac{R_e^h}{R_d} = \frac{235}{175} + (1-k)\cdot\frac{60}{175} = f_{MS} + (1-k)\cdot\frac{60}{175} = \frac{M_e}{M} \qquad (1)$$

The safety factor for mild steel in (1) amounts to $f_{MS} = 1.3428$ and for high tensile steels, see Table 1.

The bending moment M in (1) acting on a ship hull is not to be greater of the rule bending moment [7], which is the sum of still water and wave bending moments $M = M_s + M_w$, Fig. 1.

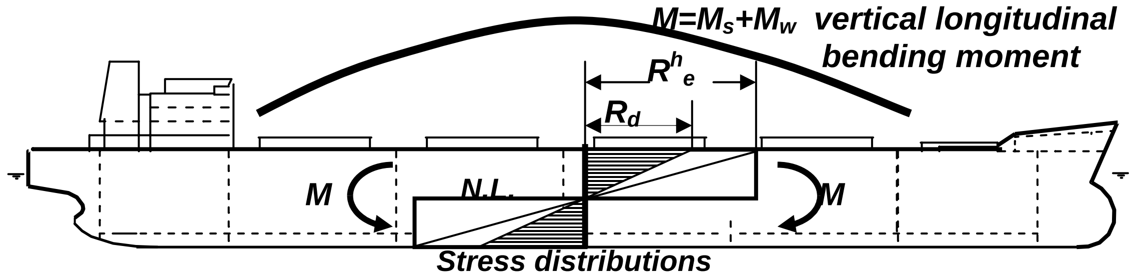

Figure 1. Elastic and plastic longitudinal vertical bending of a ship hull

The ship's required elastic section modulus, denoted as a rule section modulus [7], is defined as:

$$W_e = \frac{M_s + M_w}{R_d} = f\cdot\frac{M}{R_e^h} \qquad (2)$$

The initial yielding (first yield) in a cross-section with moment of inertia I take place at positions that are furthest from the elastic neutral axes of the ship's hull cross-section denoted $z_{\max}$.

The vertical elastic resistance moment in (1) [6], see Fig. 1., is:

$$M_e = R_{\mathrm{e}}^{\mathrm{h}}\cdot\frac{I}{z_{\max}} = R_{\mathrm{e}}^{\mathrm{h}}\cdot W_e = f\cdot M \qquad (3)$$

The elastic vertical hull section modulus in (3) is defined as $W_e = \frac{I}{z_{\max}}$ and may be viewed as the lower bound of the ultimate bending strength.

If the vertical bending moment continues to increase above the level of a vertical elastic bending moment, either yielding of elements under tension or plastic deformations and buckling of compressed elements will take place.

The plasticity theory, based on assumption of elastic-perfectly-plastic material, proves that the bending moment causing plastic deformation on the entire cross section, denoted as fully plastic resistance moment [8, 9], equals to:

$$M_p = R_e^h\cdot\frac{A}{2}d = R_e^h\cdot W_p \qquad (4)$$

The lever arm of the resisting couple in (4), denoted the plastic lever *d*, is a vertical distance between the centroids of the upper and lower half of the resisting area *A*, Fig. 3. The fully plastic resistance moment (4) corresponds to the upper limit of the ultimate bending moment.
Analogous to the elastic vertical section modulus in (3), the plastic vertical section modulus in (4), denoted fully plastic modulus, $W_p = \frac{A}{2} d$, characterizes the situation of a complete progress in plastic deformations, Fig. 1., can be calculated for intact and damaged ship hull, in an upright and declined position [10].
The shape factor, or the geometric factor of the cross-section [8, 9], is defined as the ratio of the fully plastic resistance moment and the vertical elastic resistance moment, as follows:

$$\nu = \frac{M_p}{M_e} = z_{\max} \cdot \frac{d}{2} \cdot \frac{1}{i^2} = \frac{W_p}{W_e} \tag{5}$$

The radius of gyration of the section in (5) is defined as $i = \sqrt{I / A}$.
The shape factor for cross sections of ships usually ranges from 1.1 to 1.5.
The collapse of the ship structure under vertical bending can occur rapidly, due to the formation of a plastic hinge mechanism under the action amounting to the full plastic vertical bending moment (4).
The overall safety factor against collapse is defined on basis of the safety factor against yielding (1) and the shape factor (5), as follows:

$$\lambda_c = \frac{M_p}{M} = f \cdot \nu \tag{6}$$

The hull girder transverse section is viewed as constituted of, let us say N_e structural elements such as beams, columns, beam-columns attached to a certain width of plating, girders, plates, stiffened plates etc., each contributing to the hull girder longitudinal strength with their net scantlings and sectional areas $A_i, i = 1,2,..., N_e$, as well as with appropriate yield stresses $R^h_{e,i}$.
The elementary effective cross-sectional areas A^e_i are used to calculate the overall effective sectional area $A^e = \sum_{i=1}^{N_e} A^e_i$, the position of the neutral axes and the elastic or plastic vertical hull section module W_e and W_p, respectively.
The local material correction factor for modification of the cross-sectional areas A_i of all hull longitudinal elements built of higher tensile steel to effective cross-sectional areas A^e_i [10], can be determined as follows:

$$\Gamma_i = \frac{R^h_{e,i}(high\,tensile\,steel)}{R^h_e(mild\,steel)} = \frac{295}{235} \cdot \frac{1}{k_i} - \frac{60}{235}, i = 1,2,..., N_e \tag{7}$$

The actual cross-sectional areas A_i of all longitudinal elements under compression with critical buckling stress $R_{cr,i}$ which could be buckled before the yield stress of the considered element $R^h_{e,i}$ is reached, can be locally modified to effective areas A^e_i by a correction factor, sometimes denoted as a knockdown factor [8, 9, 10]:

$$\Phi_i = \min\left(1, \frac{R_{cr,i}}{R^h_{e,i}}\right) = \min\left(1, \frac{\beta_i}{f_i}\right), i = 1,2,..., N_e \tag{8}$$

Unity in (8) indicates that there is no need for correction of the element sectional area due to buckling if the critical buckling stress exceeds the material yield stress.

The local safety factor against buckling $\beta_i = \frac{R_{cr,i}}{R_{d,i}}, i = 1,2,..., N_e$ in (8) is defined independently of the material properties for all elements as the ratio between the critical buckling stress and the compressive working stress. Typical values amount to $\beta = 1.0$ for plating and stiffener webs and $\beta = 1.1$ for stiffeners [7], indicating that the buckling of hull longitudinal elements under compression may occur prior the yielding since in practice is $\beta \leq f$, Table 1. The local safety factor against yielding is defined as $f_i = \frac{R^h_{e,i}}{R_{d,i}}$, where $R_{d,i}$ is the working stress appropriate for each element.
The relevant expressions for critical stresses R_{cr} for beam column buckling, for torsional buckling, for web local buckling of flanged ordinary stiffeners and for flat bar ordinary stiffeners, as well as for plate buckling, are available for common engineering practice in the Rules for Classification of Steel Ships [11].
The sectional areas A_i of all longitudinal hull elements also has to be locally modified for excessive shear stresses τ to effective areas A^e_i, by a factor based on von Mises equivalent stress [9]:

$$\Theta_i = \frac{\sqrt{(R^h_{e,i})^2 - 3\tau_i^2}}{R^h_{e,i}} = \sqrt{1 - 3 \cdot \left(\frac{\tau_i}{R^h_{e,i}} \right)^2}, i = 1,2,..., N_e \tag{9}$$

Since the shear stresses are small in the amidships area of the hull girder where the maximum bending moments occur, such a correction is seldom applied.
Values for material correction factor Γ for commonly applied shipbuilding steels and for correction factor $\Phi = \frac{\beta}{f}$ (for $\beta = 1$ and $\beta = 1.1$) provided for buckling are given in Table 1.
For additional non-uniformly distributed axial stresses $R_{a,i}$ across the hull section due to ships hydrodynamic resistance and eventual towing and pushing forces, the actual cross-sectional areas A_i of all elements has to be locally reduced in case the direction of axial stresses $R_{a,i}$ coincides with the direction of normal stresses due to bending, increased otherwise, by the following correction factor [9]:

$$\Lambda_i = 1 \pm \frac{R_{a,i}}{R^h_{e,i}}, i = 1,2,..., N_e \tag{10}$$

The effects of axial stresses are in general small for motionless damaged ship.
In case of towing or pushing of damaged ships, assuming small axial stresses uniformly distributed across the entire cross section, the diminution of the full plastic resistance moment can be roughly assessed by the following interaction formula [9]:

$$M_{p,a} = M_p \left[1 - \left(\frac{R_a}{R^h_e} \right)^2 \right] \tag{11}$$

The position of the plastic neutral axes and the amount of the corresponding vertical full plastic resistance moment for intact and damaged hull girder is to be obtained by means of an iterative procedure, imposing the equilibrium among all longitudinal element critical stresses, either due to yielding or due to buckling, employing the effective element cross sectional areas A^e_i, by the equation:

$$M_p = R^h_e \sum_{i=1}^{N_e} \Gamma_i \cdot A_i \cdot \Phi_i \cdot \Theta_i \cdot \Lambda_i \cdot z_i \approx R^h_e \sum_{i=1}^{N_e} \overbrace{\Gamma_i \cdot A_i \cdot \Phi_i}^{A^e_i} \cdot z_i \tag{12}$$

Note that simplifications in (12) are possible in most practical cases by neglecting Θ_i and $\Lambda_i\,, i = 1,2,...,N_e$. The amount $z_i, i = 1,2,...,N_e$ in (12) corresponds to the vertical distance of the centroids of elements cross sectional areas A_i with respect to the plastic neutral axes.

Table 1. Material factors and coefficients for shipbuilding steel

R_e^h	*k*	*1/k*	*f*	*Φ=1/f*	*Φ=1.1/f*	*Γ*
235	1.00	1.0000	1.3428	0.7447	0.8192	1.0000
315	0.78	1.2820	1.4128	0.7078	0.7786	1.3539
355	0.72	1.3888	1.4388	0.6950	0.7645	1.4880
390	0.66	1.5151	1.4593	0.6852	09.7537	1.6466

3. The ultimate bending moment of the ship's hull girder

According to the Rules for Classification of Steel Ships for ships equal to or greater than *150 m* in length, it is to be checked that the hull girder ultimate bending capacity at any hull transverse section is in compliance with the following requirement [11]:

$$\frac{M_u}{M} \geq \gamma_m \gamma_R \tag{13}$$

The ultimate bending moment in (13) is $M_u = M_{uH}$ for hogging and $M_u = M_{uS}$ for sagging, Fig. 2. The partial safety factors $\gamma_R = 1.03$ and $\gamma_m = 1.02$ account for uncertainties with respect to resistance and material, respectively.

The bending moment in sagging and hogging conditions is defined as the weighted sum of the still water and wave bending moments $M = \gamma_s \cdot M_s + \gamma_w \cdot M_w$ where $\gamma_s = 1.0$ and $\gamma_w = 1.10$ are the partial safety factors covering uncertainties on still water and wave induced hull girder loads [11].

The ultimate bending moment of a hull girder transverse section according to the Smith’s method governed by the beam theory [12], are defined as the maximum values of the curve of pure bending moment capacities *M* versus the curvature of the transverse section χ, Fig. 2.

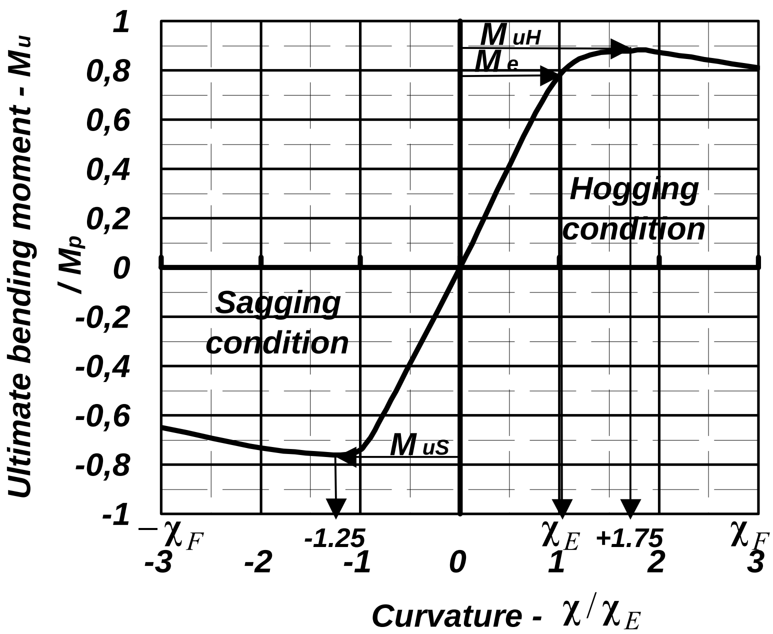

Figure 2. Curve bending moment capacity *M* versus curvature χ for a product carrier in intact condition and in an upright position

The curve $M-\chi$, Fig. 2., is to be obtained by means of an incremental-iterative procedure [8, 12]. In each step *j* of the incremental procedure the bending moment M_j is calculated for an imposed rotation angle χ_j of the hull girder transverse section around its horizontal neutral axis obtained for an increment $\Delta\chi_j$ relative to the previous step, amounting to $\chi_j = \chi_{j-1} + \Delta\chi_j$.
The induced axial strains ε_j due to rotation increment $\Delta\chi_j$, provoke lengthening and shortening of elements depending on their position. The local stresses $R_{i,j}$ induced in each structural element *i* for imposed rotation angle *j* are obtained from the load-end-shortening curves $R-\varepsilon$ given by Classification Societies, which takes into account the non-linear elasto-plastic characteristics for the possible failure mechanisms, employing the edge function Φ defined as $R_{i,j} = \Phi_i(\chi_j)\cdot R_e^h$ [11].
The procedure considers load-end-shortening curves for elasto-plastic collapse of lengthened transversely framed plating panel or ordinary stiffeners, as well as beam column buckling. torsional buckling, and web local buckling for shortened flanged ordinary stiffeners and plate buckling of shortened transversely framed plating [11].
The new position of the neutral axes relevant to the incremental step of curvature χ_j, as well as the ultimate bending moment of a hull girder defined as $M_u = \max\limits_{0\le\chi_j\le\pm 3\frac{M_e}{EI}} \left[M(\chi_j)\right]$ is to be obtained by means of an iterative procedure imposing the equilibrium among all stresses $R_{i,j}, i = 1,2,\ldots, N_e$ based on the net geometrical characteristics of the transverse section, employing the following equation.

$$M(\chi_j) = \sum_{i=1}^{N_e} R_{i,j}\cdot A_i\cdot z_i = \sum_{i=1}^{N_e} \overbrace{R_e^h\cdot\Phi_i(\chi_j)}^{R_{i,j}}\cdot\Gamma_i\cdot A_i\cdot z_i = R_e^h\sum_{i=1}^{N_e}\overbrace{\Gamma_i\cdot A_i\cdot\Phi_i(\chi_i)}^{A_i^e}\cdot z_i \qquad (14)$$

From (14) is obvious that the edge function Φ in (14) can be applied either as a local correction factor for stresses with respect to the yield stress R_e^h or as a correction factor for element's cross sectional areas A_i, as it was applied in (12). Moreover, in the case of full plastic resistance moment calculation according to (12), the correction factor Φ in (12) has the same role as the edge function Φ in (14) with respect to the ultimate bending moment calculation in (14) according to the Rules [11].

4. Residual strength of a damaged ship

It is assumed in the note that the critical situation for ship's survival occurs immediately after the accident causing huge amidships damage whilst the hull is still in an upright position. The note considers three residual strength calculation procedures with respect to vertical longitudinal bending of the ship hull girder. First, the elastic resistance moment assesses the lower limit of the ultimate bending strength. Next, the full plastic resistance moment theory corrected for buckling effects is used to assess the upper limit of the ultimate bending strength. Finally, the ultimate bending moment capacity is applied to check the ultimate strength criteria given in (13) as required by the rules of Classification Societies [11].
In addition to the mere ultimate strength check in structural design of the intact ship hull girder, the note suggests the lifetime usage of contours of constant residual strength of the damaged hull cross-section for fast ultimate strength check in case of an accident during the ship's service.

4.1. Modes of damage of cross-sections

After accidents, longitudinal structural members can suffer single continuous and multiple discontinuous cross-sectional damages. The damage of a ship's section is viewed as a rupture in the thin-walled structure of a hull girder considered as a beam. The damage of a cross section reduces the material of longitudinal structural members accompanied by the reduction in ship's longitudinal strength. The ship's hull can be damaged in three positions with respect to the floating line: under, above, or both under and above the floating line. Two modes of single continuous cross-sectional damage either on port or on starboard side of the ship's hull, Fig. 3(left), are:

- Damage of the deck and side
- Damage of the bottom and side

The shape and the dimension of an arbitrary single continuous sectional damage can be described by two parameters: the maximal depth and the extent of the rupture. Considering the ship's hull as a thin-walled structure, the maximal extent and depth of the rupture define the damaged zone regardless of the shape of the rupture, presented by the shaded area of the hull transverse section, Fig. 3(left). For the amount of the damage extent equal to the height of the hull section for the given damage depth, a damage of the entire side is encountered, Fig 3(left). The shape of the rupture in the longitudinal direction is irrelevant for the ship's hull subjected to the beam theory.
The geometric definition of multiple ruptures may be much more complicated and is not elaborated.

4.2. Residual ultimate strength calculations for a damaged hull section

In general, unsymmetrical hull damage causes unsymmetrical longitudinal bending and non-uniaxial flexure, even for the ship in an upright position. Therefore, the note accounts for elastic resistance moment theory, for full plastic resistance moment theory [8, 9] and ultimate longitudinal vertical bending moment approach [11, 12], applied to an unsymmetrical damaged hull section [10] of a ship in an upright position.
Since the vertical bending moments always act perpendicularly to the waterplane, the vertical section modulus has to be defined with respect to the same vertical plane. If the buckling has to be accounted for, separate considerations for sagging and hogging bending moments are required. This problem is resolved by an iterative numerical procedure for determination of the plastic neutral axis applied to the effective cross-sectional area of the ship's hull. The necessary conditions are that the centroid of the upper half effective cross sectional area lies in the same vertical plane as the centroid of the lower half effective cross sectional area, as well as the centroid of the entire effective cross section, Fig. 3.
According to the incremental iterative procedure recently adopted by Classification Societies [11], the bending moment $M(\chi_j)$ acting on the transverse section at each curvature χ_j is obtained by summing of all the contribution given by the element stresses. The element stress $R_{i,j}$ is to be obtained for all *i* elements and for each *j* curvature increment χ_j from the appropriate non-linear load-end shortening curves $R-\varepsilon$ [11].
The procedure is to be repeated for each step *i*, until the value of imposed curvature reaches the given limiting value $\chi_F = \pm 3\chi_E$ amounting to threefold the imposed curvature $\chi_E = \dfrac{M_e}{EI}$ till first yield, caused by the vertical elastic resistance moment M_e or permits the calculation of the extreme value of the bending moments of the curve.
The extreme values of the curve correspond to the ultimate bending moment capacities $M_u = M_{uH} = \max\limits_{0 \le \chi_j \le +3\frac{M_e}{EI}} \left[M(\chi_j)\right]$ for hogging and $M_u = M_{uS} = \max\limits_{0 \le \chi_j \le -3\frac{M_e}{EI}} \left[M(\chi_j)\right]$ for sagging condition.
The effects of fabrication imperfections, initial deflections and residual stresses on ultimate bending moment capacities [13] in this note are considered irrelevant for damaged ships. However, the diminution of the residual strength due to corrosion should be considered [8].

4.3. Residual ultimate strength contours of a damaged hull section

The calculation procedure for a single point on the contour of a residual longitudinal strength is performed for a selected damage depth and by incremental iteration of the damage extent (or vice

versa), Fig. 3(left). The iteration goes on until the assumed value of residual resistance moment of the damaged cross-section is achieved. The curve through all these points defined by their depth and extent for the given constant amount of the residual strength, represents a contour with selected constant value of residual strength of a damaged hull cross-section.
Moreover, the contours of the residual vertical full plastic resistance moment, the residual ultimate bending moment, the residual vertical elastic resistance moments as well as the contours of the residual resisting cross-sectional areas, can be easily determined for the intact and damaged ship in upright and declined positions, using the computational procedures applied in this note. Nevertheless, the numerous unaccounted practical, theoretical, environmental and modeling uncertainties call for caution by interpreting calculation results.
The practical assessment of the hull girder residual strength in case of an accident is based on the comparison between the observed damage of the hull section and the contours of residual strength, employing sensible interpolations or extrapolations when necessary. The damaged ship can be regarded as relatively safe with respect to vertical bending if the actual loading, appropriate to the ship's load case during an accident, is below the residual strength of the ship. If it is likely that the ship can survive the damage, additional calculations for hull loads, as well as for an inclined ship, can be performed using more complex procedures [10]. If it is not the case, and the damage seriously jeopardizes the ship's structure, further urgent actions are required to save lives, cargo and the environment.

5. Examples

The procedures presented in this technical note are demonstrated on two ships built in Croatian shipyards. Principal characteristics and basic information about the example ships are given in Table 2.

Table 2. Principle characteristics of considered ships in intact condition and in upright position

Items	Symbols & units	Bulk-carrier	Product-carrier
Length between perpendiculars	L_{pp} *m*	179.37	182.50
Breadth	B *m*	30.80	32.20
Depth	H *m*	15.45	17.50
Draft	T *m*	10.10	11.00
Deadweight	DWT *t*	41600	47400
Bending moment (hog/sag)	M 10^6 *kNm*	2.50 / 2.50	2.60 / 2.75
Still water bending moment	M_s 10^6 *kNm*	0.95 / 1.05	0.87 / 1.07
Wave bending moment	M_w 10^6*kNm*	1.55 / 1.45	1.73 / 1.68
Moment of inertia	I m^4	123.22	160.56
Center of gravity from B.L.	z_G *m*	7.01	7.30
Max distance from elastic N.L.	z_{max} *m*	8.44	10.20
Cross sectional area	A m^2	3.00	3.23
Cross sectional area of plating	A_o m^2	2.47	2.44
Cross sectional area of profiles	A_p m^2	0.53	0.79
Plastic lever arm	d *m*	11.60	10.51
Elastic section modulus (deck/bott)	W_e m^3	14.60/17.35	15.74/21.20
Fully plastic section modulus	W_p m^3	17.41	19.56
Shape factor	ν -	1.19	1.24
Upper yielding stress	R_e^h N/mm^2	235	235
Allowable working stress	R_d N/mm^2	175	175
Safety factor (yielding)	f -	1.34	1.34
Elastic resistance moment	M_e 10^6 *kNm*	3.41	3.70
Fully plastic resistance moment	M_p 10^6 *kNm*	4.10	4.60
Safety factor (plastic collapse)	λ_c -	1.64	1.66
Plastic moment & buckling (hog/sag)	M_p 10^6 *kNm*	3.61 / 3.20	4.00 / 3.50
Min. safety factor(collapse&buckling)	λ_c -	1.28	1.30
Imposed curvature till first yield	χ_E 10^{-3} m^{-1}	0.135	0.112

Ultimate bending moment (hog/sag)	$M_u\ 10^6\ kNm$	3.44 / 3.03	3.90 / 3.36

The examples of two merchant ships analyzed in this note offer verification that their ultimate strength against collapse and buckling under intact and damaged conditions against vertical bending is quite high.

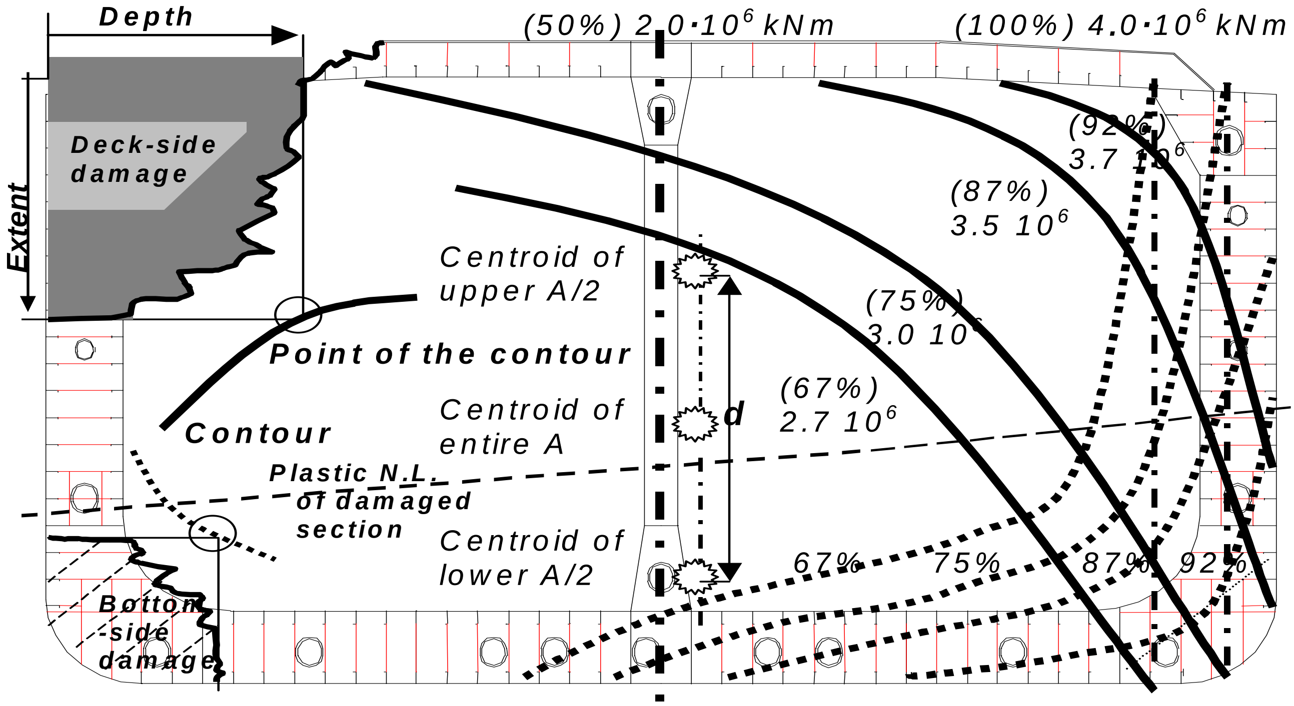

Figure 3. Left: Definition of damaged areas, points and contours of constant residual strength
Right: Fully vertical plastic resistance moment contours (buckling included) for a product carrier in a hogging condition in an upright position

For the intact product carrier in upright position with principal characteristics given in Table 2., the $M-\chi$ curves for sagging and hogging conditions are presented on Fig. 2.

The contours of constant fully plastic vertical resistance moment with buckling included for the damaged hull, are presented on Fig. 3. Note that due to the transverse symmetry with respect to the centerline, the half of the cross-section provides half of the overall bending strength.

6. Conclusion

The residual bending strength of the damaged ship in this technical note is scrutinized for the possible collapse of the ship's hull. As the theory of elasticity does not convey all information about the hull collapse, the theory of plasticity needs to be employed. It is considered first how the elastic resistance moment may be viewed as the lower limit and how the fully plastic vertical resistance moment may be used to assess the upper limit of the ultimate longitudinal load-carrying capacity based on commonly adopted beam theory, taking into account possible shear stresses, axial stresses, buckling and usage of higher tensile steel of an intact and damaged hull section. However, the Classification Societies require the ultimate strength check based on the maximum values of the curve of bending moment capacity versus the curvature of the transverse section considered, employing load-end shortening curves of hull longitudinal elements.

A practical method for post accident strength assessment is presented with particular reference to possible huge damages amidships. The graphical presentation of the residual strength of the damaged ship's hull under vertical longitudinal bending of the hull by contours with fixed values of elastic resistance moments, of fully plastic resistance moments, ultimate bending moment capacities and

residual cross-sectional area, allows a quick assessment of a ship's survival ability under damaged condition.
It is of importance to determine the residual strength of the damaged structure during very first moments after an accident in order to prepare for safe salvage operations. The contours of residual ultimate strength can be determined by an iterative numerical procedure and attached to a ship's instruction and loading manual.
An insight and better comprehension of the resistance of the ship's hull against yielding, buckling and collapse, not only in intact conditions but also in case of hull section damage, can assist improvement of the survival ability with respect to longitudinal loads in structural design.

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List of symbols

A Resisting section, cross-sectional area
d Lever arm of resisting couple, plastic lever,
E Young's modulus of elasticity
f Safety factor with respect to yielding
I Cross-sectional moment of inertia
i Radius of gyration
k Material coefficient
M Bending moment in general
R Stresses in general
R_e^h Upper yield stress
W Section modulus in general

Greek Symbols

χ Curvature, rotation angle of hull transverse section
Φ Correction factor with respect to buckling, edge function
Γ Correction factor with respect to yielding
Λ Correction factor with respect to axial stresses
λ_c Safety factor with respect to collapse
ν Shape factor
Θ Correction factor with respect to shear stresses
τ Shear stresses

Subscripts

e related to elastic
p related to plastic
s related to still water
w related to waves
a related to axial