Simplified Approval Procedure by Introduction of a Normalized Energy Function (NEF) in Line with SOLAS Regulations

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Abstract

SOLAS regulations on subdivision and damage stability, as contained in part B1 of chapter II-1, regulation 25-1, specify damage stability requirements for cargo ships over 80 m in length. On the other hand, the paragraph 25-1.3 of this regulation specifies that alternative arrangements may be accepted, if it is satisfied that at least the same degree of safety is achieved. In 2003 Germanischer Lloyd developed an approval procedure which provides an alternative solution for design and construction of double hull cargo vessels and submitted it to IMO. The execution of this procedure requires calculations of the critical collision energy absorption for at least two structural designs, a reference and a strengthened design. These calculations for 16 collision cases for each design are time consuming and cost intensive. In this article a simplified calculation procedure is proposed by using a so called "Normalized Energy Function", which describes the increase of deformation energy depending on indentations. In this way efforts for the collision calculations can be reduced considerably. The "Normalized Energy Function" NEF is established by evaluating collision energy curves derived by systematic collision computations for different structural designs using FEA. In this article a NEF for small size MPCs is presented, which is derived by evaluation of energy curves from 6 different structural designs.

Keywords

SOLAS Regulations
Approval procedure
Absorbed deformation energy curves
Normalized Energy Function (NEF)

Approval Procedure

In relation to the new SOLAS regulations on subdivision and damage stability, which require a damage stability proof for cargo vessels over 80 m in length, Germanischer Lloyd had submitted an alternative approval procedure to IMO in 2003 [1], which allows that vessels with alternative structural arrangements can achieve equivalent degree of safety in damaged situations. In this approval procedure it is the first time that the collision resistance of a side structure in damage stability calculations is considered. It is now possible to get more economical ship designs and equivalent safety by optimized arrangement of compartments and an increased collision resistance. The basic philosophy of the approval procedure is to compare the critical deformation energy of a strengthened design to that of an unstrengthened reference double hull design. This complies with the damage stability requirements in line with current regulation 25-1 of SOLAS Chapter II-1, Part B-1. Fig. 1 shows a work flow diagram of the procedure presented in [1].

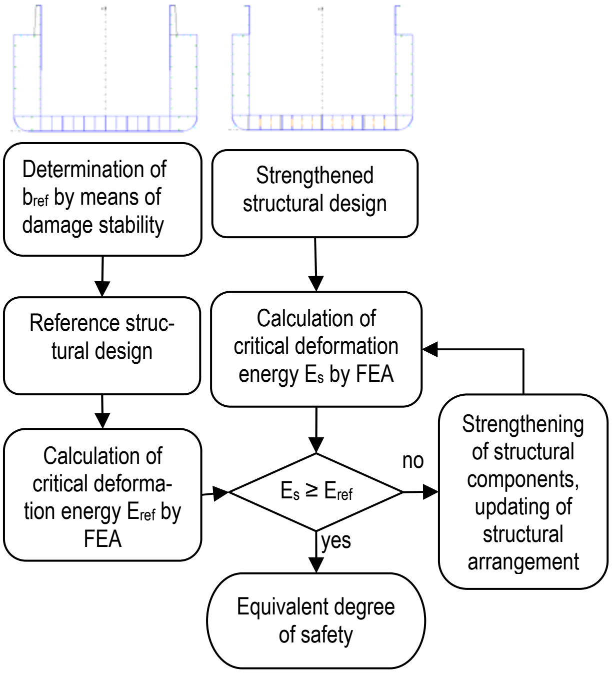

Fig. 1: Workflow of the approval procedure

The implementation of this procedure requires calculations of the energy absorptions for at least two structural designs, a reference design and a strengthened design. As collision calculations are complex, time consuming and cost-intensive, it should be aspired to simplify the procedure e.g. by a reduced number of collision calculations, but without loss of distinctive results. This can be achieved if general valid collision results concerning the energy absorption of side structures are available and suitably prepared for use in a new simplified procedure.

From damage stability calculations the strengthening index $c=b_{ref}/b_s$ can be derived, whereby b_{ref} is the double hull breadth of the unstrengthened reference design and b_s is the double hull breadth of the strengthened design. This strengthening factor index c links the damage stability calculations and collision resistance together. For designers, ship owners and shipyards it is most important to know at early design stage how much additional material for the strengthened side structure is necessary to get an equivalent degree of safety. According to this application it is advantageous to have "normalized energy functions" available for different ship types, sizes and structural arrangements. The NEF describes the dimensionless increase of the absorbed deformation energy of the struck vessel versus indentation into the side structure. In 1995 investigations about normalized energy functions for large size tankers have been carried out by Germanischer Lloyd [3].

By application of NEF the normalized energy values for the indentations at the positions of the inner walls for different double hull breadths of the reference and strengthened designs can be taken. The difference of these values defines the required increase of energy absorption by strengthening referring to the structural design with the smaller double hull breadth without any reinforcements. Collision calculations have to be performed for the smaller double hull breadth only, but for the unstrengthened and strengthened versions. The results of both versions enable a proof of the required increase of energy absorption. By introduction of NEF into the approval procedure it is no longer necessary to set up a steel structure for the unstrengthened reference design with a large double hull breadth which is not intended to be built and to perform collision calculations for it. As a result the approving time and effort for modeling and collision calculations can be reduced considerably.

Furthermore it is advantageous for structural designers that the increase of energy absorption referring to the unstrengthened side structure can be obtained directly by application of NEF if the double hull breadths b_{ref} and b_s are known. This enables a reasonable assessment of the additional structural weight for reinforcements at an early design stage to obtain an equivalent level of safety.

Generation of Normalized Energy Functions (NEF)

The Generation of NEF is based on a lot of energy curves versus indentation of struck vessels. As described in [1], an important step in the approval procedure is the calculation of critical deformation energies for defined collision cases. The critical deformation energy is defined as that amount of deformation energy, by which the inner hull is penetrated. For each structural design the following 16 collision cases have to be analysed:

- 4 striking positions in vertical direction depending on the possible draught differences of striking and struck vessels;
- 2 striking positions in longitudinal direction, namely hitting directly on a web frame and hitting between two web frames;
- 2 different bow shapes, namely conventional raking bow without bulb and bulbous bow.

As a result of systematic FE collision calculations deformation energy curves versus indentation of the struck vessels for each collision case were determined. The large number of FEA results shows that especially the level of absorbed deformation energy considerably depends on the struck locations, structural arrangements and type of striking bow shapes.

The background of the NEF is to utilize shapes of each individual energy curve $E_k(x)$, k=1, 2,…, n and at the same time to keep the standard deviations of their shapes in an acceptable range. The basic idea to generate a NEF is to scale each energy curve to their mean curve

$$\overline{E\,(x)} = \frac{1}{n} \sum_{k=1}^{n} c_k \cdot E_k\,(x) \tag{1}$$

and at same time minimizing the sum of the residuals, namely the difference between each single energy curve and the mean energy curve using least squares method:

$$\sigma\left(c_k\right) = \sum_{k=1}^{n} \int_{0}^{d_0} \gamma\,(x) \cdot \left[c_k \cdot E_k\,(x) - \overline{E\,(x)}\right]^2 dx$$

The weighting function γ(x) is used to control the standard deviation. Here this function is set as

$$\gamma\,(x) = \left(\frac{1}{E\,(x)}\right)^{0.75}$$

A set of c_k can be calculated to gain a minimal standard deviation, i.e.

$$\frac{d\sigma\left(c_k\right)}{c_k} = 0 \qquad .k = 1,2,...,n$$

Then, for each energy curve the scaling factor is derived by

$$c_k\left(d_0\right) = \frac{\int_{0}^{d_0} \gamma\,(x) \cdot E_k\,(x) \cdot \overline{E(x)}\,dx}{\int_{0}^{d_0} \gamma\,(x) \cdot \left[E_k\,(x)\right]^2\,dx} \qquad k = 1,2,...,n \tag{2}$$

The significant indentation value d_0 has to cover the occurring penetration depths of struck vessels but at least up to the critical penetration depths at rupture of the inner hull. Because of the dependence of the mean curve $\overline{E(x)}$ on scaling factors c_k this minimizing procedure has to be performed by iterations. First of all an energy curve is selected as an initial mean energy curve. From this initial mean curve each scaling factor can be derived using (2). Subsequently the new mean energy curve can be calculated from each c_k using (1), and so on. Finally, the NEF is derived as the mean curve of all scaled energy curves. This procedure converges very quickly. When considering different collision cases the probability of such occurrences should be regarded. Probability factors and their relation to different draughts of the vessels are explained in [2] and shown in Fig. 2. A NEF successfully is derived when the standard deviations versus penetration depths are in acceptable limits. This has to be shown by generation of the NEF.

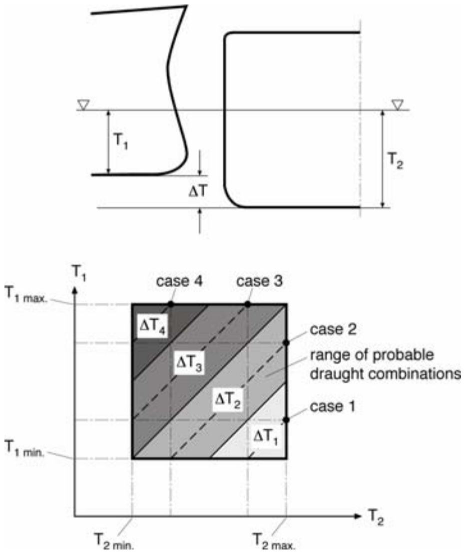

Fig. 2: Collision cases depending on draught differences between striking and struck vessels

The NEF represents the dimensionless increase of the absorbed deformation energy versus indentation of struck vessels. It should be insensible against individual collision cases, structural arrangements and type of striking bows. NEFs can be derived for different ship types and sizes. To which extent these NEFs conform can be shown by comparison. In case of sufficient conformity of all NEFs only one function could be derived for all ships which would considerably simplify the approval procedure.

Example Multipurpose Cargo Ship (MPC):

This vessel represents a typical multipurpose cargo ship with a double hull and one large hold. The ship is characterized by following dimensions:

L_{oa}	90.00 m
L_{pp}	85.00 m
B	13.00 m
Double hull breadth	1.30 m
Depth to main deck	7.00 m
Scantling draught	5.70 m
Ballast draught	3.90 m
Hold length	63.0 m
Displacement	4200 t
Speed	12.0 kn
Ice class notation	GL E2

The general arrangement is shown in Fig. 3.

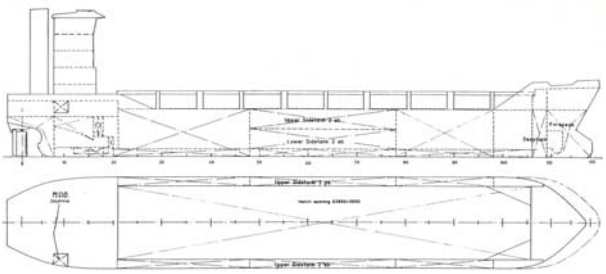

Fig. 3: General arrangement of a multi purpose cargo ship

The main sections show structural designs according to GL Rules with strengthening for ice class (Fig.4) and with minimum scantlings without strengthening for ice class (Fig. 5)

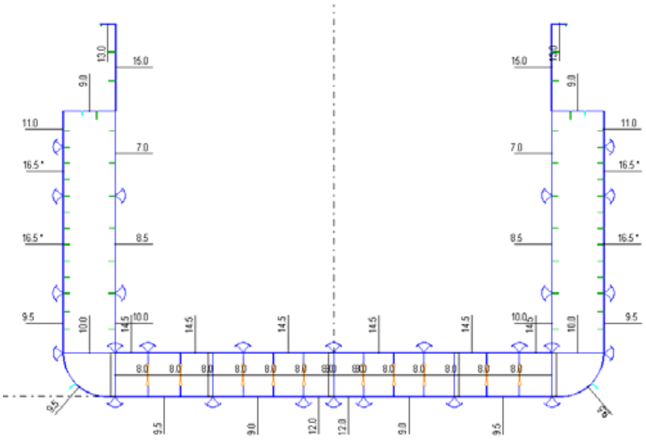

Fig. 4: Main section, including strengthening for ice class (org)

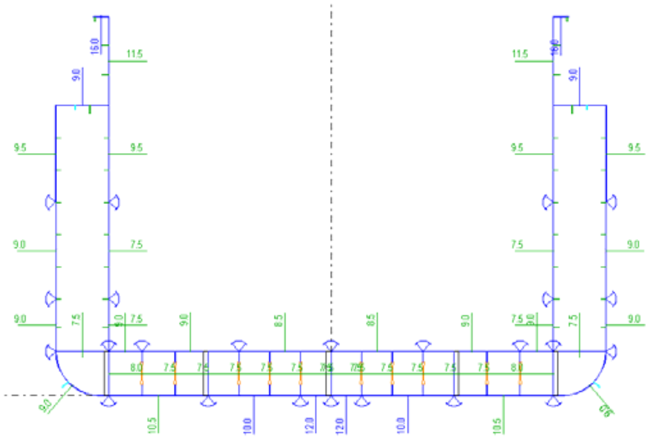

Fig. 5: Main section, with minimum scantlings and without any strengthening (b1)

Generation of FE Models

Based on the main section drawings a finite element model was set up using the GL design program POSEIDON. The FE model extends over the whole cargo hold length. All plates are idealized by shell elements and stiffeners by beam elements. In the range near the striking positions nonlinear elements are used while in the area far from striking positions elastic elements are sufficient. As striking vessels two different bow shapes are to be considered, namely conventional raking bow without bulb and with bulbous bow. The FE models of striking bows are applied as rigid and are scaled and modified from standard bow shapes. Fig. 6 shows the FE models of the struck and striking vessels for one collision case exemplarily.

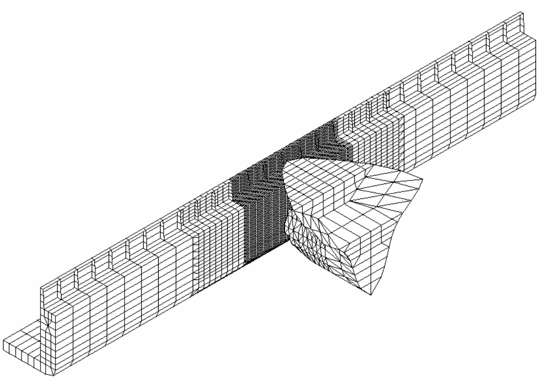

Fig. 6: FE models of striking and struck vessels for one collision case

Definition of Collision Cases

The definition of collision cases corresponds to the approval procedure [1], which is based on the COLL notation of GL Rules, Section 33, Strengthening against Collisions [2]. The computations are to be carried out under the following assumptions:

- A rectangular central impact between striking and struck vessels in the horizontal plane is considered.
- The struck vessel has no speed, while the striking vessel hits the side of the struck vessel with a reasonable speed.
- Based on the ballast and design draughts of the ships involved in the collision the draught differences between them are chosen in a way that the range of possible striking positions in vertical direction is covered.
- In the longitudinal direction of the struck vessel two striking positions, hitting on a web frame and between two web frames are investigated.
- Ships of approximately equal displacements and design draughts are assumed.

Fig. 2 illustrates all possible vertical collision positions as a rectangular area enclosed by two vertical lines T_{1min} and T_{1max} and two horizontal lines T_{2min} and T_{2max}. Each point in this area represents a possible draught combination of both vessels. All points on an inclined line of 45 degrees have a same draught difference and define only one vertical collision position, but at different draughts. In order to cover all possible draught differences only 4 cases were selected tagged by the inclined lines ΔT_1 to ΔT_4. Under the assumption that all draught combinations have same probabilities Fig. 2 shows clearly that the mean draught differences ΔT_2 and ΔT_3 are likely to occur more frequently than the extreme draught differences ΔT_1 and ΔT_4. This can be expressed by weighting factors which are derived from the partial area related to each ΔT. In case that both vessels have identical design draughts weighting factors of 1/ 3/ 3/ 1 are obtained for the cases 1 to 4. At generation of NEFs the collision cases are considered using these weighting factors. For each structural design 16 collision cases are to be calculated.

Calculation of Deformation Energy Curves

The calculations are performed using the explicit FEM program code LS-DYNA. The collision speed of the striking vessels is assumed 10 m/s (19.4 kn) as constant. Generally a length of collision time of 0.4 s is simulated, which corresponds to 4 m penetration depth of the struck vessel. The most important results of collision calculations are the plastic deformation energy curves versus penetration depths of struck vessels and the corresponding critical penetrations at rupture of the inner hull.

Typical results for a raked bow with bow bulb are shown in Fig. 7. The cases 1 and 2 are characterized by predominant contact of the bulbous bow. Such scenarios generally obtain energy curves and critical penetration depths on a lower level. In cases 3 and 4 the upper raked bow and the bulbous bow simultaneously are in contact. This results in a considerably increase of absorbed deformation energy and a reasonable increase of critical indentation.

The deformation energy curves of all 16 collision cases for the steel structure with minimum scantlings are illustrated in Fig. 8. The critical indentations at rupture of inner hull are marked by dots. It can be recognized that for different collision cases the level of absorbed energy and the critical indentation at rupture vary in a large range. The failure criterion considered in the FEA follows the recommendation of the approval procedure [1].

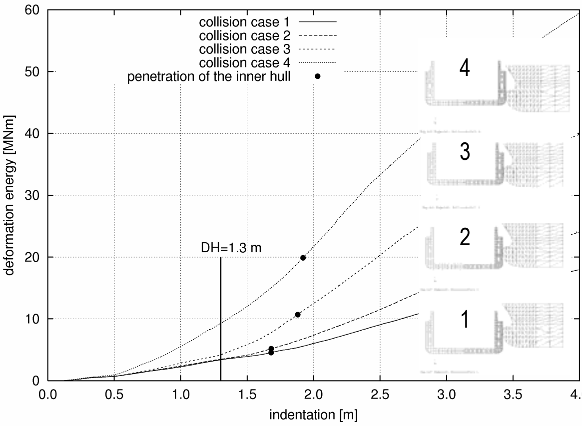

Fig. 7: Typical developments of deformation energy versus indentation

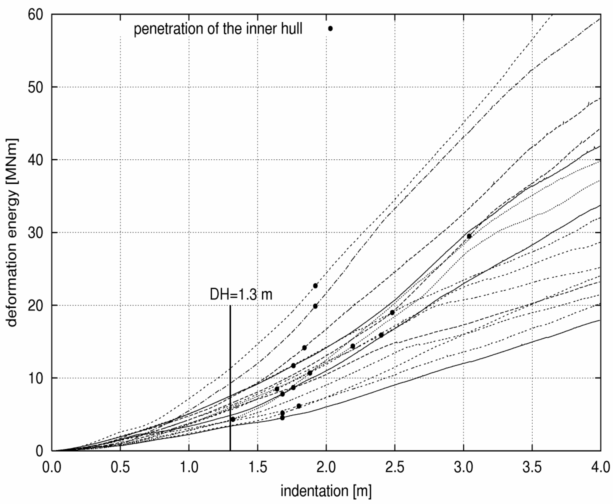

Fig. 8: MPC, Structural design, minimum scantlings (b1), energy curves of all 16 collision cases

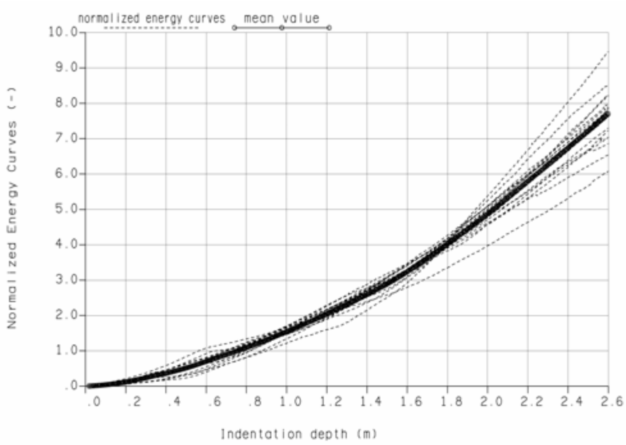

Fig. 9:, MPC, Structural design, minimum scantlings (b1), energy curves of all 16 collision cases after scaling

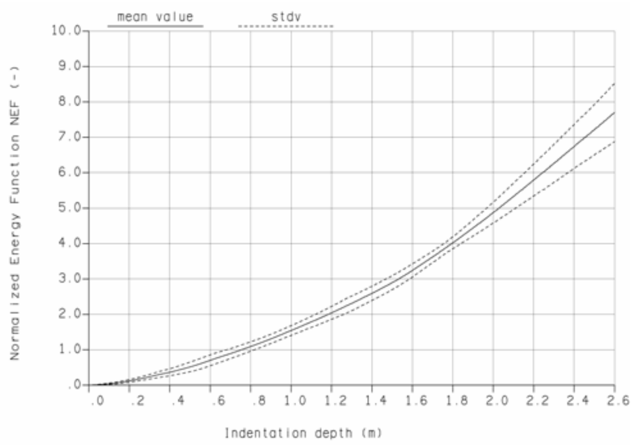

Fig. 10: MPC, Structural design, minimum scantling, NEF (mean value and stdv).

The energy curves are scaled according to the mathematical derivation described previously. The evaluated indentation range for generating the NEF corresponds to a strengthening index $c=b_{ref}/b_s=2.0$, which means that a double hull breadth b_s to be built corresponds only to 50% of the required double hull breadth b_{ref} which complies with the SOLAS regulations. By strengthening the side structure with the smaller double hull breadth b_s it has to be achieved that the energy absorption is increased up to that of the side structure with the reference double hull breadth b_{ref}. It is obvious that a strengthening index value of 2.0 would result in substantial reinforcements. Generally it can be expected that for index values below 2.0 economical solutions can be obtained. However, in special cases it may be favourable to realize higher index values by substantial increase of material.

The double hull breadth b_s of the MPC presented here is 1.3 m. Assuming that a strengthening index value of 2.0 is required, reinforcements have to be arranged to achieve equivalent deformation energy to a side construction with a double hull breadth of 2.6 m. The required increase of energy absorption can be obtained directly by application of the NEF.

Fig. 9 shows all 16 energy curves after scaling by dashed curves. The mean curve is emphasized by markers. The absolute energy values have now no significance, solely the shapes of the curves are important. Therefore, the range of the values can be chosen arbitrarily. The displayed indentation range up to 2.6 m corresponds to a strengthening index value of 2.0. Fig. 10 shows the generated NEF. The upper and lower curves indicate the scatter band within the standard deviation. Inside of this scatter band there are about 70% of all evaluated energy curves. Due to the small scatter band it can be concluded that a suitable NEF was found.

The idea is that NEFs are insensitive to structural designs. For evidence of this idea NEFs were derived for different structural designs, commented in following table:

Label	Description
org	Double hull breadth 1.3 m, ice class notation GL E2, scantlings acc. to Germanischer Lloyd Rules, as built, Fig. 4
b1	Double hull breadth 1.3 m, minimum scantlings acc. to Germanischer Lloyd Rules, Fig. 5
b2	Double hull breadth 2.0 m, minimum scantlings acc. to Germanischer Lloyd Rules, Fig. 12
e1	Double hull breadth 1.3 m, comparable to org, arrangement of 3 additional stringer decks, Fig. 13
e2	Double hull breadth 1.3 m, comparable to org, side longitudinal stiffeners are replaced by T-sections, Fig. 14
e3	Double hull breadth 1.3 m, comparable to org, arrangement of 3 additional side stringers. Fig. 15

The comparison between the unstrengthened and strengthened designs (b1, Fig, 5 and org, Fig. 4) shows that the shell plating of 9 mm thickness is replaced in the range 2.05 to 6.4 m above base line by an ice belt of

16.5 mm thickness with a yield stress of 355 MPa. Furthermore the number of side longitudinals is duplicated from 7 to 14.

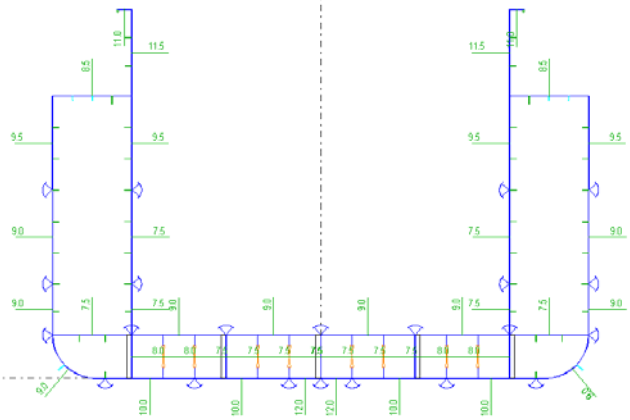

Fig. 12: Structural design with a double hull breadth of 2.0 m (b2)

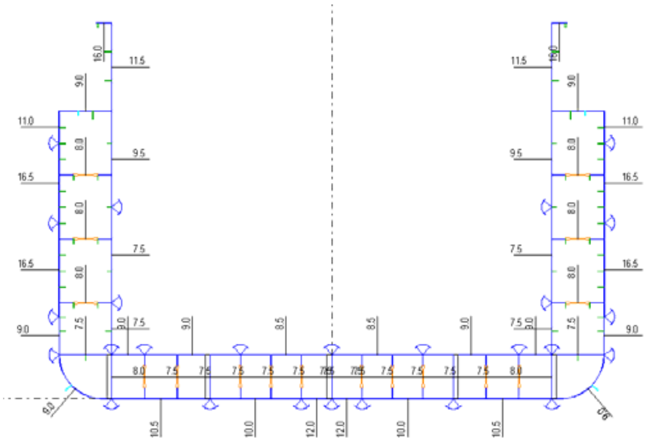

Fig. 13: Structural design for ice class notation GL E2 with 3 additional stringer decks (e1)

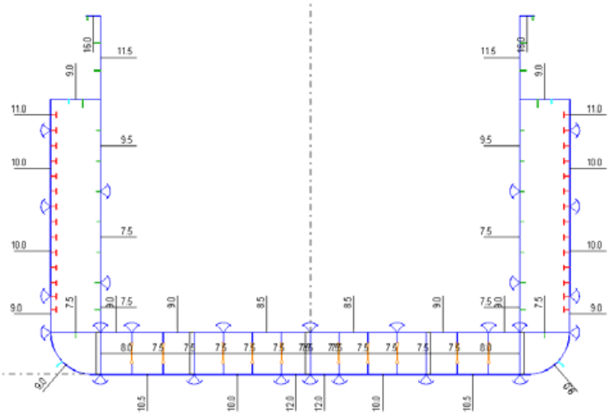

Fig. 14: Structural design for ice class notation GL E2, side longitudinals are reinforced by T-sections (e2)

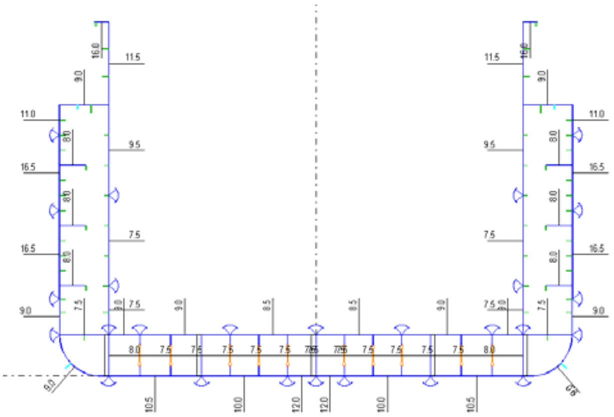

Fig. 15: Structural design for ice class notation GL E2 with 3 additional side stringers (e3)

For all structural designs NEFs were generated, each from 16 collision cases as explained above. In total 96 collision calculations were done. All 6 NEFs after scaling are summarized in Fig. 16. It can be recognized that all curves are close together. The solid line in the figure indicates the mean NEF derived from all 6 structural designs. Fig. 17 shows the mean NEF and the scatter band limited by the standard deviation. The small scatter band gives evidence that it was possible to derive a NEF for small size MPCs which is insensitive to different structural arrangements and hence can be used for different designs.

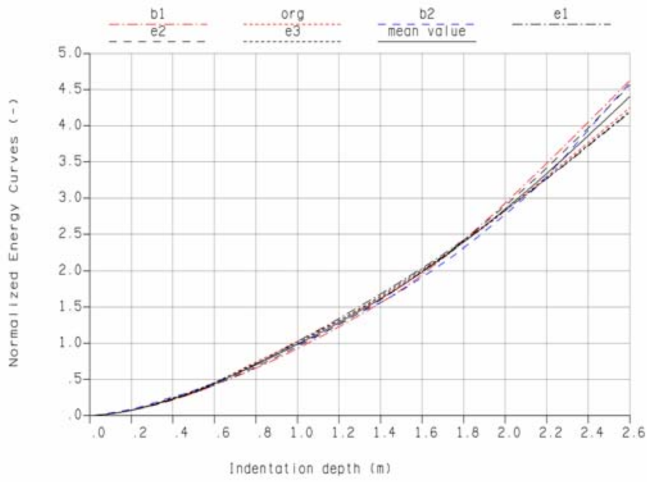

Fig. 16: NEFs for different structural designs

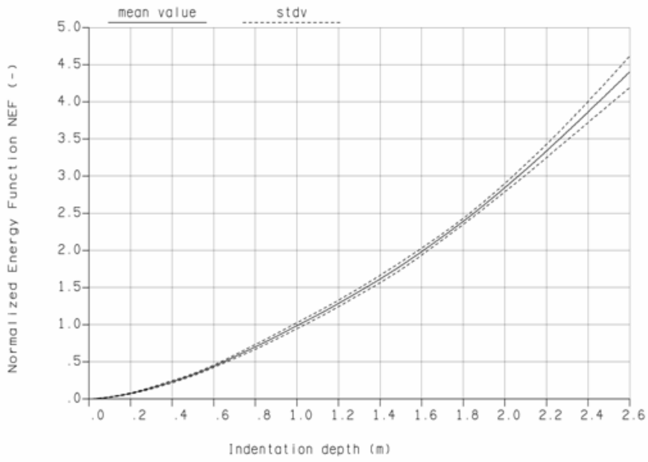

Fig. 17: Final NEF for small size MPCs and scatter band of standard deviation

Summary

The presented results for small size MPCs have achieved sufficient evidence to develop a simplified alternative approval procedure using a „Normalized Energy Function“ (NEF) to obtain alternative structural arrangements and an equivalent degree of safety in damaged conditions as required by SOLAS Regulations 25-1.3, Part B-1.

The workflow chart of the simplified approval procedure in Fig. 18 clarifies that by introduction of the NEF it is no longer necessary to set up a steel structure for the unstrengthened reference design with the larger double hull breadth b_{ref}. This allows a substantial simplification of the approval procedure in [1].

First of all the minimum double hull breadth b_{ref} required by SOLAS regulations has to be determined and the double hull breadth b_s to be built with reinforcements has to be chosen by the ship designers.

Normalized energy values E_{ref} and E_s can be taken directly from the NEF curve at the positions b_{ref} and b_s of both inner walls. The difference of both values indicates the required increase of the deformation energy, which must be achieved by strengthening of the side structure with minimum scantlings.

Collision calculations for the unstrengthened structure with minimum scantlings are accomplished to obtain absolute deformation energy values.

By following collision calculations absolute deformation energy values for a strengthened structural design are determined. A comparison reveals whether the required reference deformation energy by reinforcements is reached or not. If the required reference energy has been achieved, both designs are comparable. An equivalent degree of safety is approved. Otherwise additional strengthening measures are necessary and the collision calculations have to be repeated. It is noted that the larger double hull breadth b_{ref} of the reference design should be the required minimum determined by damage stability calculations.

Furthermore it is advantageous for structural designers that the required increase of energy absorption can be taken directly from the NEF. This enables a reasonable assessment of additional steel weight for reinforcements to fulfil the requirements of the approval procedure at an early design stage.

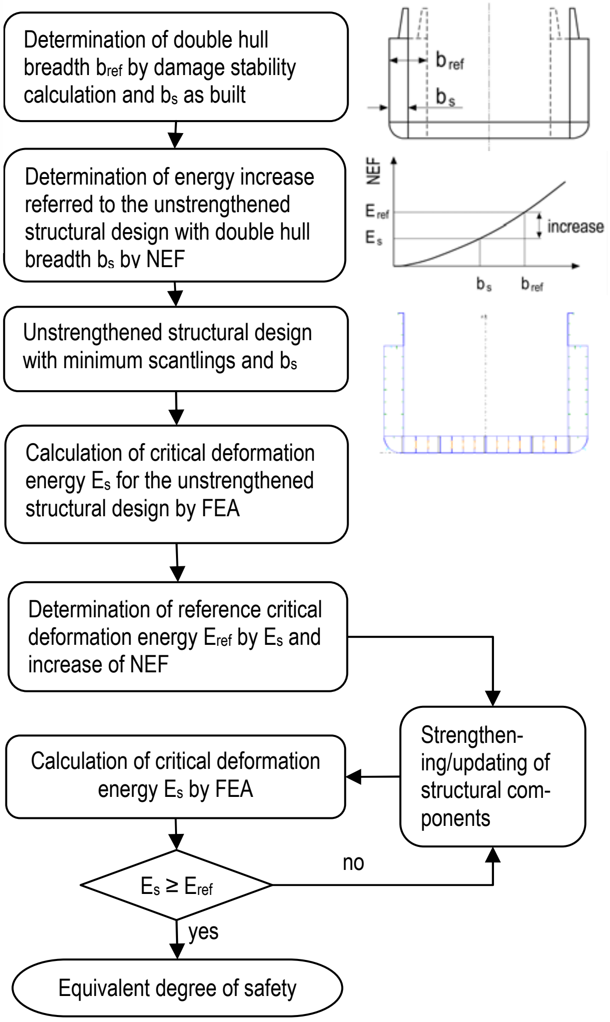

Fig. 18: Workflow of the simplified approval procedure using NEF

References

[1] Approval Procedure Concept for Alternative Arrangements, IMO Document SLF 46/INF. 10, 3. June 2003

[2] Germanischer Lloyd Rules, I Ship Technology, 1 Seagoing Ships, Chapter 1 Hull Structures, Section 33, Strengthening against Collisions

[3] Assessment of the Collision Resistance of Ships for Classification Purposes, Böckenhauer, M. and Egge, E.D. (1995), *MARIENV'95*, 1995.