RISK MODEL USED TO DEVELOP GOAL-BASED STANDARDS FOR SHIP STRUCTURES OF SINGLE SIDE BULK CARRIER

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SUMMARY

The assessment of safety level in terms of failure probability for a bulk carrier structure was carried out using a risk model comprising foreseeable failure scenarios and scenario events, described by mathematical models.

The theory used involves statistics and probabilistic distributions approximating the statistics. The statistics of fault tree basic events are worked out on the basis of simulations of ship motion in irregular waves. The deterministic model enabling simulation of ship motion in waves is essential in the fault tree analysis.

The paper presents the computation of failure probability of a bulk carrier hull and hatch cover structures. The results of computations provide grounds for discussions on further development of risk models.

NOMENCLATURE

m	ship mass,
$V_Q = (V_{Q1}, V_{Q2}, V_{Q3})$	velocity of the ship mass centre,
$\Omega = (\omega_1, \omega_2, \omega_3)$	ship angular velocity,
$L = (l_{Q1}, l_{Q2}, l_{Q3})$	ship angular momentum,
$R_{UQ} = (x_{UQ1}, x_{UQ2}, x_{UQ3})$	position vector of the ship mass centre in relation to the inertial system U, moving with a constant speed equal to the average speed of the vessel,
(φ, θ, ψ)	Euler's angles representing roll, pitch, yaw,
F_W, F_D and F_R	Froude–Krylov, diffraction and radiation forces, respectively,
M_{QW}, M_{QD}, M_{QR}	moments of the above mentioned forces in relation to the mass centre,
$G = (0, 0, -g)$	gravitational acceleration,
F_A and M_{QA}	additional forces and moments such as damping forces or those generated by the rudder,
D	rotation matrix,
D_{Ω}	matrix which transforms Euler components of rotational velocity $(\dot{\varphi}, \dot{\theta}, \dot{\psi})$ into Ω.
f, g, g_B, h, h_{Hi}, i = 1,….,4	probability density functions,
η, ξ,	parameters of the Weibuill distribution,
Pr (A)	probability of event A,
P ($X<x$)	probability of random variable X assuming a value less than x.

Random variables:

M_U	ultimate bending moment of hull structure,
M_S	still water bending moment,
M_W	wave vertical bending moment,
Σ_Y	extreme stress value in hatch cover structure at its collapse,
Σ_{LC}	extreme stress generated by the green seas in the hatch cover,
F_U	ultimate force for single corrugation of transverse bulkhead,
F_L	sloshing force acting on single corrugation of transverse bulkhead,
Σ_{LF}	stress in the ship side frame caused by wave loads and cargo inertial forces acting on the ship structure,
Σ_{FY}	yield point of the frame material,
$M_H, \Sigma_C, F_B, \Sigma_F$,	random variables representing limit states functions.

Probabilistic parameters of the probability distributions considered:

$\overline{m}_U$	mean value of the ultimate bending moment of the hull girder,
s_U	standard deviation of the ultimate bending moment of the hull girder,
$\overline{m}_S$	mean value of the still water bending moment,
$\overline{m}_W$	mean value of wave bending moment,
s_s	standard deviation of the still water bending moment,
H_S	significant wave height,
T_o	average wave zero up-crossing period.

Events:
SL terminal event (ship loss),
C_1B, S_iB, i=1,2,3,4, HS scenarios of ship sinking,
C_1, S_i, $B_{i/i-1}$, i=1,2,3,4, basic events described by mathematical models.

Fault tree symbols:

 "or" gate, output occurs if at least one of the input events occurs,

 "and" gate, output occurs if all of the input events occur,

 intermediate or terminal event.

1. INTRODUCTION

IMO's Maritime Safety Committee Working Group on GBS has developed the following five-tier system of standards, [1]:

- Tier I: overall goal for ship design and construction;
- Tier II: functional requirements, including prescriptive requirements such as design life, environmental conditions, structural strength, fatigue life and coating life;
- Tier III: process of verifying classification societies' rules by IMO;
- Tier IV: classification societies' rules;
- Tier V: industry standards.

Verified class rules (Tier IV) are assumed to meet the functional requirements and consequently meet the goals. The five-tier system introduces a hierarchy to the existing regulatory system.

At present GBS are progressed along two parallel tracks – following up the prescriptive (or traditional) approach for bulk carriers and oil tankers and pursuing the safety level approach [1], [2], [3], [4].

The latter approach assumes that the goals of Tier I take the form of safety objectives (for ship, cargo, passengers, crew, environment, etc.), defined by risk level (eg probability of failure and fatality); and that these safety objectives are achieved when each ship function (Tier II) such as manoeuvrability, seakeeping performance, stability and floatability, ship strength and fire protection, satisfies the risk level set for each function.

The safety level (probability of failure) for each ship function, can be determined with the use of a risk model – a fault tree with mathematical models used to describe basic events. For bulk carriers strength (one of its functions) this includes failure of the hull girder, collapse of hatch cover due to green seas loads, collapse of the frames and failure of the corrugated bulkhead.

The paper presents a simple risk model, comprising different scenarios of bulk carrier structure failure, applied in safety level assessment of a panamax size bulk carrier. The problems encountered in building the risk models are discussed.

2. SIMPLE RISK MODEL OF BULK CARRIER STRUCTURE

A fault tree is a graphic model of various parallel and sequential combinations of faults that result in the occurrence of the predefined undesired event [5]. It describes the logical interrelations of basic events that lead to the undesired event - which is the terminal event of the fault tree.

The terminal event SL in ship structure analysis is sinking of the ship due to the loss of structural strength. In the case of single side skin bulk carrier structures the following scenario may lead to the terminal event:

- loss of hull girder strength *(HS)* ,
- side structure failure and corrugated bulkheads collapse due to hold flooding (S_iB, i=1,2,3,4 is the number of the hold),
- No 1 hold hatch cover collapse caused by green water and corrugated bulkhead collapse due to hold flooding (C_1B).

In construing the fault tree, it was assumed that the failure of hatch cover No 1 or hull side in way of holds 4, 3, 2, and 1, leads to hold flooding and that collapse of the bulkhead between flooded and not flooded holds leads to the sinking of the ship.

The analysed bulk carrier is of Panamax size and has seven holds. Hold No 5 is the ballast hold and the side failure in way of this hold does not lead to the sinking of the ship. Statistical data shows that holds Nos 6 and 7 do not entail problems, so they are not included in the fault tree.

Fatigue strength of the side structure is not considered in this paper but appropriate probabilistic models for fatigue strength should be built in the future.

The analysis covered only influence of hatch covers strength in hold No 1 subject to water pressure (green seas), on flooding of the hold. The probability of flooding the remaining holds resulting from exceeding ultimate strength of their hatch covers was assumed as negligible

The fault tree is a qualitative model that can be evaluated quantitatively. The probability theory is basic for fault tree analysis because it provides an option to treat analytically randomly occurring events and enables their quantitative assessment.

The sea, the ship response to waves and ship operation are of a random character and therefore appropriate deterministic and probabilistic models need to be developed and used to make a quantitative assessment of particular events of ship structure failure. The fault tree with the basic events described by a mathematical model is called the risk model of the undesired event - in this case the loss of ship structure strength leading to ship sinking (loss of ship function determined by Tier II). The risk model enables identification of the risk (probability) of ship function failure and appraisal of its conformity with the risk level set as the criterion. The simple fault tree leading to terminal event *SL* is presented in Fig. 1.

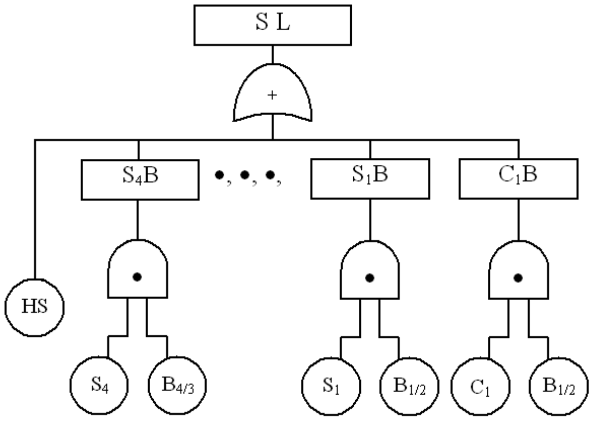

Fig. 1. Simple fault tree of bulk carrier structure failure

Scenarios S_iB, i=1,...,4, comprise the following basic events: S_i, i=1,...,4, is the side structure failure in way of hold Nos. 1, 2, 3 and 4 due to the collapse of the frames, $B_{i/i-1}$, i=4,3,2 and $B_{1/2}$ is the loss of the strength of corrugated bulkhead between holds No i-1 and i, while the scenario C_1B comprises: event C_1, which is the loss of strength of hatch cover No 1 due to green seas, and $B_{1/2}$ – which is the basic event as described above.

3. PROBABILISTIC MATHEMATICAL MODELS

3.1. PROBABILITY OF BULK CARRIER SINKING DUE TO STRUCTURE FAILURE

Basing on the assumptions made in building the fault tree, the probability of ship sinking is determined by the following sum of probabilities:

$$\Pr\ (SL) = \Pr(HS) + \Pr(C_1B) + \sum_{i=1}^{4} \Pr(S_iB). \tag{1}$$

The random variables assigned to the events occurring in formula (1) (see also Chapter 2) are as follows:

- for hull girder strength *HS*

$$M_H = M_U - (M_S + M_W), \tag{2}$$

- for hatch cover strength C_1

$$\Sigma_C = \Sigma_Y - \Sigma_{LC}\ , \tag{3}$$

- for corrugated bulkhead strength $B_{i/i-1}$ i = 2,3,4

$$F_B = F_U - F_L\ , \tag{4}$$

- for collapse of the side frames S_i, i = 1,2,3,4

$$\Sigma_F = \Sigma_{FY} - \Sigma_{LF}\ . \tag{5}$$

The degree of safety depends on the margin between the actual value of load effect and value of the load effect that the structure can ultimately sustain – formulae (2) to (5). The margins M_H, Σ_C, F_B, Σ_F are called the limit states functions. The failure will occur when the limit state is less than zero.

In case of hull girder strength, the failure will occur when the ultimate vertical bending moment M_U for the hull girder structure is less than the sum of still water bending moment M_S and wave bending moment M_W. The situation is similar for corrugated bulkheads. The failure will occur when sloshing forces F_L in the flooded hold acting on single corrugation of the bulkhead exceed the ultimate force value F_U. The side is assumed to have lost integrity when the stress Σ_{LF} in the frame face plate is greater than the yield point Σ_{FY} of the frame face plate material. Whereas the hatch cover is deemed to have lost integrity when the ultimate strength of the cover compressed upper plating or its stiffeners is breached by the green seas effect.

Loss of side and hatch cover integrity result in flooding of the hold. The method applied to determine hull girder, bulkhead, side and hatch cover strength is presented in chapter 4.2.

All load effects M_S, M_W, Σ_{LC}, F_L, Σ_{LF}, and the ultimate for the structure values M_U, Σ_Y, F_U, Σ_Y are random variables so the limit state functions M_H, Σ_C, F_U, Σ_F are also random variables.

Taking into account the limit state function random variables (formulae (2) to (5)), the probability of hull girder strength loss is determined by the formula:

$$\Pr(HS) = \mathrm{P}(M_H < 0) = \int_{-\infty}^{0} \mathrm{f}\,(m_H)\,dm_H\,, \tag{6}$$

where f is the probability density function of random variable M_H.

The probability that the sequence of events C_1 and $B_{1/2}$ occurs (see Fig. 1) is equal to

$$\Pr\ (C_1B) = \Pr(B_{1/2} \mid C_1)\Pr(C_1)$$

where

$$\Pr(C_1) = \mathrm{P}\left(\sum\nolimits_C < 0\right) = \int_{-\infty}^{0} \mathrm{g}(\sigma_C)\, d\sigma_C \,, \qquad (7)$$

$$\Pr(B_{1/2} \mid C_1) = \mathrm{P}(F_B < 0 \mid C_1) = \qquad (8)$$

$$\int_{-\infty}^{0} \mathrm{g}_B(\mathrm{f}_B \mid C_1)\,\mathrm{df}_B \,.$$

The probability that the sequence S_i and $B_{i/i-1}$, i = 2,3,4, or S_1 and $B_{1/2}$ (scenarios) occurs is equal to

$$\Pr(S_i B) = \mathrm{P}(B_{i/i-1} \mid S_i)\Pr(S_i), \qquad i = 2,3,4. \qquad (9)$$

(for S_1B similarly), where

$$\Pr(S_i) = \mathrm{P}\left(\sum\nolimits_{Fi} < 0\right) = \int_{-\infty}^{0} \mathrm{h}_i(\sigma_F)\,\mathrm{d}\sigma_F \,, \qquad (10)$$

and

$$\Pr(B_{i/i-1} \mid S_i) = \mathrm{P}(F_{Bi/i-1_i} \mid S_i) = \qquad (11)$$

$$\int_{-\infty}^{0} \mathrm{g}_{B_i}(\mathrm{f}_B \mid \sigma_F)\,\mathrm{df}_B \,, i = 2,3,4$$

3.2. COMPOSITIONS OF PROBABILITY DISTRIBUTIONS

The probability density functions f, g, g_B, h_i and h_{Bi} are functions, which depend on random variables constituting the sum or difference of other random variables, and which have individual probability distributions. Therefore, an appropriate composition of distributions (sum or difference of these random variables) is required to obtain functions f, g, g_B, h_i and h_{Bi} (see (6) to (11)).

Let (M_S, M_W) be two dimensional random variables having probability density function $f = f(m_S, m_W)$. Inequality $M = Ms + Mw < m$ will be satisfied for those pairs of (m_S, m_W) for which $m_W + m_S$ is smaller than m, i.e. for those points (m_S, m_W) of the plane Om_Sm_W which are in the domain D_m under the straight line $m_s+m_w=m$, (Fig. 2).

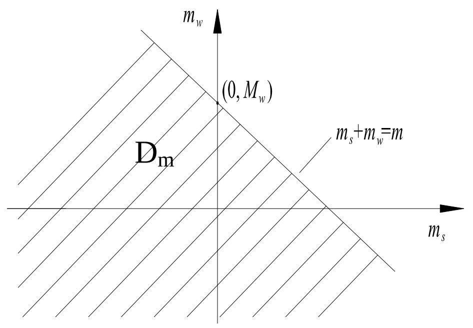

Fig. 2. Definition of domain D_m

The cumulative distribution of random variable M is determined by the formula:

$$\mathrm{H}(m) = \Pr[(M_s, M_w) \in D_m] = \int_{D_m} \mathrm{f}(m_s, m_w)\,\mathrm{d}m_s \mathrm{d}m_w \qquad (12)$$

which can be written in the form

$$\mathrm{H}(m) = \int_{-\infty}^{\infty}\left[\int_{-\infty}^{m-m_s} \mathrm{f}(m_s, m_w)\,\mathrm{d}m_w\right]\mathrm{d}m_s \,. \qquad (13)$$

The derivative of cumulative distribution (13) gives the following probability density function of random variable

$$\mathrm{h}(m) = \int_{-\infty}^{\infty} \mathrm{f}(m_s, m - m_s)\,\mathrm{d}m_s \,. \qquad (14)$$

Assuming that random variables M_s and M_w are independent variables, the following formula is obtained:

$$\mathrm{h}(m) = \int_{-\infty}^{\infty} \mathrm{f}_s(m_s)\,\mathrm{f}_w(m - m_s)\,\mathrm{d}m_s \,. \qquad (15)$$

Probability density function g of the sum (difference) of random variables M_S and M_W is obtained as the convolution $\mathrm{h}(m) = \mathrm{f}_S(m_S) * \mathrm{f}_W(m_W)$ of the probability density functions f_S and f_W [6].

3.3. PROBABILITY DISTRIBUTIONS USED IN THE SHIP STRUCTURE RISK MODEL

The statistical distributions of the ultimate load effect sustained by the structure, e.g. the probability distribution of ultimate bending moment M_U, are normally approximated by the log-normal distribution:

$$\mathrm{f}_u(x) = \frac{1}{\zeta_x \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\zeta}\right)^2\right], 0 \le x \le \infty,$$

where $\lambda = \ln(\overline{m_U}) - \frac{1}{2}\zeta^2, \ \zeta^2 = \ln\left(1 + \frac{S_u^{\,2}}{\overline{m_U}^2}\right),$

$\overline{m_U}$ and s_U are the mean value and the standard deviation, respectively. Log-normal probability distributions are also used to describe the mechanical properties of steel.

Some considerations on random character of M_S are given in [7]. Statistical distribution of M_S for bulk carriers, where the mean value is 60% of the design value for a load condition given in Loading Manual for the ship (alternate, homogeneous or ballast load) and the coefficient of variance is equal to 0.4, is recommended in [7]. It seems that the above value of coefficient of variance is very large and the assumptions applied in the paper are as follows:

- There are typical loading conditions of bulk carriers such as homogeneous, alternate and ballast conditions, and their probability of occurrence can be specified.
- Each specific loading condition is random by nature due to the differences in distribution of cargo loaded according to this specific loading condition during the ship's particular voyages.
- The probability distribution of still water vertical bending moment *Ms*, corresponding to the specific loading condition, can be approximated by normal distribution N(m_S, s_S), with the following probability density function

$$\mathrm{f}_l(x) = \frac{1}{s_s\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\overline{m}_s}{s_s}\right)^2\right], -\infty \le x \le \infty, \tag{17}$$

where $\overline{m_S}$ is the mean value and S_S is the standard deviation. It was assumed that $S_S = 0.08\,\overline{m_S}$.

Simulation of ship structure response to irregular waves in an assumed sea state enables the determination of its local maxima and number of the maxima. The step function representing the numerical probability density function of the considered ship structure response can be obtained by multiplying the number of maxima belonging to the particular interval by probability of the given sea state occurrence, dividing it by the total number of maxima occurrences in the sea state and by the length of the interval and then, summing them for all sea states. The step function is normally approximated by Weibull distribution

$$\mathrm{F}(x) = 1 - \exp\left[-\left(\frac{x-\varepsilon}{\eta-\varepsilon}\right)^{\xi}\right], \tag{18}$$

with the probability density function

$$\mathrm{f}(x) = \frac{\zeta}{\eta-\varepsilon}\left(\frac{x-\varepsilon}{\eta-\varepsilon}\right)^{\zeta-1} \exp\left[-\left(\frac{x-\varepsilon}{\eta-\varepsilon}\right)^{\xi}\right], \tag{19}$$

where η, ξ and ε are the Weibull distribution parameters.

3.4. PREDICTION OF SHIP STRUCTURE RESPONSE TO THE WAVES.

Seas and oceans are normally divided into distinct areas A_i, i = 1,2,...,n, [9], characterised by the shape of the spectral density function. Wave spectrum representing the steady state sea conditions (short term sea state) depends on the significant wave height H_s and average zero up-crossing period T_o [8].

The distributions of such events as ship structure response to waves, represented by random variables M_W, Σ_{LC}, F_L, and Σ_{LF}, depend on the sea state occurrence represented by random two-dimensional variable (H_S,T_o).

The short term response of the ship to waves (eg wave bending moment M_W) is the set of probability distributions (eg density functions) of the given random variables for one sea state in a given area A_i, i = 1,...n, and for various ship courses, ship forward speeds, etc.

Long-term statistics of the given ship response is the accumulation of response statistics referring to: sea areas A_i, i = 1,...n, short-term sea states, ship courses in relation to waves and ship's loading conditions, taking into account the frequencies of their occurrence.

The long-term probability density function f(y) of the ship response y (eg wave bending moment M_W as the random variable) can be expressed in the form:

$$\mathrm{f}(y) = \sum_m \sum_l \sum_k \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{f}_{klm}(y \mid (h_s, t_0))\mathrm{g}(h_s, t_0)\mathrm{d}h_s \mathrm{d}t_0\, p_{kl}\, p_l\, p_m \tag{20}$$

where $\mathrm{f}_{klm} = \mathrm{f}_{klm}(y \mid (h_s, t_o))$ is the probability density function of the random variable y in the sea state condition (H_S, T_o). Taking into account the formula determining the conditional distribution and approximating the integral occurring in (20) by the sums, the following formula is obtained:

$$\mathrm{f}(y) = \sum_m \sum_l \sum_k \sum_j \sum_i \mathrm{f}_{ijklm}(y \mid (h_s, t_o)) p_{ijl}\, p_{kl}\, p_l\, p_m \tag{21}$$

where:

f_{ijklm} - is the short term probability density function of random variable y;

p_m - is the probability of the ship's loading condition occurrence (different drafts for different loading conditions);

p_l - is the probability of ship presence in sea area A_l, l = 1, ...,n;

p_{kl} - is the probability of ship course in relation to waves in sea area A_l (uniform distribution in the interval [0,2π] is used);

p_{ijl} - is the probability of the short term sea state, determined by (H_S, T_o), occurrence in the sea area A_l. l=1,...,n.

The probability distributions of the sea states occurrence are given in the form of a matrix – called scatter diagram, which presents the probabilities p_{ijl} of sea state occurrence in the interval product $[H_{si}, H_{si+1}]_l \; x \; [T_{oj}, T_{oj+1}]_l$, i = 1,...,r, j = 1,...,s, l=1,...,n, [9].

In the present class rules only the sea areas of the North Atlantic, the areas featuring the most severe wave conditions, are used to provide the safety margin. However, world-wide trading (all sea areas) should be taken into account in the risk model as this model should reflect the reality.

The areas covered by routes 1 to 7 denoted in Fig.3, with appropriate probability of ship presence on route, are taken into account in the risk model (Fig.3).

The numerical long-term probability density functions (21) of random variable y, representing different ship structure response to waves, are determined in simulations of ship motion and the structure behaviour in irregular waves.

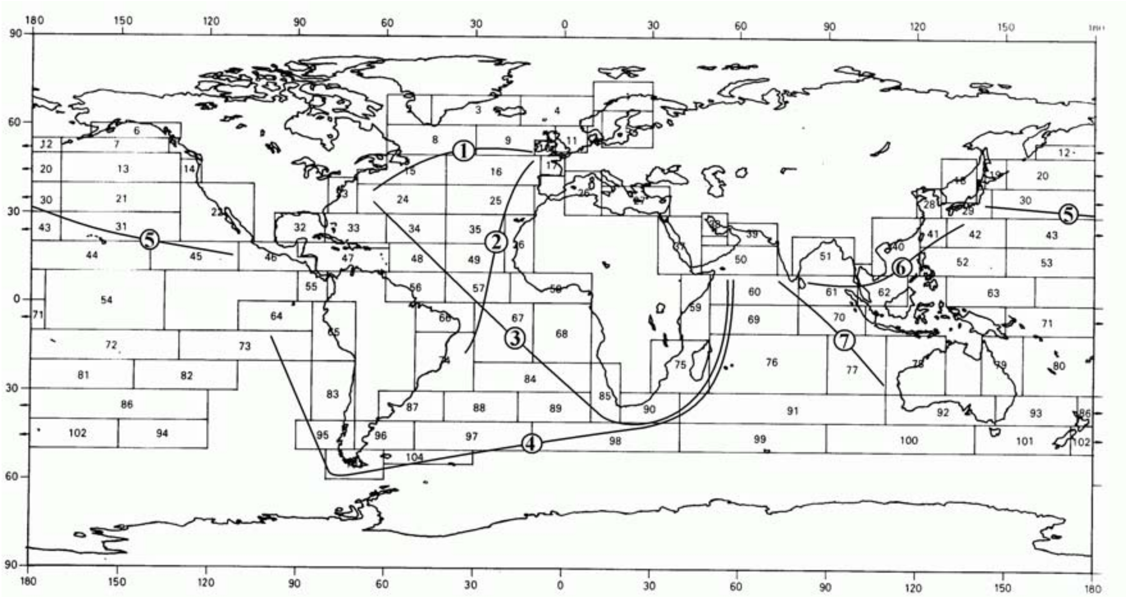

Fig. 3. Routes taken into account

4. DETERMINISTIC MODELS

4.1. SIMULATION OF SHIP MOTION IN IRREGULAR WAVES

The simulation of vessel motions in waves is based on numerical solutions of non-linear equations of motion (22). The non-linear model used is presented in [10].

It is assumed that the hydrodynamic forces acting on the ship and defining the equations of its motions can be split into Froude-Krylov forces, diffraction and radiation forces as well as other forces, such as rudder forces and non linear damping.

The Froude-Krylow forces are obtained by integrating the pressure caused by irregular waves, undisturbed by the presence of the ship, over the actual wetted ship surface

The diffraction forces are determined as a superposition of diffraction forces caused by the harmonic components of the irregular wave. The irregular wave is assumed to be a superposition of harmonic waves. It is assumed that the ship diffracting the waves is in its mean position. This is possible under the assumption that the diffraction phenomenon is described by a linear hydrodynamic problem. The variables of diffraction function are given as product of space and time variables with the space factor of the function being the solution of the hydrodynamic problem and the known time factor. Such an approach significantly simplifies calculations because bulky computations can be performed at the beginning of the simulations and the ready solutions can be applied for determining the diffraction forces during the simulation.

The radiation forces are determined by added masses for infinite frequency and by the so-called memory functions given in the form of convolution. The memory functions take into account the disturbance of water, caused by the preceding ship motions, affecting the motion of the ship in the time instant considered, [11].

The equations of ship motion in irregular waves are written in the non-inertial reference system. The system is fixed to the ship in the centre of its mass Q and the equations of ship motion assume the following form [10]:

$$
\begin{aligned}
& m[\dot{V}_Q(t) + \mathbf{\Omega}(t) \times V_Q(t)] = F_W(t) + \\
& + F_D(t) + F_R(t) + F_T(t) + F_A(t) + mD^{-1}\, G, \\
& \dot{\mathbf{L}}(t) + \mathbf{\Omega}(t) \times \mathbf{L}(t) = \mathbf{M}_{QW}(t) + \\
& + \mathbf{M}_{QD}(t) + \mathbf{M}_{QR}(t) + \mathbf{M}_{QT}(t) + \mathbf{M}_{QA}(t), \qquad (22) \\
& \dot{\mathbf{R}}_{UQ}(t) = \mathbf{V}_Q(t) - \mathbf{\Omega}(t) \times \mathbf{R}_{UQ}(t), \\
& (\dot{\varphi}(t), \dot{\theta}(t), \dot{\psi}(t))^T = D_\Omega^{-1} \mathbf{\Omega}(t)
\end{aligned}
$$

The ways of solving 3D hydrodynamic problems and determining forces appearing in the equation of motion are presented in [10]. The non-linear equations of motion are solved numerically according to the method presented in [12].

4.2. SIMULATION OF SHIP STRUCTURE RESPONSE TO IRREGULAR WAVES

Some calculated ship responses to wave parameters as functions of time and wave elevation are shown in Fig.4. They are calculated for wave spectrum defined by H_S = 10m, T_o= 8s and ship heading the waves. Sloshing force shown in Fig.4 is acting on the bulkhead between holds No 4 and 3, assuming that flooded hold No 4 is empty,.

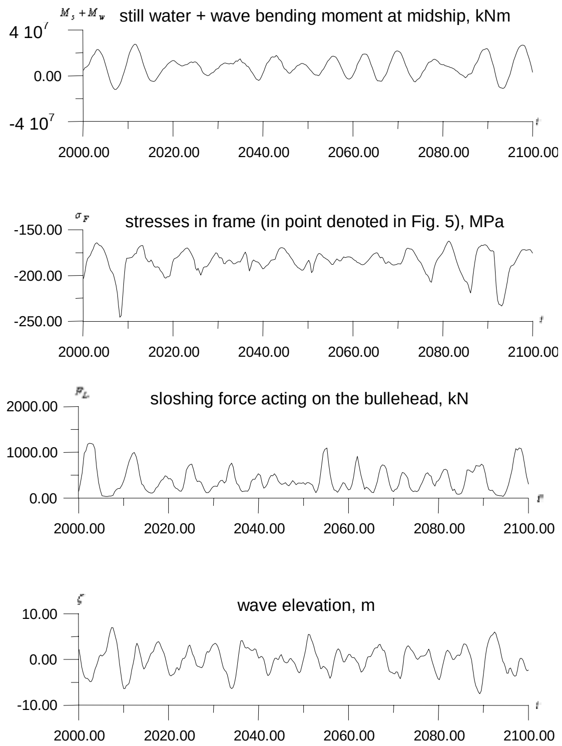

Fig. 4. Time history of: vertical bending moment M_S+M_W in the midship of hull, stresses σ_F in the side frame of hold No 4, perpendicular to the bulkhead sloshing force F_L acting on one corrugation of the bulkhead and the wave elevation

The ultimate vertical bending moments (sagging and hogging) for the bulk carrier considered were calculated and presented in [13].

The wave bending moments, generated in hull cross section $x = x_1$ are calculated as the result of action of external pressures excited by waves and inertial loads acting on aft part of the hull to the considered cross section $x = x_1$. An example of the time history of vertical bending moment $M_W(x_1,t)$ in the midship is presented in Fig. 4. The presented moment is the superposition of still water bending moment M_S and wave moment M_W.

The frames of the analyzed ship have the form of T-bars with integral brackets at the ends. It was assumed, that ultimate frame strength is reached when compressive stresses Σ_F in frame's face plate at its lower end are equal to yield point Σ_{FY}. Such an approach to the problem of ultimate strength of beams is recommended in [14].

The biggest stress values in the frames of a bulk carrier occur in the region where the prismatic part of frame passes to the lower bracket (Fig. 5). Only the lower parts of the frames situated in the middle of the hold's length were accounted for in the calculations.

The stress values in frames are calculated using an original concept of pressure influence coefficients. The values of these coefficients were calculated separately (before the simulation of ship motion in waves) using FEM. A three hold hull model, built of shell and rod finite elements, was used. The external pressure values in selected points of hull plating (including the pressure on the actual wetted part of the side) and cargo pressure in selected points of inner bottom and hopper tank sloping plating, calculated during simulation of ship motion and multiplied by the influence coefficients give the values of stresses in frames. It was assumed that the pressure values change linearly between the selected points referred to above.

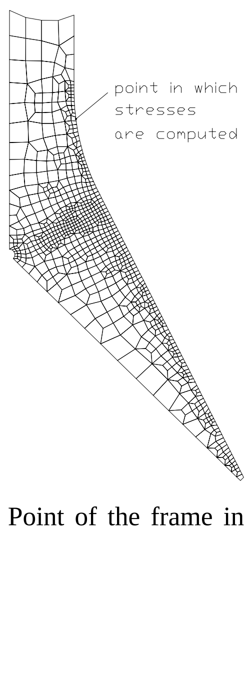

Fig. 5. Point of the frame in which the greatest stresses occur

It was assumed that the loss of bulkhead integrity and the 'progressive flooding' follow loss of ultimate strength capacity of the corrugated part of the bulkhead, bent by sloshing in flooded hold.

The ultimate strength of the bulkhead was estimated by conducting a nonlinear FEM analysis (large displacements and plastic flow of material) for a single corrugation of the bulkhead. The applied FEM model made of shell finite elements is shown in Fig. 6. In FEM calculations, pressure distribution on the bulkhead was used as required by [17] for empty holds, neglecting the load pressure on the other side of the bulkhead. The loss of ultimate bulkhead strength capacity resulted in elastic-plastic buckling of the face plates' corrugations in the lower and middle parts (Fig. 6).

Calculated ultimate values F_U of transverse force acting on the single bulkhead's corrugation were used as a criterion of bulkhead's damage from sloshing loads determined in the computer simulation of liquid motion in flooded hold, where kinematic excitation of the tank (ship hold) results from ship motion in irregular waves, [16]. An example of calculations results is shown in Fig. 4.

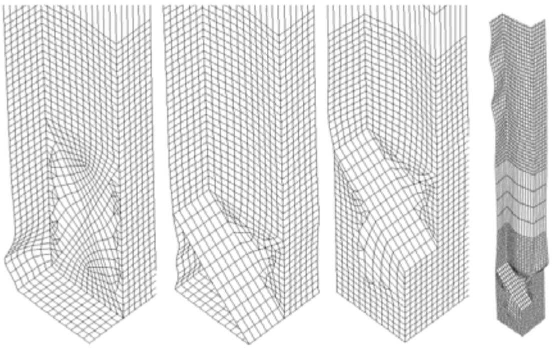

Fig 6. The destroyed bulkhead single corrugation

Hatch cover of the ship's hold No 1 has the form of two panels contacting in a frame plane of the ship. The panels are assumed not to exert mutual loads on each other and are simply supported along longitudinal and transverse hatch coamings. The actual structure of the ship's hatch covers was taken into account as well as the hypothetical strengthening with additional stiffeners of top plating to meet the criteria included in [15].

It was assumed that loss of ultimate hatch cover capacity occurs under green loads on meeting one of the two conditions given below, that is confirmed by analysis reported in [18]:

a) exceeding ultimate strength of the compressed hatch cover top plating near the hatch cover edge in plane of ship symmetry,
b) total stress values in hatch cover top plating stiffeners, resulting from general bending of the cover and local bending of the stiffener supported by hatch cover girders directed along the ship, reach the yield point.

Parametric formulas for ultimate strength of compressed plating (given in [14]) were used for the calculations. Both of the assumed forms for exceeding ultimate strength of hatch covers were found in non-linear FEM computations presented in [18].

The stress values which cause collapse of the cover structure in the forms a) or b) listed above, were assessed while simulating ship motion (also green seas) in irregular waves and applying a linear-elastic FEM model of cover structure. An example of results is shown Fig.7.

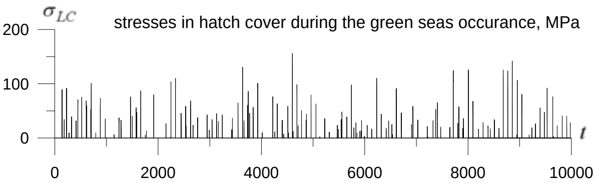

Fig. 7. Time history of stresses in the hatch cover caused by green seas

Computed stress values were then corrected by applying some factors to take into account effective width values of compressed plates reaching their ultimate strength. Values of the factors were assessed applying parametric formulas given in [14].

Stress values in linear-elastic range were calculated applying the concept of influence coefficients for values of pressure acting on the cover, similar to the concept applied to side frames.

5. CALCULATING THE PROBABILITY OF SHIP LOSS DUE TO STRUCTURE FAILURE

5.1. PROBABILITY DISTRIBUTIONS

There are many uncertainties in assessing ship structure safety [14]. They regard the following:

- the material properties such as yield stress, fatigue strength, notch toughness, effects of welding etc.
- analysis of ship structure strength, which necessarily involves assumptions, approximations, and idealisations in formulating mathematical models of the physical environment,
- quality of construction, and
- operational effects (eg. deformation of the structure), etc.

Basing on statistical data for yield stresses, the standard deviation of the distribution is equal to 0.1 of the mean value. In order to include the above mentioned uncertainties it was assumed that the standard deviations of the distributions of random variables representing the structure ultimate strength are equal to 0.15 of their mean values, that agrees with the value proposed in [7]. The parameters of log-normal distribution for random variables used in the analysis are presented in Table 1. The Table also shows how the corrosion and assumed strengthening case of a particular structure is taken into account.

Table 1. Parameters of log-normal distribution

Random variable	Mean value			
	structure as built	factor used to obtain structure		
		corroded	strengthened	strengthened and corroded
M_U sag, KNm	4580000	0.9	1.1	1.1 x 0.9
M_U hog, KNm	5450000	0.8	1.2	1.2 x 0.8
Σ_{FY}, MPa	265	1	1	1
F_U, hold 4, KN	1863	0.9	1.33	1.33 x 0.9
F_U, hold 1, KN	1896	0.9	1.33	1.33 x 0.9
Σ_Y, MPa	265	1	1	1

The hatch cover and frame corrosion was taken into account by reducing their section modulus. The strengthened frame means that the section modulus in the considered cross section (Fig. 5) was increased 2 times. The strengthened hatch cover means that it fulfils the requirements in [15]. In case of bulkhead, strengthening means that it fulfils requirement [17], which result in increased F_U by 1.33.

It was assumed that "as built" and corroded state of the ship contribute to the probability of failure in 60% and 40%, respectively.

The following loading conditions have been selected from Loading Manual of the bulk carrier considered:

- Homogenous loading condition: $\overline{m}_s$ =706840 kNm at midship, sagging.
- Alternate loading condition: $\overline{m}_s$ =1227490 kNm at midship, hogging.
- Ballast condition: $\overline{m}_s$ = 1364600 kNm at midship, hogging.

The distribution of each loading condition is the normal distribution $N(\overline{m}_S, s_S)$.

It was also assumed that particular loading conditions can occur with the following probabilities: 1° homogenous, p_1=0.4; 2° alternate, p_2=0.3; 3° ballast, p_3=0.3.

The probability distributions of random variables representing the considered responses of ship structure to waves are determined using the simulations. Together with the simulation of the ship motion in waves, the wave bending moment, sloshing force acting on the bulkhead corrugation, stresses in the lower part of the frames and stresses in the hatch cover are determined as functions of time (Fig.4 and 7) and their local extrema are identified and used to build the step function. The step functions representing probabilistic distributions of appropriate random variables were calculated as described in subchapter 3.3.

In the case of the wave vertical bending moment, the step function was calculated separately for minima (sagging) and maxima (hogging) (Fig. 4). For hatch cover and bulkheads, the step functions were calculated for maxima (Fig. 4 and 7) and in case of frames for the minima (Fig. 4). The Weibull distribution found (using the least square method) was used to approximate the step probability density functions. This distribution was used to calculate the failure probability of ship structure.

5.2. PROBABILITY OF STRUCTURE FAILURE - QUANTITATIVE ASSESSMENT OF SHIP LOSS

The probability of ship loss, Pr(*SL*), was computed according to formula (1), (6), (7), (8), (9), (10) and (11). The composition of distributions was made according to formula (15). Examples of these computations are presented in Fig. 8 and 9.

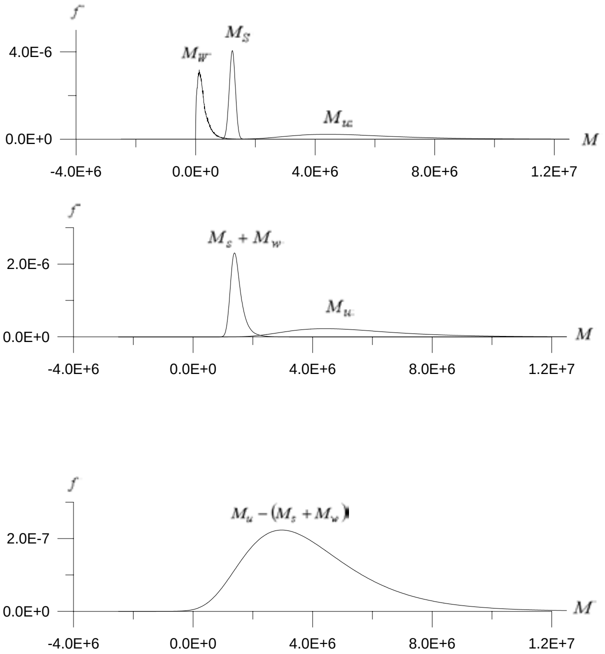

Fig. 8. The probability distributions of hull girder strength

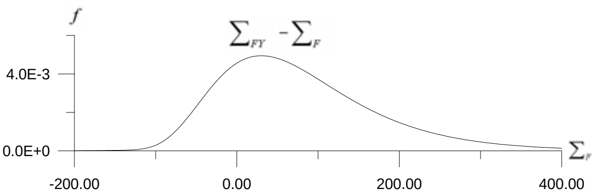

Fig. 9. The probability distributions of frame strength (in way of hold No 4)

The computations of probability of ship loss event *SL* according to the fault tree presented in Fig.1 for ship as built and strengthened, taking into account the probability of a given loading condition and ship's corrosion state impact on the probability of failure are presented in Tables 2 and 3.

Table 2. Probability of loss of the as built ship

No. of L_C	$Pr\ (SL) = 0.6\ Pr(SL_a) + 0.4\ Pr(SL_c) = 6.08\ 10^{-2}$				
	Ship structure as built				
	$Pr(SL_a) = Pr(HS) + 4Pr(S_4B) + Pr(C_1B) = 3.70\ 10^{-2}$				
	$Pr(HS) = 2.47\ 10^{-3}$	$Pr(S_4B) = 8.63\ 10^{-3}$		$Pr(C_1B) = 2.73\ 10^{-10}$	
		$Pr(S_4) = 1.66\ 10^{-1}$	$Pr(B_{4/3}) = 5.2\ 10^{-2}$	$Pr(C_1) = 3.64\ 10^{-5}$	$Pr(B_{1/2}) = 7.5\ 10^{-2}$
1º ho	0.00082	0.22030	----	$5.2\ 10^{-5}$	----
2º al	0.00127	0.2426	0.052	$5.2\ 10^{-5}$	0.075
3º bl	0.00555	0.01677	----	0.0	----
	Ship structure corroded				
	$Pr(SL_c) = Pr(HS) + 4Pr(S_aB) + Pr(C_1B) = 9.66\ 10^{-2}$				
	$Pr(HS) = 4.65\ 10^{-3}$	$Pr(S_4B) = 2.3\ 10^{-2}$		$Pr(C_1B) = 5.11\ 10^{-6}$	
		$Pr(S_4) = 2.76\ 10^{-1}$	$Pr(B_{4/3}) = 8.3\ 10^{-2}$	$Pr(C_1) = 4.41\ 10^{-5}$	$Pr(B_{1/2}) = 1.16\ 10^{-1}$
1º ho	0.00167	0.36796	----	$6.3\ 10^{-5}$	----
2º al	0.00616	0.39997	0.083	$6.3\ 10^{-5}$	0.1165
3º bl	0.0071	0.02928	----	0.0	----

Table 3. Probability of strengthened ship loss

No. of L_C	$Pr\ (SL) = 0.6\ Pr(SL_a) + 0.4\ Pr(SL_c) = 2.99\ 10^{-3}$				
	Ship structure with increased scantlings				
	$Pr(SL_a) = P_r(HS) + 4Pr(S_4B) + Pr(C_1B) = 1.37\ 10^{-3}$				
	$Pr(HS) = 7.37\ 10^{-4}$	$Pr(S_4B) = 1.58\ 10^{-4}$		$Pr(C_1B) = 2.76\ 10^{-7}$	
		$Pr(S_4) = 8.27\ 10^{-3}$	$Pr(B_{4/3}) = 1.91\ 10^{-2}$	$Pr(C_1) = 1.05\ 10^{-5}$	$Pr(B_{1/2}) = 2.63\ 10^{-2}$
1º ho	0.00041	0.00936	----	$1.5\ 10^{-5}$	----
2º al	0.00029	0.01022	0.0191	$1.5\ 10^{-5}$	0.0163
3º bl	0.00162	0.00485	----	0.0	----
	Ship structure with increased scantlings and corroded				
	$Pr(SL_c) = Pr(HS) + 4Pr(S_aB) + Pr(C_1B) = 5.44\ 10^{-3}$				
	$Pr(HS) = 3.64\ 10^{-3}$	$Pr(S_4B) = 4.5\ 10^{-4}$		$Pr(C_1B) = 5.4\ 10^{-7}$	
		$Pr(S_4) = 1.40\ 10^{-2}$	$Pr(B_{4/3}) = 3.21\ 10^{-2}$	$Pr(C_1) = 1.19\ 10^{-5}$	$Pr(B_{1/2}) = 4.57\ 10^{-2}$
1o ho	0.00088	0.01432	----	$1.7\ 10^{-5}$	----
2o al	0.00380	0.02229	0.0321	$1.7\ 10^{-5}$	0.0457
3o bl	0.0077	0.00520	----	0.0	----

Due to the long-lasting computations the following failure probabilities have been determined for events *HS*, S_4, $B_{4/3}$ and C_1 only and it was assumed that: scenarios S_iB, i=3,2 and 1 have the same failure probability as S_4B.

The assumptions give:

$$Pr(SL)=Pr(HS)+Pr(C_1B)+4Pr(S_4B) \quad (23)$$

The computations are in progress.

6. DISCUSSION

The fault tree used in the paper involves various complicated theories, sophisticated software and bulky computations, and to build the risk model (Fig. 1) many assumption have been introduced regarding:

- Fault tree – due to the bulky computations only essential scenarios of bulk carrier sinking have been taken into account.
- Probability distribution – for example, it was assumed that probability distributions standard deviations of the ultimate load effect (eg representing the load limit that a structure can sustain) is equal to 0.15 of the mean value. This assumption accounts for uncertainties in ship designing, construction (imperfection during construction) and ship operation (eg., its deformation, etc.).
- Wave conditions – the scatter diagram representing World Wide trading routes was developed taking into account the assumed probability of the ship's presence on different routes (Fig. 3).

The computations of failure probability of "as built" panamax size bulk carrier presented in Table 2 show that:

- the weakest structure is the ship side frames installed between rigid tanks, and its probability of collapse is at the level of 10^{-1},
- the most probable scenario of ship sinking is the loss of the side integrity, and then, collapse of the bulkhead due to the sloshing and progressive ship flooding leading to sinking,
- the calculated probability of ship loss per year Pr(*SL*)/25= 2.43 10^{-3}/year, which is high.

The strengthening of the ship as presented in Table 1 increases the safety (Table 3) to the level Pr(*SL*)/25= 1.2 10^{-4}, which could be acceptable.

The numerical step probability distribution function was determined basing on simulation of ship motion in waves and its structure response to waves in 10000s for 121 sea states and for 3 ship headings (1 head and 2 bow seas). The Weibull approximation of the numerical distribution function depends on the time of simulation as statistics depend on simulation time interval. Therefore, the minimum time of simulation should be studied.

Examples of the difference in numerical and Weibull distribution are shown in Fig. 10 and 11.

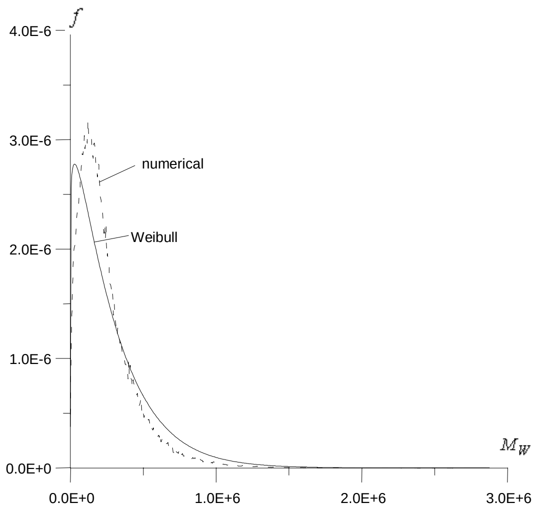

Fig. 10. The difference between numerical and Weibull distribution of hull girder wave bending moment

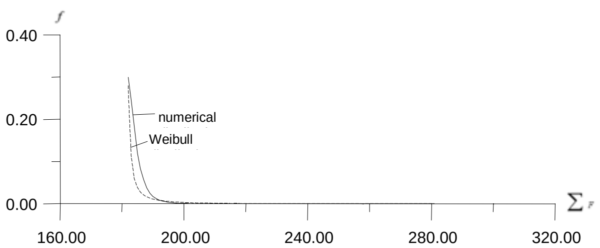

Fig. 11 The difference between numerical and Weibull distribution of frame stresses

Many assumptions have been introduced to built the risk model and only some events causing failure of ship structure have been taken into account. The assumptions need verification and the fault tree needs supplementation.

Yet the examples presented show that the risk model is a good tool for measurements of safety for different ship structures and that appropriate strengthening of the ship structures, eg frames and bulkheads, could significantly increase single skin bulk carrier hull structure safety.

7. CONCLUSIONS

In case of ship structure, the fault tree makes it possible to take into account different scenarios of ship sinking due to its structure failure – those known from statistics [4] and those which can be foreseen.

Probability theory is the tool for the fault tree analysis but to determine the probability distribution of random variables representing various failures, the basic events must be described by mathematical models and simulated with use of computer programs developed on the basis of these models. In this sense the fault tree combines the theory of stochastic processes, mechanics of sea waves, structure mechanics and probability theory, forming the risk model.

The risk model, based on its fault tree (usually characterised by high complexity), gives grounds for cooperation. The probability of particular basic or intermediate events can be computed separately in different institutions and put together, provided these probabilities are computed basing on the same probabilistic space.

The risk model needs further development and validation indicated in the discussion, but even the simple risk model presented in this paper enables to conclude that the risk model is a good tool to measure safety of ship structure. Referring to the same probability space the risk model can be used to measure the safety level of different ship structures.

The computations will be continued for other bulk carriers (handy and cape size) in order to derive, basing on the theories and on results of computations, the safety criteria for particular events of the fault tree (Fig. 1) and to develop the safety level (probability of failure) for the strength of bulk carrier structure – function of Tier II.

In the approach applied in this paper and for further work it has been assumed that:

- the criteria for particular events will be included in the rules of classification societies (Tier IV),
- the rules criteria should have the form of mathematical formulae depending on the characteristic values of ship loads and the capability of the ship structure to withstand the loads and on the

structure failure probability – like for example in [19],

- the probabilistic distributions, representing the ship structure capability to withstand the loads, describe the actual regime of ship designing and construction enforced by industry standards (Tier V).

Such an approach should ensure that the safety level of ship structure strength (ship function of Tier II) is achieved when ship designing and construction satisfies class rules (Tier IV) and industry standards (Tier V).

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Jan Jankowski started his ship-related career as a hull assembler at a shipyard. Graduating in naval architecture in 1976, he joined the Polish Register of Shipping as a field surveyor in PRS branch offices. In 1981 promoted to Head Office, he focused on development of rules for hull, which required further studies at the Faulty of Mathematics at Gdańsk University. In 1992 he was granted a PhD majoring in wave loads acting on ships. He was appointed Head of the Polish Register of Shipping in 1998, later becoming President of the PRS Management Board within a new organisational structure.

Marian Bogdaniuk graduated in naval architecture from the Gdańsk University of Technology in 1980. Ever since, he has been an academic and research staff member at the GUT Faculty of Ocean Engineering and Ship Technology. In 1988 M. Bogdaniuk presented his doctoral thesis on loads, acting on ship structures, generated in result of ship cutting the water surface. Since 1994 he has also been working for the Polish Register of Shipping (PRS) as an engineering expert. His work for PRS focuses on strength assessment of ship hulls and offshore structures and research projects on development and upgrading of classification Rules.