Damage Stability Approval Procedure under Consideration of Collision Resistance

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ABSTRACT

Paragraph 1 of the regulation 25-1 of SOLAS, Part B-1, SOLAS as amended, 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 with alternative arrangements, provided that at least the same degree of safety is achieved
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1. INTRODUCTION

Until mid 1998, the SOLAS regulations on subdivision and damage stability, as contained in part B-1 of SOLAS chapter II-1, regulation 25-1, specify probabilistic 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 comply with these damage stability regulations. As a consequence of this, a significant increase in building costs and operational restrictions, due to additional subdivision, such as a transverse bulkhead in the cargo hold area for cargo vessels of such sizes are anticipated.

In 2009, revised similar probabilistic damage stability regulations will come into force, also applicable for passenger vessels. The permeability assumptions for ro-ro spaces have been altered, leading to a requirement for a higher level of safety. Some current designs of ro-ro cargo and ro-ro passenger vessels will need enhanced survival capabilities to meet the new requirements.

Paragraph 25-1.3 of the current SOLAS regulation specifies that for any particular ship or group of ships alternative arrangements may be accepted, provided that the same degree of safety is maintained. Some flexibility is allowed for structural designs with improved safety level. In relation to damage stability it means preventing penetration of the inner hull by increasing collision resistance for double hull vessels.

Within the scope of the EU-Project Crash Coaster, Germanischer Lloyd has worked out an approval procedure which provides a standard for evaluation and approval of alternative solutions for design and construction of 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, however, varies depending on a number of 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 increase the loading capacity and reduce operational restrictions.

The purpose of this approval procedure is to provide a standard for evaluation and approval of alternative solutions for design and construction of generl cargo vessels described in regulation 25-1,pp of SOLAS, Part B-1. This procedure has been forwarded to IMO (SLF 46/Inf.10,) by Germany and other flag states authorities have indicated their willingness to accept this approval procedure.

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 the subdivision, e.g. number and positioning of longitudinal and transverse and bulkheads or watertight decks. In reality, whether a compartment floods or not also depends on the strength of involved structural components such as contributions of plate thickness or arrangements of stringers and stiffeners. In case of a collision with a double hull vessel, the penetration of the shell and inner hull indicates the flooding of wing tanks and inboard holding space. This critical situation can be described by the 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 leading to compliance with the applicable damage stability requirements.

The calculation of critical deformation energy, the energy value absorbed by the struck ship when the inner hull is penetrated, is calculated 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 probabilistic damage stability requirement as laid out in current SOLAS Part B-1, the attained subdivision index A shall not be less than the required subdivision index R defined as the function of the subdivision length:

$A \geq R$ with

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

$$R_0 = (0.002 + 0.0009 \cdot L_s) \quad (2)$$

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 the reduction factor r, which represents the probability that the holding space will not be flooded. It is calculated as follows:

$$\text{for } J \geq 0.2 \cdot \frac{b}{B} \quad (3)$$

$$r = \frac{b}{B} \cdot \left(2.3 + \frac{0.08}{J + 0.02}\right) + 0.1 \text{ if } \frac{b}{B} \leq 0.2 \quad (4)$$

$$r = \frac{0.016}{J + 0.02} + \frac{b}{B} + 0.36 \text{ if } \frac{b}{B} > 0.2 \quad (5)$$

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

$$J \geq 0.2 \cdot \frac{b}{B}, \quad (6)$$

$$\text{for } J = 0.2 \cdot \frac{b}{B}, \quad (7)$$

where b is the double hull breadth and J is the dimensionless damage length. It can be seen in Fig. 1 that the reduction factor r is assumed to be proportional to the ratio between double hull breadth b and the width of the ship B, increased in the range of $\frac{b}{B} \leq 0.2$. 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

$$c = \frac{b_{ref}}{b_s} \geq 1.0 \tag{8}$$

is defined [GL, 1992], where b_s is the double hull breadth of an initial design, which does 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:

f for $J \geq 0.2 \cdot \frac{c \cdot b_s}{B}$ (9)

$$r = \frac{c \cdot b_s}{B} \cdot \left(2.3 + \frac{0.08}{J + 0.02}\right) + 0.1 \tag{10}$$

if $\frac{c \cdot b_s}{B} \leq 0.2$

$$r = \frac{0.016}{J + 0.02} + \frac{c \cdot b_s}{B} + 0.36 \tag{11}$$

if $\frac{c \cdot b_s}{B} > 0.2$ (12)

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

$$J \geq 0.2 \cdot \frac{c \cdot b_s}{B} \tag{13}$$

for $J = 0.2 \cdot \frac{c \cdot b_s}{B}$ (14)

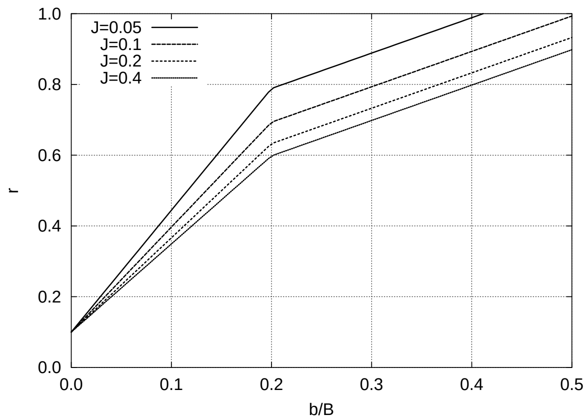


Fig. 1: Reduction factor r in relationship with b/B.

In this way sufficient survival capability for a vessel can be attained without needing to survive the flooding of the cargo hold area. This can be achieved if the breadth of the double hull b is increased to a certain value b_{ref}. An excessive double hull breadth cannot be accepted in the practice due to the enormous loss of cargo hold space and higher unacceptable heeling angles in the case of wing tank damages. The inclusion of a strengthening factor c, can raise the p_i values of double hull damages without loss of cargo hold space or higher unacceptable heeling angles.

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, can 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 collision resistance or degree of safety for both designs can be achieved by comparing both critical energy values. 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 the same degree fo safety for 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 keeping the initial double hull breadth b_s the side structure of the initial design can be improved and strengthened so that its critical deformation energy is at least equal to that of the reference structural design (Fig. 2):

$$E_s = E_{ref}$$

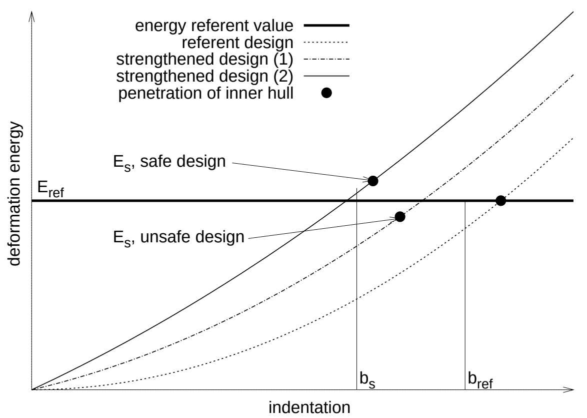


Fig. 2: Comparison of the deformation energy for reference and strengthened designs.

3. WORKING FLOW OF THE APPROVAL PROCEDURE

Application of the approval procedure can be carried out as follows:

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 normal scantlings by a classification society but it does not need any additional strengthening such as ice strengthening;

The necessary strengthening factor c, or the double hull breadth b_{ref} should be determined by damage stability calculations under consideration of the reduction factor r.. Of course this is only applicable if the flooding of the cargo hold or inner hull leads to unacceptable survival values s.

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 again only needs to comply with requirements of minimal scantlings by a classification society without any additional strengthening.

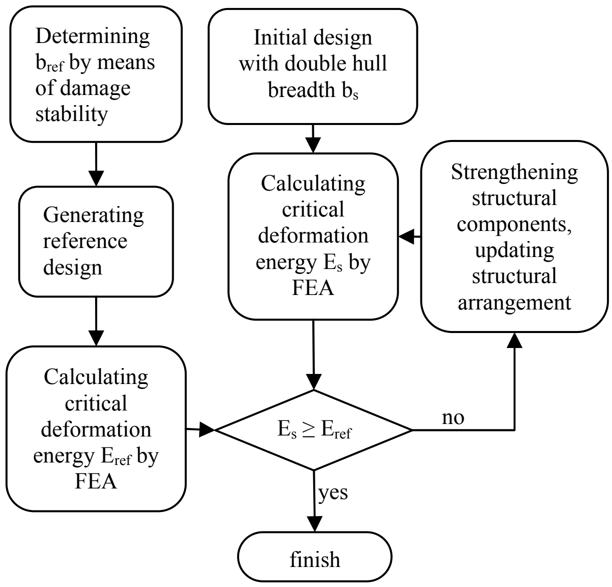
By means of FEA, the mean value of the critical deformation energy E_{ref} for the reference design, by which the inner hull is penetrated, shall be calculated for different defined collision scenarios.

Similar as described above, 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.

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 and/or by updating the structural arrangement to increase the collision resistance;

For the updated structural design the enhancement of collision resistance shall be continued until the condition of the energy equivalence $E_s \geq E_{ref}$ is achieved.

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 by 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 should be generated for both initial and reference structural designs. Principally the generation of the FE models shall account for all plastic deformations induced in each considered collision case. At least a whole length of the hold should be modelled. Generally at both ends of the hold all 3 translatory degrees of freedom shall be restricted. In such cases where a global bending of the ship sections is not significant for evaluation of plastic deformation energy, it is sufficient to consider half of ship sections only. In these cases the transverse displacements at the MS can be constrained. After creating a FE model, a test collision calculation should 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 should be idealized sufficiently fine, 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.

4.3 Failure Criteria

As mentioned before, 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. As a critical damage stability threshold it indicates leakage and flooding of the inboard hold space. In a FEA this critical situation is represented by the initial fracture of a finite element, which has an extremely large plastic strain at 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 regarding 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 remain constant for further calculation.

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 by many factors. First 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 resulting from complicated loads in the structures. In addition, it is also influenced by the production process, manufacture quality as well as environmental and operational conditions.

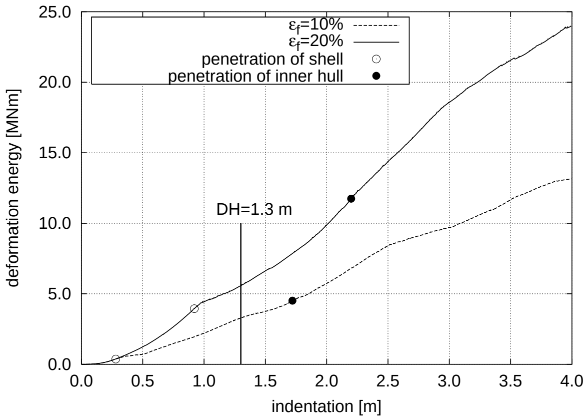


Fig. 3: Comparison of deformation energy from different definitions of failure strain values.

4.4 Definition of Striking Ship and Striking Bow

A ship with similar general particulars, such as displacement, design draughts, length and width as the struck ship is assumed to be the striking ship. At least two types of striking bow shapes shall be used for calculations regarding 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 to the main dimensions, such as B/T, H/T, block coefficient C_b, and the stem angle φ. Two standard striking bow sizes are defined as follows:

- The forecastle deck is 2.5 m higher than the main deck;
- The stem angle φ for bow shape 1 (without bulb) is 65°;
- The most front coordinate of the bulbous bow is the 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.

An individual bow can be generated from these definitions by distorting the shape of the standard bow. Its size is based on the main dimensions as well as the geometrical parameters of an existing ship.

In many collision cases the striking bow has only slight deformations compared with the side construction of a struck ship, so that a striking ship can generally be defined as rigid. Only for special configurations, i.e. 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 significantly by the plastic deformation of the striking ship. In these cases the striking ship must be considered deformable and the detailed arrangement in the striking bow should therefore be modelled.

4.5 Definition of Collision Cases

For the definition of collision cases the following assumptions are made:

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

The extent of critical deformation energy absorbed by a struck ship varies depending on the striking positions on a struck ship. In the vertical direction the striking positions are defined by the actual draught differences of striking and struck ships in the range of design and ballast draughts of both ships as follows:

$$\Delta T_1 = T_{2\max} - \frac{3 \cdot T_{1\min} + T_{1\max}}{4} \tag{15}$$

$$\Delta T_2 = T_{2\max} - \frac{T_{1\min} + 3 \cdot T_{1\max}}{4} \tag{16}$$

$$\Delta T_3 = \frac{T_{2\min} + 3 \cdot T_{2\max}}{4} - T_{1\max} \tag{17}$$

$$\Delta T_4 = \frac{3 \cdot T_{2\min} + T_{2\max}}{4} - T_{1\max} \tag{18}$$

T_{1max} is the design draught of the striking ship and T_{1min} is the ballast draught of the striking ship, while T_{2max} and T_{2min} are the design and ballast draughts of the struck ship respectively. The 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 ΔT_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 ΔT_i, I = 1,2,3,4 one collision case corresponds to the maximum masses possible for both striking and struck ships. The weighting factors for these 4 equivalent draught differences are 1 - 3 - 3 – 1 and correspond to the percentage of the respective areas.

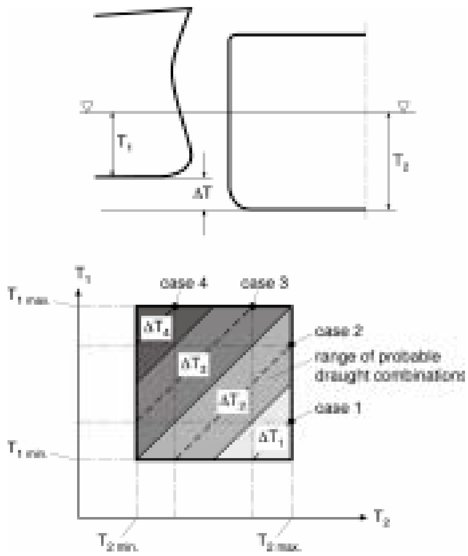


Fig. 4: Definition of striking positions in vertical direction:

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. Thus two typical colliding positions among longitudinal direction are defined;

- the middle point between two web frames, which includes the middle range of 0.5 web spacing;
- directly 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, at 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;

$$\overline{E}_{m,1} = \frac{1}{8} \cdot (E_{m,1,1} + 3 \cdot E_{m,1,2} + 3 \cdot E_{m,1,3} + E_{m,1,4}) \quad (19)$$

between two web frames for striking bow shape 2;

$$\overline{E}_{m,2} = \frac{1}{8} \cdot (E_{m,2,1} + 3 \cdot E_{m,2,2} + 3 \cdot E_{m,2,3} + E_{m,2,4}) \quad (20)$$

on a web frame for striking bow shape 1;

$$\overline{E}_{r,1} = \frac{1}{8} \cdot (E_{r,1,1} + 3 \cdot E_{r,1,2} + 3 \cdot E_{r,1,3} + E_{r,1,4}) \quad (21)$$

on a web frame for striking bow shape 2;

$$\overline{E}_{r,2} = \frac{1}{8} \cdot (E_{r,2,1} + 3 \cdot E_{r,2,2} + 3 \cdot E_{r,2,3} + E_{r,2,4}) \quad (22)$$

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:

$$\overline{E}_{r,2} = \frac{1}{8} \cdot (E_{r,2,1} + 3 \cdot E_{r,2,2} + 3 \cdot E_{r,2,3} + E_{r,2,4}) \quad (23)$$

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

For the purpose of comparison at least two side structural designs, reference and strengthened, must be evaluated. In this approval procedure at least 32 FEA must be performed.

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

$$E_{ij,k,s} \geq 0.6 \cdot E_{ij,k,ref} \quad (24)$$

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

5. SUMMARY

Since July 1998 damage stability requirements are applicable for cargo vessels of 80 m in length and upwards. As consequence a significant increase in building costs and operational restrictions due to additional subdivisions, such as transverse bulkheads, for such size of cargo vessels are anticipated. In 2009 damage stability requirements will come into force which may impact ro-ro(pax) vessels due to a different assessment of the perme-ability of the ro-ro spaces. Alternative arrange-ments could be acceptable, provided that at least the same degree of safety is provided. In this paper an alternative approval procedure in relation to the same degree of safety has been presented based on collision resistance. The basic philosophy of the approval procedure is to compare the critical deformation energy in case of a side collision of a strengthened structural design to that of a reference design which has complied with the damage stability requirements of SOLAS. By means of the strengthening of side structural components or changing side structural arrangements 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 experience in applying this approval procedure has been obtained.

6. ACKNOWLEDGEMENT

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