Approval Procedure Concept for Alternative Arrangements

Dr.-Ing. L. Zhang, Dr.-Ing. E. D. Egge, Dipl.-Ing. H. Bruhns
Germanischer Lloyd AG
Vorsetzen 35
D-20459 Hamburg, Germany

ABSTRACT: Until mid 1998, the SOLAS regulations on subdivision and damage stability, as contained in part B1 of SOLAS chapter II-1, regulation 25-1, specify damage stability requirements for cargo ships only over 100 m in length L_s. Since1998-07-01, new design and construction of cargo vessels between 80 and 100 m in length must also be required to calculate damage stability. As consequence of this update a significant increase in building costs and operational restrictions due to additional subdivisions, such as a transverse bulkhead for such size of cargo vessels are awaited. On the other hand, the paragraph 25-1.3 of this regulation specifies that for particular ship or group of ships alternative arrangements may be accepted, provided that it is satisfied that at least the same degree of safety is achieved. The notation "same degree of safety" allows some flexibility of structural designs with improved safety degree. In relation to damage stability it means preventing penetration of inner hull and increasing collision resistance. Within the scope of the EU-Project Crash Coaster Germanischer Lloyd has worked out an approval procedure which first time provides a standard for evaluation and approval of alternative solution for design and construction of such size of cargo vessels. The double hull breadth of any particular design has a major influence on the damage stability in case of an inner hull penetration. The safety level obtained from a double hull breadth, however, varies dependent on certain design features, e.g. local and global strength. The basic philosophy of the approval procedure is to compare the critical deformation energy in case of side collision of a strengthened structural design to that of a reference design complying with the damage stability requirement described in the SOLAS regulation. The strengthened structural design will provide more loading capacity and reduce operational restrictions.

1. INTRODUCTION

Paragraph 1 of the regulation 25-1 of SOLAS, Part B-1 [SOLAS, 1997] specifies damage stability requirements for design and construction of new cargo ships over 80 m in length L_s, contracted on or after July 1 1998. On the other hand paragraph 3 of this regulation specifies that a particular ship or group of ships may be accepted as alternative arrangements, provided that it is satisfied that at least the same degree of safety as represented by these regulations is achieved.

The purpose of this approval procedure is to provide a standard for evaluation and approval of alternative solutions for design and construction of general cargo vessels described in regulation 25-1 of SOLAS, Part B-1.

Looking for the current damage stability requirement based on a probabilistic calculation method, the flooding of compartments is only related to the geometric arrangement of subdivisions, e.g. number of subdivisions or double hull breadth. In reality if a compartment floods or not, depends also on the strength of involved structural components, such as contributions of plate thickness or arrangements of stringers and stiffeners. In the case of a collision the first penetration of the shell and inner hull indicates the flooding of wing tanks and inboard holding space. This critical situation can be described by amount of deformation energy absorbed by the struck ship during the collision. The basic philosophy of the approval procedure is to compare the critical deformation energy in case of side collision of a strengthened design to that of a reference double hull design which complies with the damage stability requirement detailed in the regulations 25-3, 25-4 and 25-5 of SOLAS, Part B-1.

The calculation of critical deformation energy defined as the energy value absorbed by the struck ship at the moment when the inner hull is penetrated, is by means of the Finite Element Analysis (FEA) for two types of striking bow shapes and at different collision positions in both longitudinal and vertical directions

2. APPROVAL PRINCIPLE

According to the damage stability requirement (SOLAS Regulation Part B-1, 25-3, 25-4 and 25-5) the attained subdivision index A shall not be less than the required subdivision index R defined only as the function of the subdivision length:

$$A \geq R$$

with $A = \sum p_i \cdot s_i$ and $R = 1 - \dfrac{1}{(1 + \dfrac{L_s}{100} \cdot \dfrac{R_0}{1 - R_0})}$,

where $R_0 = (0.002 + 0.0009 \cdot L_s)$.

The attained subdivision index A is the summation of the flooding probability of each compartment or group of compartments p_i multiplied by the probability of survival after flooding s_i. In the case of a double hull design p_i for the inboard holding space will be reduced by multiplication of a factor (1-r). The reduction factor r, which represents the probability that the holding space will not be flooded, shall be calculated as follows:

for $J \geq 0.2 \cdot \dfrac{b}{B}$

$$r = \frac{b}{B} \cdot \left(2.3 + \frac{0.08}{J + 0.02} \right) + 0.1 \qquad \text{if } \frac{b}{B} \leq 0.2$$

$$r = \frac{0.016}{J + 0.02} + \frac{b}{B} + 0.36 \qquad \text{if } \frac{b}{B} > 0.2 \, .$$

For $J < \cdot 0.2 \dfrac{b}{B}$ the reduction factor r shall be determined by linear interpolation between $r = 1$, for $J = 0$ and

$r =$ as for the case where $J \geq 0.2 \cdot \dfrac{b}{B}$, for $J = 0.2 \cdot \dfrac{b}{B}$,

where b is the double hull breadth and J is the dimensionless damage length. It is shown in the Fig. 1 that the reduction factor r is proportional to the ratio between double hull breadth b and the width of the ship B, especially in the range of $\frac{b}{B} \leq 0.2$ the r raises much rapidly as the $\frac{b}{B}$ value increases. In compliance with the requirements of the damage stability a safe side structural design can be achieved, if the breadth of the double hull b is to be increased to a certain value b_{ref}. For this purpose a strengthening factor

$$c = \frac{b_{ref}}{b_s} \geq 1.0$$

shall be defined [GL, 1992], where b_s is the double hull breadth of an initial design, which dose not meet the requirements of the damage stability, and b_{ref} is the double hull breadth of a reference design, with which the conditions of a minimal standard subdivision required by damage stability will be fulfilled.

Replacing b mentioned above with the $b_{ref} = c \cdot b_s$ the required reduction factor r can then be calculated as the function of c:

for $J \geq 0.2 \cdot \frac{c \cdot b_s}{B}$

$$r = \frac{c \cdot b_s}{B} \cdot \left(2.3 + \frac{0.08}{J + 0.02} \right) + 0.1 \qquad \text{if } \frac{c \cdot b_s}{B} \leq 0.2$$

$$r = \frac{0.016}{J + 0.02} + \frac{c \cdot b_s}{B} + 0.36 \qquad \text{if } \frac{c \cdot b_s}{B} > 0.2$$

For $J < 0.2 \cdot \frac{c \cdot b_s}{B}$ the reduction factor r shall be determined by linear interpolation between $r = 1$, for $J = 0$ and $r =$ as for the case where $J \geq 0.2 \cdot \frac{c \cdot b_s}{B}$, for $J = 0.2 \cdot \frac{c \cdot b_s}{B}$.

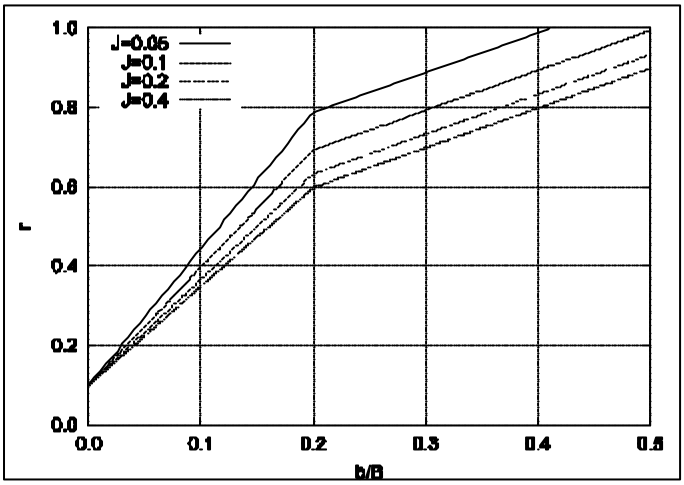


Fig. 1: Reduction factor r in relationship with b/B.

In this way the damage stability for a whole ship or for certain holding spaces required by SOLAS Part B-1, regulation 25-3, 25-4 and 25-5 can be demanded if the strengthening factor c, or with other word the breadth of the double hull b is increased to a certain value b_{ref}. But in fact an excessive double hull breadth cannot be accepted in the practice because of enormous lose of the holding space and much more trim in the case of wing tank damages.

On the other side, the flooding of the inboard holding space, indicated by the first penetration of the side longitudinal bulkhead (inner hull), depends not only on the geometrical arrangement of subdivisions but also on the collision resistance of the side structure in case of side collision damages. As measurement for the collision resistance of a side structure a critical deformation energy value E absorbed by the struck ship, when the first penetrating of the side longitudinal bulkhead (inner hull) occurs, shall be calculated. For the reference design with b_{ref} this energy value is E_{ref}, and for a strengthened design with the initial double hull breadth b_s it is E_s. The equivalence of the same degree of safety for both designs can then be achieved by comparing both critical energy values. It means that a structural design with the initial double hull breadth b_s can be strengthened so that its collision resistance is not less than that of the reference design with the double hull breadth b_{ref}. The requirement of same degree of safety of both designs, according to SOLAS Part B-1, Regulation 25-1 paragraph 3, can then be specified by:

$$E_s \geq E_{ref}$$

To comply with this requirement and at the same time to keep the initial double hull breadth b_s the side structure of the initial design shall be improved and strengthened so that its critical deformation energy is at least equal to that of the reference structural design (Fig. 2):

$$E_s = E_{ref} \, .$$

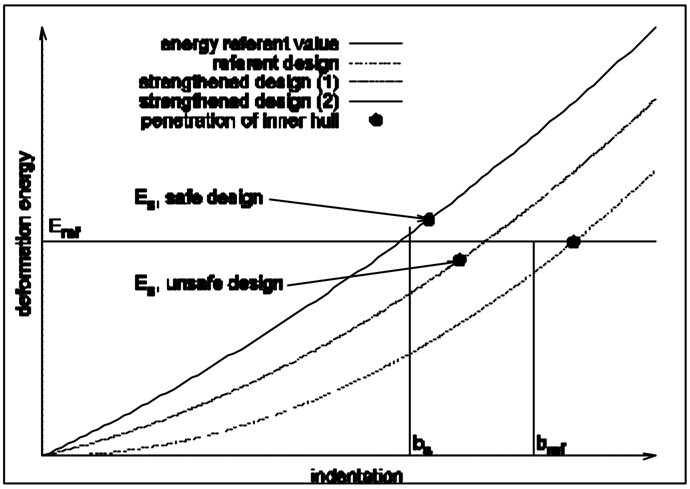


Fig. 2: Comparison of the deformation energy for reference and strengthened designs.

3. WORKING FLOW OF THE APPROVAL PROCEDURE

An application of the approval procedure will be basically followed by 7 steps:

Step 1
Generating an initial structural design with a double hull breadth b_s, which does not meet the damage stability requirements. However, this design should comply with requirements of minimal scantlings by a classification society but it does not need any additional strengthening, for example ice strengthening;

Step 2
The reference double hull breadth b_{ref} should be determined from the damage stability requirement in accordance with SOLAS Part B-1

Regulation 25-3, 25-4 and 25-5 under consideration of the reduction factor r.

Step 3
Based on the reference double hull breadth b_{ref} a correspondent reference structural design shall be provided. However, from the point of view of strength the reference side structural design only needs to comply with requirements of minimal scantlings by a classification society without any additional strengthening.

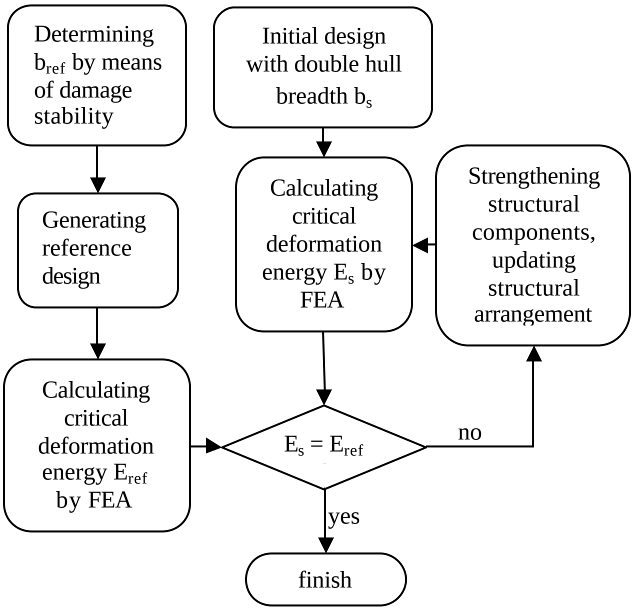
Step 4
By means of FEA the mean value of the critical deformation energy E_{ref} for the reference design, by which the inner hull is penetrated, shall be calculated for different defined collision cases;

Step 5
Similar as in the step 4 the critical deformation energy value E_s for the structural design with b_s, by which the first penetration of inner hull occurs, shall also be calculated by FEA;

Step 6
Comparing E_{ref} with E_s, if $E_s \geq E_{ref}$, then the structural design with the double hull breadth b_s has at least a same degree of safety standard as the reference design with b_{ref} in accordance with the paragraph 3 of SOLAS Part B-1, Regulation 25-1, otherwise the actual design with the initial double hull breadth b_s should be improved by strengthening certain components of the side structural or/and by updating the structural arrangement to increase the collision resistance;

Step 7
For the updated structural design the step 5 and 6 shall be repeated until the condition of the energy equivalence $E_s \geq E_{ref}$ is demanded.

For clarity purpose, a work flow for the described approval procedure is displayed as follows:



4. CALCULATION OF CRITICAL DEFORMATION ENERGY

Critical deformation energy in each case is generally calculated by means of the Finite Element Analysis (FEA). The analysis shall be carried out using a recognized explicit finite element code (LS-DYNA, PAM-CRASH, MSC/DYTRAN, ABAQUS etc.) capable of dealing with both geometrical and material nonlinear effects as well as realistic rupture of elements.

4.1 *Generation of FE Models*

First of all, two FE models shall be generated for both initial and reference structural designs. Principally the generation of the FE models shall catch all plastic deformations induced in each considered collision cases. It is recommended that at least a whole length of the hold shall be modelled. For symmetrical collision cases it is allowed that only half of a hold length is taken into account. Generally at both ends of the hold all 3 translatory degree of freedom shall be restricted. In the cases that a global bending of the ship sections is not significant for evaluation of plastic deformation energy it is sufficient only to consider half of ship sections. In these cases the transverse displacements at the MS can be constrained. After accomplishing a FE model a test collision calculation shall be carried out to ensure that there is no occurrence of plastic deformations near the constraint boundaries.

Generally areas near collision positions in a side structure shall be sufficient fine idealized, while other parts can be modelled much coarser. The size of the element mesh shall be suitable for reasonable interpretation of local folding deformations and for determination of realistic failure of elements based on practical failure criteria of materials. From calculation experience the maximal element length shall not be more than 200 mm in collision areas. Usually plate structures, such as shell, inner hull, web as well as stringer can be idealized as shell elements and stiffeners can be represented as eccentric beam elements. Cut outs and manholes in collision areas shall be taken into account during the idealization.

4.2 *Material properties*

Since a collision calculation involves extreme structural behaviour with both geometrical and material nonlinear effects, the input of material properties up to the ultimate tensile stress has a significant influence on the extent of critical deformation energy. It is generally recommended to use true stress-strain relationship, which can be obtained from a tensile test in the following way:

$$s = C \cdot e^n ,$$

where

$$n = \ln(1 + A_g)$$

and

$$C = R_m \cdot \left(\frac{e}{n} \right)^n .$$

A_g is the maximal uniform strain related to the ultimate tensile stress R_m. Both values can be measured from a specimen tensile test. e is the natural logarithmic constant. For shipbuilding steel with a maximal R_{eH} up to 355 MPa, if only ultimate stress R_m is available, following approximation can be used to obtain proper A_g value from a known R_m ([MPa]) value:

$$A_g = \frac{1}{0.24 + 0.01395 \cdot R_m} .$$

4.3 *Failure Criteria*

As mentioned the most important specified measurement for the energy equivalence for different structural designs is the critical energy value, by which the inner hull of a struck ship is penetrated and as a critical point it indicates leakage and flooding of the inboard holding space. In a FEA this critical situation will be represented by the initial fracture of a finite element, which has an extreme large plastic strain in this moment.

Usually the first rupture of an element in a FEA will be defined with a failure strain value. If the calculated strain, such as plastic effective strain, principal strain or for a shell element strain in the thickness direction exceeds its defined failure strain value, the element will be “fractured” and deleted from the FE model. The deformation energy in this element will keep in a constant value in the further calculation steps.

Calculations with LS-DYNA have shown that the deformation energy responds very sensitively to the defined failure criteria. Fig. 3 illustrates the developments of deformation energy with different plastic failure strain values of 10% and 20% respectively. It is shown that the definition of the failure strain value is a most important key point for a correct prediction of realistic critical deformation energy and that it can result in an incorrect assessment of the energy absorption, if an improper failure criterion is defined [Lehmann, etc., 2001].

In fact the development of a rupture of a structural component is a very complicated process and is influenced from many factors. Firstly it is directly related to material characteristics such as yield stress, the maximal uniform strain and the fracture strain. Secondly it is well known from numerous practical experiences and theoretical investigations that an initiation of a fracture depends also on the stress states resulted under complicated loads in the structures. In addition, it is also influenced from production process, manufacture quality as well as environmental and operational conditions. For a FEA mesh size, element shape as well as selected element types plays also very important roles because in reality a fracture process is developed from a uniform deformation state over the whole component to a very local necking in a very small area with extreme large strain values. To obtain practical failure strain definitions under consideration of element size, stress state and manufacture influence many thickness measurements from prototype damaged structure components such as shell plating and stiffeners etc. have been carried out and the uniform strain, the necking as well as the necking length have been determined. From many evaluations of different thickness measurements the following definition for failure strain is recommended [Scharrer, etc., 2002]:

$$e_f(l_e) = e_g + e_e \cdot \frac{t}{l_e},$$

where ε_g is the uniform strain and ε_e is the necking, t and l_e is the plate thickness and an individual element length respectively. It is commonly recommended that the ratio l_e/t is not less than 5 for shell element. The values of uniform strain and the necking achieved from the thickness measurements are related to the calculated stress states and they are assigned in the following table:

stress states	1-D	2-D
ε_g	0.079	0.056
ε_e	0.76	0.54
element type	beam, truss	shell, plate

Much more realistic ε_g and ε_e values can be achieved if additional thickness measurements from prototype damage cases and experiments have been evaluated.

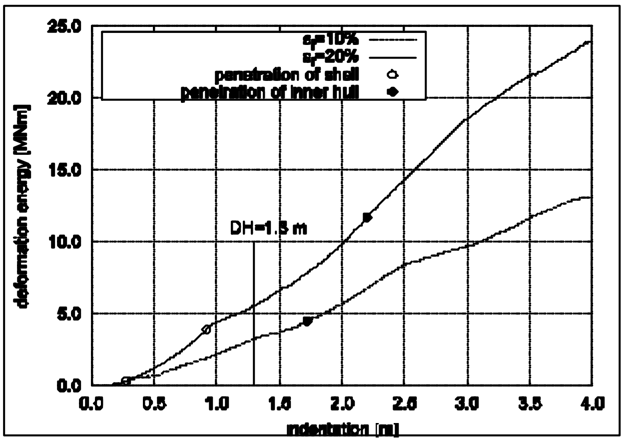


Fig. 3: Comparison of deformation energy from different definitions of failure strain values.

4.4 *Definition of Striking Ship and Striking Bow*

A ship with a nearly same main measurement, such as displacement, design droughts, length and width as the struck ship is to be assumed as the striking ship. It is desired that at least two types of striking bow shapes shall be used for calculations of the critical deformation energy:

- bow shape 1: striking bow contour without bulb;
- bow shape 2: striking bow contour with bulb.

The bow size and bow shape of the striking ship are related with the main measurement, such as B/T, H/T, block coefficient C_b, and the stem angle f. Two standard striking bow sizes are defined as following:

- The forecastle deck is 2.5 m higher than the main deck;
- The stem angle f for bow shape 1 (without bulb) is 65 grads;
- The most front coordinate of the bulbous bow is same as that of the forecastle deck;
- The height of the bulbous bow is equal to the design draught of the striking ship;
- The maximal width of the bulbous bow corresponds to 40% of the design draught.

From these definitions an individual bow can be generated by distorting the shape of the standard and its size is based on the main measurement as well as the geometrical parameters of an existed striking ship.

Because in many collision cases the striking bow has only slight deformations compared with the side construction of a struck ship, a striking ship will generally be defined as rigid. Only for special situations, if the struck ship has a very strong strengthened side construction compared to the striking bow, the structural behaviour of the struck ship can be influenced by the plastic deformation of striking ship significantly. IN these cases the striking ship must be considered as deformable and the detailed arrangement in the striking bow should also be modelled. For this purpose there is a program available from GL to generate a detailed standard bow construction with and without bulb based on the main measurement of a striking ship.

4.5 *Definition of Collision Cases*

For the definition of collision cases following assumptions are necessary:

- The striking angle between striking and struck ship is assumed 90 grads in the horizontal plane;
- The struck ship has no speed, while the striking ship hits on the side of the struck one perpendicularly with a reasonable speed.

The extent of critical deformation energy absorbed by a struck ship varies depending on striking positions on a struck ship. IN the vertical direction the striking positions are definitively decided by the actual draught differences of striking and struck ships in the range of design and ballast draughts of both ships in the following way (Fig. 4):

$$\Delta T_1 = T_{2\max} - \frac{3 \cdot T_{1\min} + T_{1\max}}{4},$$

$$\Delta T_2 = T_{2\max} - \frac{T_{1\min} + 3 \cdot T_{1\max}}{4},$$

$$\Delta T_3 = \frac{T_{2\min} + 3 \cdot T_{2\max}}{4} - T_{1\max},$$

$$\Delta T_4 = \frac{3 \cdot T_{2\min} + T_{2\max}}{4} - T_{1\max},$$

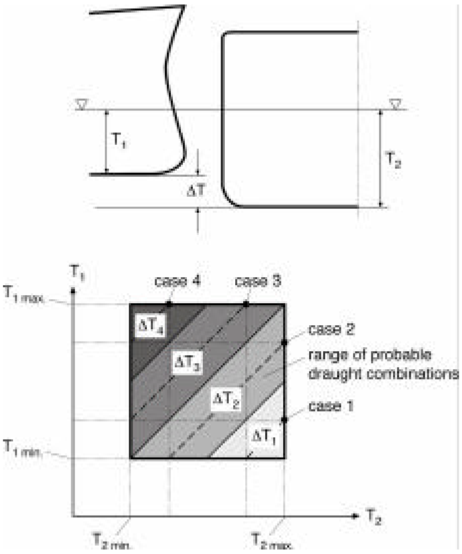


Fig. 4: Definition of striking positions in vertical direction

where $T_{1\max}$ is the design draught of the striking ship and $T_{1\min}$ is the ballast draught of the striking ship, while $T_{2\max}$ and $T_{2\min}$ are the design and ballast draughts of the struck ship respectively. The area restricted by T_1=T1min, $T_1=T_{1\max}$ and $T_2=T_{2\min}$, $T_2=T_{2\max}$ in Fig. 4 is the total collision possibilities. It is shown from the Fig. 4 that a whole draught range from ballast to design draught is divided into 4 equal parts for both striking and struck ships. Due to the assumption of same ballast and design draughts of both striking and struck ships each diagonal connecting an equivalent division represents an equal draught difference, in which the lines ?T_i, i=1,2,3,4 for the 4 partial areas represent the whole draught differences between striking and struck ships. Therefore, for each diagonal ?T_i, i=1,2,3,4 one collision case is defined, which always corresponds to the maximal possible masses for both striking and struck ships (the highest point of a diagonal). The weighting factors for these 4 equivalent draught differences correspond to the percentage of the correspondent areas and equal to 1 3 3 1.

Additionally different arrangements of a side structure in a struck ship in the longitudinal direction will also lead to the change of critical deformation energy value. Thus two typical colliding positions among longitudinal direction are defined:

1. the middle point between two web frames, which includes the middle range of 0.5 web spacing;
2. directly colliding on a web frame, which includes the side range of 0.25x2 web spacing.

4.6 *Evaluation of Calculated Deformation Energy*

As defined, for evaluation of the critical deformation energy for one side structure of a struck ship totally 16 FEA (4 striking positions in the vertical direction and 2 positions in the longitudinal direction, as well as two striking bow shapes with and without bulb) should be carried out. Based on the 16 calculated critical deformation energy values, by which the inner hull is penetrated, the mean value of the critical energy can be determined by averaging the 16 energy values with defined weighting factors. First of all, the energy for each vertical striking position case should be weighted as follows:

between two web frames for striking bow shape 1:

$$\overline{E}_{m,1} = \frac{1}{8} \cdot (E_{m,1,1} + 3 \cdot E_{m,1,2} + 3 \cdot E_{m,1,3} + E_{m,1,4}),$$

between two web frames for striking bow shape 2:

$$\overline{E}_{m,2} = \frac{1}{8} \cdot (E_{m,2,1} + 3 \cdot E_{m,2,2} + 3 \cdot E_{m,2,3} + E_{m,2,4}),$$

on a web frame for striking bow shape 1:

$$\overline{E}_{r,1} = \frac{1}{8} \cdot (E_{r,1,1} + 3 \cdot E_{r,1,2} + 3 \cdot E_{r,1,3} + E_{r,1,4}),$$

on a web frame for striking bow shape 2:

$$\overline{E}_{r,2} = \frac{1}{8} \cdot (E_{r,2,1} + 3 \cdot E_{r,2,2} + 3 \cdot E_{r,2,3} + E_{r,2,4}).$$

Then the average value from these 4 weighted energy values is the critical energy for a side structural design, e.g. for the reference structural design:

$$E_{ref} = \frac{1}{4} \cdot (\overline{E}_{m,1} + \overline{E}_{m,2} + \overline{E}_{r,1} + \overline{E}_{r,2}).$$

For the initial or strengthened side structural design the critical deformation energy value E_s can be achieved in the same way.

For the comparing purpose there are at least two sides structural designs, reference and strengthened, must be evaluated. It means that in this approval procedure at least 32 FEA must be performed.

To avoid unfavorable collsion cases, by which an extremely low critical deformation energy value can appear for a strengthened structural design, following conditions must also be santisfied for each individual critical energy value:

$$E_{ij,k,s} \geq 0.6 \cdot E_{ij,k,ref},$$

where i=1,2, j=1,2,3,4 and k=m, r.

5. EXSAMPLE

For the representative purpose an example of a typical multi purpose cargo ship with a double hull and one large holding will be approved with the described procedure.

The ship length L_{pp}=85 m, for which the proof of damage stability in accordance with the new regulation 25-1 of SOLAS, Part B-1, will be required. The main measurement are as follows:

L_{oa}	90.00 m
L_{pp}	85.00 m
breadth	13.00 m
double hull breadth	1.30 m
depth to main deck	7.00 m
scantling draught	5.70 m
balast draught	3.90 m
holding length	63.0 m
deadweight	4200 t
speed	12.0 kn
ice class	Swedish Finnish 1B

The general arrangement is shown in Fig. 5. The large holding is from fr.21 to fr. 106. The main section is shown in Fig. 6. With a double hull breadth b=1.3 m the initial structural design does not meet the damage stability requiements.

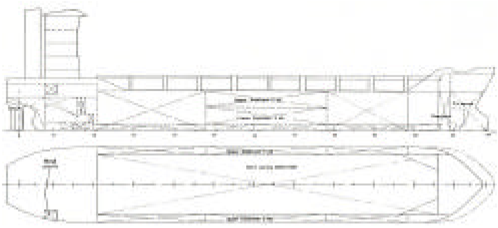


Fig. 5: General arrangement of a multi purpose cargo ship

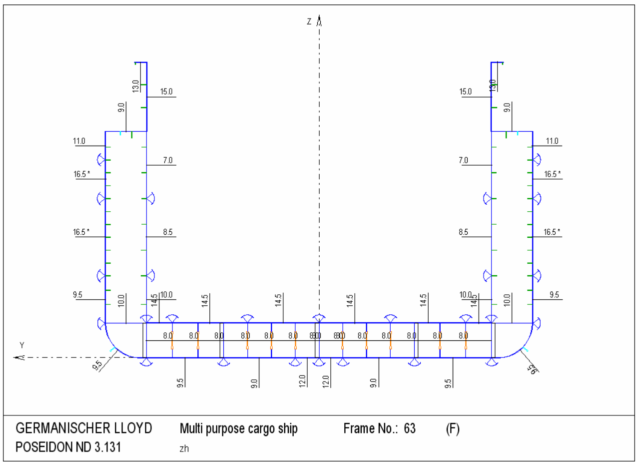


Fig. 6: Main section of the original design

Step 1: *Establishing anInitial Design*

Based on the original drawings an initial structural design with the minimal scantlings required by is performed according to the GL rule for seagoing ships version 2003 [GL rule, 2003] by means of the structural design program POSEIDON [POSEIDON, 2003] (Fig. 7). In the initial design the ice strengthening does not be considered.

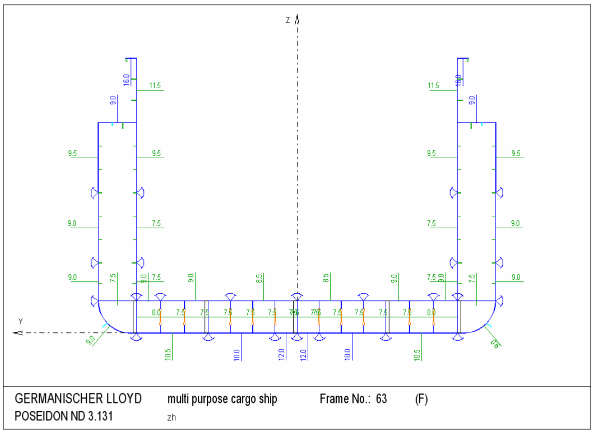


Fig. 7: Initial design with minimal scantlings acc. to GL rule

Step 2: *Determination of a Reference Double Hull Breadth b_{ref}*

The reference double hull breadth b_{ref} should be determined from the damage stability requirements in accordance with SOLAS Part B-1 Regulation 25-3, 25-4 and 25-5 under consideration of the reduction factor r. For the large holding length = 63 m the relative length of this compartment J=62.9/84.98=0.74 = 0.2b/B

$$r = \frac{b_{ref}}{B}\left(2.3+\frac{0.08}{J+0.02}\right)+0.1$$

$$b_{ref} = 5.655\cdot(r-0.1)$$

From the calculation of attained subdivision index the required reduction factor for the holding is r=0.454, which corresponds to a necessary b_{ref}=2.0 m

Step 3: *Determination of a Reference Structural Design*

Based on the reference double hull breadth b_{ref} a reference structural design is performed as shown in Fig. 8. However, the reference side structural design does need only to comply with requirements of minimal scantlings by the GL rules without any additional strengthening. Due to the large double hull breadth b_{ref} the transverse strength is sufficient if the web spacing is increased to 3 frame spacing (2.22 m) instead of 2 frame spacing (1.48 m).

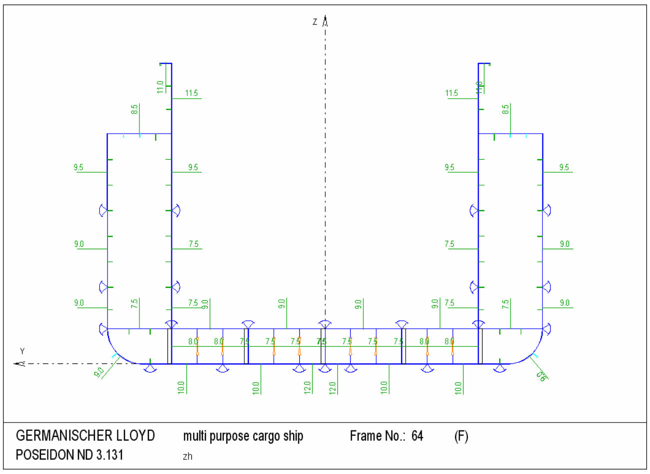


Fig. 8: Reference design with minimal scantlings acc. to GL rule

Step 4: *Calculating Critical Deformation Energy E_{ref}*

Step 4.1: Generating FE Models

Based on the main section data a FE model has been generated using the design program POSEIDON. The FE model includes the whole length of the large holding (x=15 to 78 m). All plate structures are idealized as shell elements and all stiffeners as beam elements. In the range near the striking positions nonlinear elements have been used while the area far from striking positions only linear elastic elements have been generated. In the possible striking affected areas the element size is equal to185x200 mm. The FE models of the two striking bow shapes with and without bulb have been generated using the GL program BUGGEO. Both FE models for striking and struck ships have been merged together in appropriate positions and then translated into the LS-DYNA format. The FE models are shown in the Fig. 9.

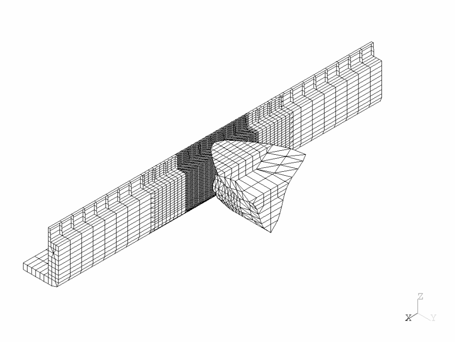


Fig. 9: FE model of striking bow and struck ship for reference design

Step 4.2: Assembling of Collision Cases

Under the assumption that both striking and struck ships have same draught, the striking positions in the vertical direction have been determined depending on the draught differences between design and ballast draughts (table 1 and Fig. 10):

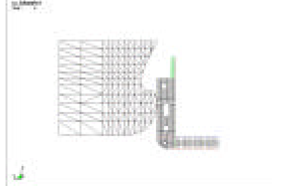
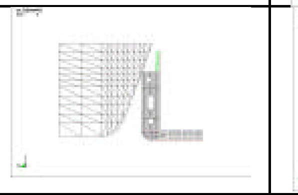
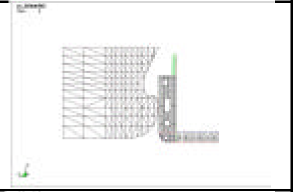
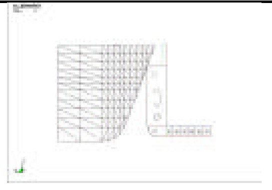
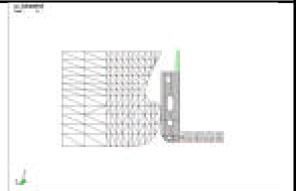
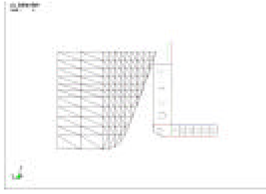
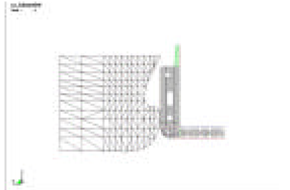
case	bow shape 1, without bulb	bow shape 2, with bulb
case 1		
case 2		
case 3		
case 4		

Fig. 10: Collision cases for both bow shapes, reference design

Step 4.3: Calculating Critical Deformation Energy

For each collision case there is one explicit FEA performed by using program code LS-DYNA version 960. The collision speed of striking ship is 10 m/s (19.5 kn) as constant. The total simulated collision scenarios time is 0.4 sec, which corresponds to 4 m indentation for the struck ship. As results total plastic deformation energy depending on the indentation of the struck ship is calculated and the critical value of this energy, when the first penetration of the inner hull of the struck ship occurs, has also been achieved. The calculated plastic deformation energy value for the penetration of the shell as well as the critical deformation energy of the penetration of the inner hull for different collision cases are shown in table 2.

T_{1max}=T_{2max}=5.70 m; T_{1min}=T_{2min}=3.90 m		?T [m]
case 1	$\Delta T_1 = T_{2\max} - \frac{3\cdot T_{1\min} + T_{1\max}}{4}$	1.35
case 2	$\Delta T_2 = T_{2\max} - \frac{T_{1\min} + 3\cdot T_{1\max}}{4}$	0.45
case 3	$\Delta T_3 = \frac{T_{2\min} + 3\cdot T_{2\max}}{4} - T_{1\max}$	0.45
case 4	$\Delta T_4 = \frac{3\cdot T_{2\min} + T_{2\max}}{4} - T_{1\max}$	1.35

Table. 1: Draught differences between striking and struck ships

striking between two webs					
bow shape	coll. case	penetration of shell		penetration of inner hull	
		indent [m]	energy [MNm]	indent [m]	energy [MNm]
1	1	0.680	1.026	2.481	8.502
	2	0.640	1.086	2.920	13.708
	3	0.561	0.737	1.480	3.487
	4	0.640	1.082	1.961	8.323
	$\overline{E}_{m,1}$				***8.551***
2	1	0.320	0.469	2.360	4.201
	2	0.320	0.474	2.440	6.347
	3	0.320	0.493	2.441	9.477
	4	0.320	0.538	2.481	21.448
	$\overline{E}_{m,2}$				***9.140***
striking at a web					
bow shape	coll. case	penetration of shell		penetration of inner hull	
		indent [m]	energy [MNm]	indent [m]	energy [MNm]
1	1	0.241	0.234	3.160	20.119
	2	0.280	0.601	2.520	17.737
	3	0.761	2.686	2.360	17.735
	4	1.521	8.075	3.440	37.557
	$\overline{E}_{r,1}$				***20.512***
2	1	0.440	1.298	2.520	10.025
	2	0.521	1.765	2.521	12.397
	3	0.521	1.962	2.520	24.276
	4	0.640	3.651	2.520	33.441
	$\overline{E}_{r,2}$				***19.186***

Table 2: Critical deformation energy for the reference design

The mean value of the critical deformation energy can be obtained as follows:

$$E_{ref} = \frac{1}{4}\cdot(\overline{E}_{m,1} + \overline{E}_{m,2} + \overline{E}_{r,1} + \overline{E}_{r,2})$$

$$= \frac{1}{4}\cdot(8.551 + 9.140 + 20.512 + 19.186)$$

$$E_{ref} = 14.347 \text{ [MNm]}$$

Step 5: *Calculating the mean critical deformation energy E_s*

Step 5.1: Generating FE model
The FE models are shown in the Fig. 11.

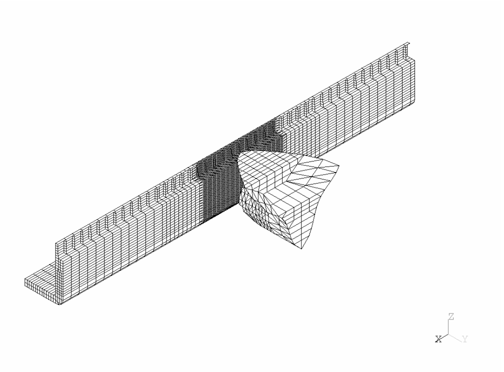


Fig. 11: FE model of striking bow and struck ship, initial design

Step 5.2: Determination of collision cases

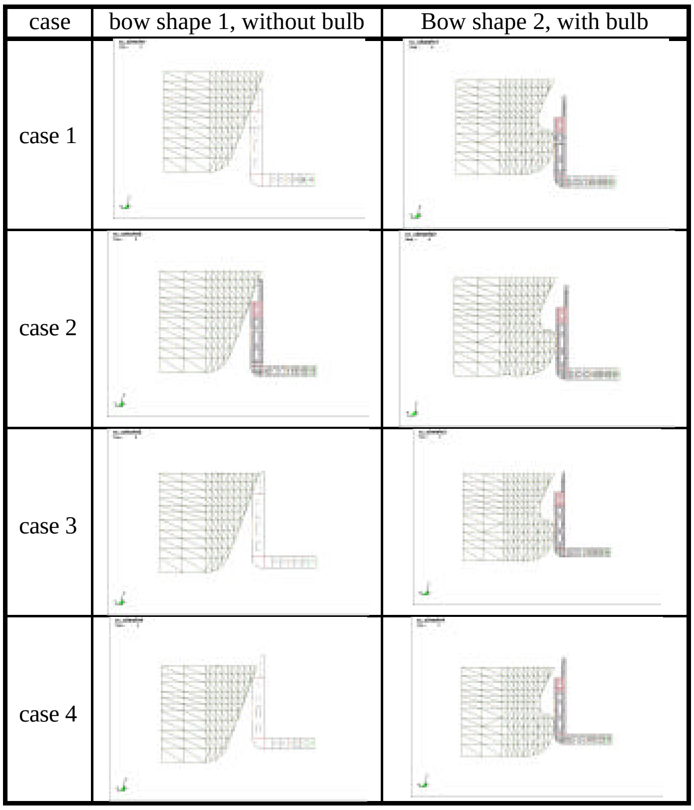


Fig. 11: Collision cases for both bow shapes, initial design

Step 5.3: Calculating the critical deformation energy
The calculated plastic deformation energy for the penetration of the shell as well as the critical deformation energy of the penetration of the inner hull of different collision cases and for the initial structural design is shown in table 3.

striking between two webs					
bow shape	coll. case	penetration of shell		penetration of inner hull	
		indent [m]	energy [MNm]	indent [m]	energy [MNm]
1	1	0.560	1.122	1.320	4.325
	2	0.520	1.220	1.760	8.700
	3	0.440	0.626	1.641	8.496
	4	0.480	0.706	2.200	14.469
	$\overline{E}_{m,1}$				***8.800***
2	1	0.280	0.366	1.680	4.549
	2	0.280	0.362	1.681	5.172
	3	0.280	0.377	1.881	10.681
	4	0.280	0.453	1.920	19.882
	$\overline{E}_{m,2}$				***8.999***
striking at a web					
bow shape	coll. case	penetration of shell		penetration of inner hull	
		indent [m]	energy [MNm]	indent [m]	energy [MNm]
1	1	0.360	0.830	2.401	15.905
	2	0.560	2.308	2.480	19.000
	3	1.880	12.877	1.761	11.710
	4	1.760	10.483	3.040	29.490
	$\overline{E}_{r,1}$				***17.191***
2	1	0.480	1.435	1.800	6.157
	2	0.560	1.885	1.681	7.809
	3	0.480	1.572	1.840	14.168
	4	0.440	2.161	1.921	22.682
	$\overline{E}_{r,2}$				***11.846***

Table 3: Critical deformation energy for the initial structural design

The mean value of the critical deformation energy can be obtained as follows:

$$E_s = \frac{1}{4}\cdot(\overline{E}_{m,1} + \overline{E}_{m,2} + \overline{E}_{r,1} + \overline{E}_{r,2})$$

$$= \frac{1}{4}\cdot(8.800 + 8.999 + 17.191 + 11.846)$$

$$E_s = 11.709 \text{ [MNm]}$$

Step 6: *Comparing E_{ref} with E_s:*

$$E_s = 11.709 < E_{ref} = 14.347 \text{ [MNm]}$$

Due to this fact the actual design with the double hull breadth b_s should be improved by strengthening certain components of the side structure or/and updating the structural arrangement to increase the collision resistance.

Step 7: *Structural Design with Ice Strengthening*

According to the current damage stability calculation method in the SOLAS Regulation ice strengthening has not any influences on the calculating results. In fact this strengthening can contribute much more collision resistances and at the same time it will significantly reduce the probability of the flooding of inboard holding space. Therefore the first measurement to increase collision worthiness is to take the ice strengthening into account.

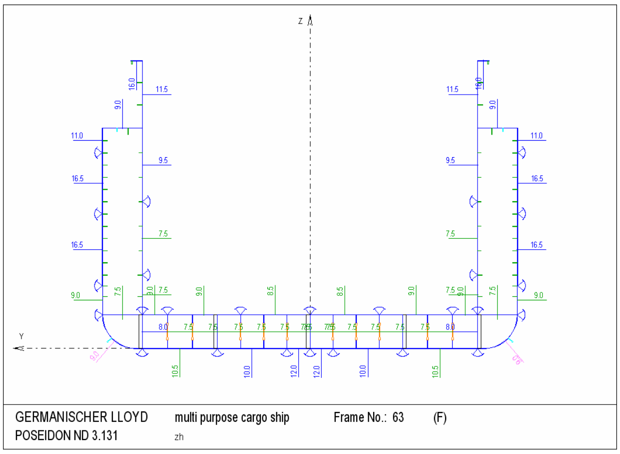


Fig. 12: Actural structural design with ice strengthening

striking between two webs					
bow shape	coll. case	penetration of shell		penetration of inner hull	
		indent [m]	energy [MNm]	indent [m]	energy [MNm]
1	1	0.396	0.749	1.433	6.941
	2	0.636	2.088	1.835	10.723
	3	1.560	9.813	1.680	11.180
	4	1.081	4.961	3.040	33.906
	$\overline{E}_{m,1}$				***13.320***
2	1	1.160	9.184	2.241	17.724
	2	0.956	7.166	2.072	16.977
	3	0.680	4.172	1.920	16.974
	4	0.320	0.976	1.800	20.613
	$\overline{E}_{m,2}$				***17.524***
striking at a web					
bow shape	coll. case	penetration of shell		penetration of inner hull	
		indent [m]	energy [MNm]	indent [m]	energy [MNm]
1	1	0.200	0.377	3.081	28.239
	2	0.520	2.189	2.640	25.011
	3	1.920	14.999	3.400	44.544
	4	1.840	12.728	3.320	41.373
	$\overline{E}_{r,1}$				***34.785***
2	1	0.720	4.180	2.080	13.804
	2	0.840	5.910	2.001	18.578
	3	0.720	5.265	1.761	18.182
	4	0.601	4.254	1.760	23.031
	$\overline{E}_{r,2}$				***18.389***

Table 4: Critical deformation energy for the strengthened structural design

In this way the shell plates in the range of z=2.05 m to 6.4 m have been replaced using high tensile steel (R_{eH}=355 MPa). Thickness of the plates in this range has also been increased to 16.5 mm while the breadth of the double hull is same as that of the initial design. Additionally the numbers of longitudinal stiffeners have also been increased to 14 instead of 7. Fig. 12 illustrates the main section of the strengthened structural design.

From the ice strengthened structural design a FE model has been generated. The assembling of collision cases as well as the calculation procedure for the critical deformation energy is same as in the step 5. The calculation results are shown in table 4.

The mean value of the critical deformation energy can be obtained as follows:

$$E_s = \frac{1}{4}\cdot(\overline{E}_{m,1}+\overline{E}_{m,2}+\overline{E}_{r,1}+\overline{E}_{r,2})$$

$$= \frac{1}{4}\cdot(13.320+17.524+34.785+18.389)$$

$$E_s = 21.005 \text{ [MNm]}$$

Comparing E_{ref} with E_s:

$$E_s = 21.005 > E_{ref} = 14.347 \text{ [MNm]}$$

$$\frac{E_s}{E_{ref}} = 1.464$$

From the comparison it is clear that the calculated mean critical deformation energy for the strengthened structural design is 46% more than that of the reference design.

The deteiled comparson of the calculated critical energy for each collision case between the strangthened and the reference structural design is illustrated in the table 5:

striking between two webs				
bow shape	collision case	strengthened design E_s [MNm]	reference design E_{ref} [MNm]	$\frac{E_s}{E_{ref}}$
1	1	6.941	8.502	0.816
	2	10.723	13.708	0.782
	3	11.180	3.487	3.206
	4	33.906	8.323	4.074
2	1	17.724	4.201	4.219
	2	16.977	6.347	2.675
	3	16.974	9.477	1.791
	4	20.613	21.448	0.961
striking at a web				
1	1	28.239	20.119	1.404
	2	25.011	17.737	1.410
	3	44.544	17.735	2.512
	4	41.373	37.557	1.102
2	1	13.804	10.025	1.377
	2	18.578	12.397	1.499
	3	18.182	24.276	0.749
	4	23.031	33.441	0.689

Table 5: Comparing of critical deformation energy for each collision case between strengthened and reference design

The comparing results in table 5 have shown that E_s/E_{ref} values vary from 0.689 to 4.219 for individual collision case and no value is smaller than the required minimum 0.6. The comparison has also shown that the critical energy for different collision cases, which correspond to different striking positions, varies very strongly from case to case.

The comparion of E_s/E_{ref} mean values has indicated that the side structural design with ice strengthening has a predominated collision resistance than the reference one. It comes to a conclusion that this structural design with ice strengthenning can be accepted as an alternative design which at least has reached the same degree of safety as represented by the new regulation of SOLAS Part B.

For the clearify purpose the developments of the plastic deformation energy depending on the indentation for each collision case and for the initial, the reference and the strengthened structural design are illustrated in Fig. 13 and Fig. 14.

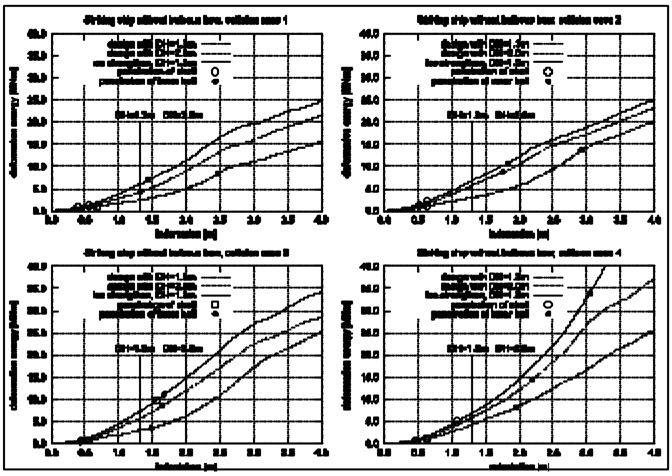


Fig. 13: Development of deformation energy depending on indentations for all designs and all collision cases, striking bow without bulb

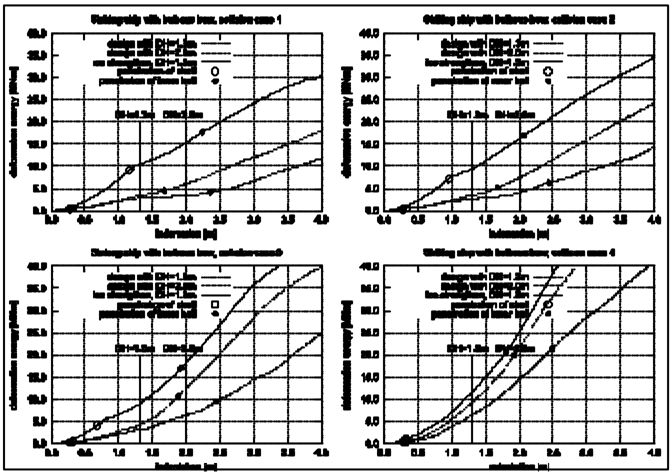


Fig. 14: Development of deformation energy depending on indentations for all designs and all collision cases, striking bow with bulb

6. SUMMARY

Since7.1.1998 new design and construction of cargo vessels from 80 m in length must be required to calculate damage stability. As consequence a significant increase in building costs and operational restrictions due to additional subdivisions, such as a transverse bulkhead for such size of cargo vessels are awaited. On the other hand, the paragraph 25-1.3 of this regulation specifies that for particular ship or group of ships alternative arrangements may be accepted, provided that it is satisfied that at least the same degree of safety is achieved. In this paper an alternative approval procedure in relation to the same degree of safety has been presented. The basic philosophy of the approval procedure is to compare the critical deformation energy in case of side collision of a strengthened structural design to that of a reference design which has complied with the damage stability requirement described in the SOLAS regulation. The example has shown that by means of the strengthening of side structural components or changing side structural arrangements the solution of the same degree of safety can be achieved and the strengthened structural design will provide more loading capacity and reduce operational restrictions. The considered collision cases, which depend on striking bow shapes and striking positions, can be reduced if more experiences applying this approval procedure have been attained.

7. ACKNOWLEDGEMENT

This work thankfully was partially funded by the European Commission in the scope of the project CRASHCOASTER (G3RD-CT-2000-00253).

REFERENCES

SOLAS Regulation, Part B-1, 25-1, 25-2, 25-3, 1997

GL Annual Report 1992 pp. 18-22, Germanischer Lloyd, 1992

Lehmann, Egge, Scharrer, Zhang, The 8th International Symposium Calculation of Collision with the Aid of Linear FE Models, on Practical Design of Ships and Other Floating Structures (PRADS) 2001, Vol. II, pp. 1293-1300

Scharrer, Zhang, Egge, Abschlußbericht zum Vorhaben MTK0614, Kollisionsberechnungen in schiffbaulichen Entwurfssystemen, Bericht Nr. ESS 2002.183, Germanischer Lloyd 2002

GL rule Part 1 Seagoing Ships, Chapter 1 Hull Structures Germanischer Lloyd, 2003

Tutorial for Hull Design Software POSEIDON, Germanischer Lloyd, 2003