Proceedings of the ASME 2019 38th International
Conference on Ocean, Offshore and Arctic Engineering
OMAE2019
June 9-14, 2019, Glasgow, Scotland, UK

OMAE2019-96666

MULTIOBJECTIVE RELIABILITY-BASED DESIGN OF SHIP STRUCTURES SUBJECTED TO FATIGUE DAMAGE AND COMPRESSIVE COLLAPSE

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ABSTRACT

This work deals with reliability-based design and optimization of ship structures subjected to stochastic loads and accounting for the local fatigue damage and ultimate global strength. The reliability multi-objective structural optimization is performed in minimizing the structural component net-section area, lateral deflection and fatigue damage. The probability of compressive collapse and fatigue damage of the ship hull is used to define the minimum risk of structural collapse and best design solution. The Pareto frontier solutions calculated by the Non-Dominated Sorting Genetic Algorithm (NSGA-II) is employed in defining the feasible solutions of the design variables. The first order reliability method is employed to estimate the beta reliability index based on the topology of the structural component as a part of the Pareto frontier solutions. Comparing with the original design solution, the optimized section area decreased by 9%.

1 INTRODUCTION

Steel stiffened panels are mainly used for building ships and offshore structures. They withstand tensile and compressive axial loads and lateral pressure. For the safety of the ship structure, it is critical in predicting its load carrying capacity accurately. Under complex loading conditions, the effect of the lateral pressure on the structural strength depends on the interaction with the axial and lateral loads [1].

The limit state method has been widely applied in ship design as presented in [2]. Recent developments in structural reliability and optimization methods allow being employed new design methods coupled with the reliability and risk analysis, in which the uncertainties related to governing design variables can be considered directly. The First Order Reliability Methods, FORM approach [3] has been used for structural reliability assessment very intensively, and the Formal Safety Assessment [4, 5] was recently employed in [6] to perform a hull girder safety assessment of a tanker ship and in [7-9] for a conceptual ship design of a multipurpose ship.

The Pareto frontier, ultimate limit state, and target reliability, defined as additional constraints, are used nowadays to identify the optimal design solution [10].

Combining the risk and reliability methods with the structural optimization techniques, the three-step multiobjective reliability-based design approach is developed here. First, the structure topology is determined, where the scantling of the stiffened plate is performed and optimized, in which the design governing variables and the objective functions are defined. The objective functions are related to the minimum net section area resulting in minimum weight, minimum lateral deflection to avoid a possible local buckling and minimum local fatigue damage. Several constraints related to the structural topology, global ultimate strength and risk related to the entire structural collapse are also introduced.

NSGA-II [11] is employed to ensure that the optimal solution can be obtained quickly with sufficient quantity and accuracy, where simultaneous minimization of the net sectional area, structural deflection and fatigue damage is performed.

The Pareto frontier method [12, 13] is used to determine the optimal design solution, which satisfies all constraints and minimizes the three objective functions. The results are used as a basis for a reliability-based optimization, which is required to guarantee the structural integrity and safety during the service life of the ship. This step accommodates the uncertainties of the design variables, and highly demanding computational methods are involved.

The target risk or reliability levels are used for performing RBDO for the ship structure defining the most acceptable design solution in minimizing the total consequence cost over the service life of the structure, where the failure results in economic losses represented in a monetary term.

2 SHIP MAIN DIMENSION

A 175,000-ton bulk carrier is used as a target ship, where the length between the perpendiculars is L = 289 m, the depth is D = 24.7 m, the breadth is B = 45 m, the design draft is d = 18 m and the block coefficient is C_b = 0.79.

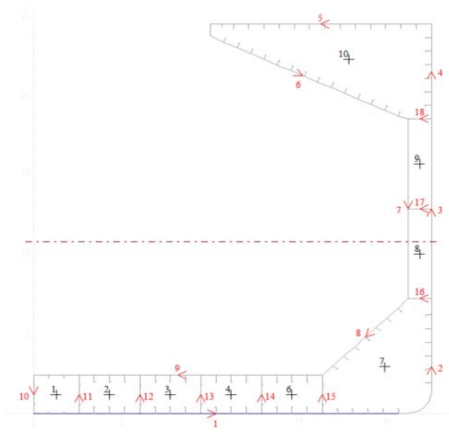

Figure 1 Half cross section of ship hull

The ship hull cross-section is shown in Figure 1. The cross-section contains 129 plates and 98 stiffeners. The longitudinal stiffened plate is composed of a tee-bar profile, with a spacing of 860 mm and a frame span of 2,950 mm.

The details of the longitudinal stiffeners are presented in Table 1, and Young's modulus is E=2.1E5 N/mm^{2,} and the Poisson ratio is 0.3.

Table 1 Longitudinal stiffeners

No.	Dimensions (mm)	Type	Yield Stress (MPa)
1	200×20	Flat bar	320
2	150×18	Flat bar	320
3	250×25	Flat bar	320
4	200×20	Flat bar	320
5	$420 \times 12 + 100 \times 20$	Tee-bar	320
6	$420 \times 12 + 100 \times 30$	Tee-bar	320
7	$320 \times 12 + 100 \times 18$	Tee-bar	320
8	$300 \times 12 + 100 \times 12$	Tee-bar	320
9	$300 \times 12 + 100 \times 16$	Tee-bar	320
10	$350 \times 12 + 100 \times 20$	Tee-bar	360
11	$300 \times 12 + 100 \times 18$	Tee-bar	360
12	300×30	Flat bar	360
13	200×20	Flat bar	360
14	350×30	Flat bar	360
15	$300 \times 12 + 100 \times 24$	Tee-bar	360

3 GEOMETRY AND LOADS

The most critical loading condition for the analyzed ship hull is the alternate hold loading condition with odd-holds loaded with high-density cargoes and even-holds empty. The position of the stiffened plate, chosen for optimization, is a part of the bottom of the ship. The stiffener type is T-bar. The initial geometry parameters of the stiffened plate are shown in Table 2.

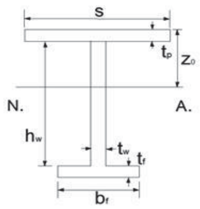

Figure 2 T-type stiffened plate cross-section

The still water and wave-induced bending moments in hogging and sagging and local static and dynamic pressure loads as defined by IACS [2] are used here. The initial inertia moment of the midship net section concerning the neutral axis is $I_{na} = 603.2\ m^4$ and the midship section modulus, concerning the bottom line, is $W_b = 55.3\ m^3$. The initial geometry descriptors of the stiffened plates are presented in Table 3 and will be redefined during the optimization process.

Table 2 Stiffened plate

Width of bottom plate, s	860 mm
Bottom plate thickness, t_p	18 mm
Web height, h_w	420 mm
Web thickness, t_w	12 mm
Flange Breadth, b_f	100 mm
Flange thickness, t_f	20 mm

The optimized longitudinal stiffener is subjected to an axial load resulting from the vertical still water and wave-induced bending moments as:

$$\sigma_{global} = \frac{M_{sw} + \Psi M_w}{W_{bottom\ ship}} \quad (1)$$

where Ψ is a combination factor between the still water and wave-induced loads ranging from 0.8 to 0.95 depending on the assumptions and it is assumed here to be a deterministic one of 0.9 [14]. The stiffener plate is also subjected to a lateral load, which is induced by the hydrostatic and dynamic local pressure:

$$q_{local} = (P_{sw} + \Psi P_w)s \quad (2)$$

The stiffened plate is assumed to be a simply supported beam subjected to a uniformly distributed lateral load, q_{local} and axial force:

$$T = A(M_{sw,s} + \Psi M_{w,s})/W_{bottom\ ship} \quad (3)$$

where A is the net sectional area of the stiffened plate [10].

The maximum stresses at the middle of the beam are calculated as:

$$\sigma_{max,x=0} = \sigma_{local} + \sigma_{global} \quad (4)$$

where:

$$\sigma_{local}(P_{sw}, P_w) = \frac{m_{x=0}}{W_{stiffened\ plate}} \quad (5)$$

$$\sigma_{global}(M_{sw,s}, M_{w,s}) = \frac{M_{sw,s} + \Psi M_{w,s}}{W_{bottom\ ship}} \quad (6)$$

where $m_{x=0}$ is the local bending moment induced by the lateral pressure.

4 STRUCTURAL OPTIMISATION

The goal of the structural design is to find the optimal acceptable solutions by satisfying the imposed constraints on the structures, which is usually regarded as a single objective optimization problem.

However, many design problems are multistate, multi-specific or need to optimize multiple objectives simultaneously. There may be trade-offs between the goals, and improving one feature requires compromising another. The challenge is to identify solutions that are part of the Pareto optimal set design, where no further improvement can be achieved without degrading one of the others.

Pareto optimization problems have been found in various research fields, and different computational methods have been developed to identify the Pareto frontier [12, 13].

4.1 Decision variables

In this study, there are five decision variables considered to define the shape of the cross-sectional area of the stiffened plate. Choosing the appropriate range of the decision variables is a fundamental issue, which can facilitate finding solutions that meet the specific requirements in the subsequent Pareto frontier calculation.

The decision variables assumed here are:

$$x_1 = t_p,\ x_2 = h_w,\ x_3 = t_w,\ x_4 = b_f,\ x_5 = t_f \quad (7)$$

The original dimensions of the stiffened plate with its attached plate considered here is $t_p = 0.018\ m$, $b_f = 0.1\ m$, $t_f = 0.02\ m$, $h_w = 0.42\ m$, $t_w = 0.012\ m$.

Since the optimal design will be based on the initially designed solution, the decision variables are not expected to change too much. So it can be used as a starting reference for the definition of the ranges of the variables:

$$x_{i,min} \leq x_i \leq x_{i,max}, i \in [1,5] \quad (8)$$

the minimum values of the decision variables are assumed as [0.012, 0.4, 0.012, 0.1, 0.012] and the maximum values of the decision variables as [0.03, 0.5, 0.03, 0.2, 0.03].

4.2 Objective functions

Three critical factors are taken into consideration leading to three objective functions that need to be built and meet the constraints.

The first two objective functions are related to the structural response of the stiffened plate defined as a minimization of the weight, which leads to a minimizing of the net sectional area and minimizing the structural deflection:

$$F_1 = \min\{z_{x=l/2}\} \quad (9)$$

$$F_2 = \min\{A\} \quad (10)$$

The structural deflection is defined by using the solution of the differential equation of a simply supported beam subjected to a uniformly distributed lateral load, q_{local} and an axial force, T as defined in [15] and $z_{x=l/2}$ is the deflection at the middle of the span and A is the net-sectional area of the stiffened plate.

The third objective function is related to the minimization of the fatigue damage:

$$F_3 = \min\{D_{x=0}\} \quad (11)$$

The fatigue damage, D is calculated based on the fatigue damage assessment approach as stipulated in [16] for the welded joints at supports where S-N curve I is selected with $log_{\bar{a}} = 12.164$ and m=3.0. The assumed stress concentrator assumed is K_a=1.6.

4.3 Constraints

To avoid a local buckling, the dimensions of the flange, web and attached plate of the stiffened plate have to satisfy the following restrictions [2]:

$$G_1:\ x_1 - \frac{s}{C}\sqrt{\frac{\sigma_y}{235}} > 0 \quad (12)$$

$$G_2:\ x_3 - \frac{h_w}{C_w}\sqrt{\frac{\sigma_y}{235}} > 0 \quad (13)$$

$$G_3:\ x_5 - \frac{b_f}{C_f}\sqrt{\frac{\sigma_y}{235}} > 0 \quad (14)$$

where s is the distance between the longitudinal stiffeners, C=100, $C_w = 75$, $C_f = 12$.

5 RELIABILITY ASSESSMENT

The reliability analysis performed here is using the First Order Reliability Method, FORM that identifies a set of primary random variables, which influence the limit-state under consideration.

The limit-state function defines a failure surface when equals to 0, which is, in fact, an (n-1) dimensional surface in the space of n primary variables. The formation of the Reliability-Based Design Optimization, RBDO is similar to the one of the optimizations where the objective limits state function, $g(\mathbf{b}, \mathbf{x})$ is minimised, and it is subject to constraints, where **b** is the vector of the deterministic design variables and **x** is the vector of the random variables.

The design surface is divided into a safe region when $g(\mathbf{b}, \mathbf{x}) > 0$ and an unsafe one when $g(\mathbf{b}, \mathbf{x}) < 0$. The failure probability of a structural component concerning a single failure mode can formally be written as:

$$P_f = P[g(b, x) \leq 0] \quad (15)$$

where P_f denotes the probability of failure. In practical applications, the FORM provides a reasonably good accuracy [3].

The required safety index is defined here as β_{target}, which is calculated based on the minimum risk of structural collapse.

The Beta index of all feasible design solution, corresponding to the Pareto frontier solutions are checked concerning the target safety index, where $\min\{\beta_{target} - \beta_i\}$ is the best suitable design solution.

5.1 Limit states

5.1.1 Ultimate strength

The limit state function related to the ultimate strength of the ship hull is defined as [10]:

$$g_1(\mathbf{b}, \mathbf{x}) = x_u \sigma_u(\mathbf{b}, \mathbf{x}) - \sigma_{max}(\mathbf{b}, \mathbf{x}) \quad (16)$$

where

$$\sigma_{max}(\mathbf{b}, \mathbf{x}) = \sigma_{global,max}(\mathbf{b}, \mathbf{x}) + \sigma_{local,max}(\mathbf{b}, \mathbf{x}) \quad (17)$$

$$\sigma_{global,max} = (x_{m,sw} M_{sw} + \psi x_{m,w} M_w)/W_{bottom,\ ship} \quad (18)$$

$$\sigma_{local,max} = k_2 (x_{p,sw} p_{sw} + \psi x_{p,w} p_w) l / W_{stiff} \quad (19)$$

The software MARS2000 [17] is used to estimate the ultimate strength, $\sigma_u(\mathbf{b}, \mathbf{x})$ of the ship hull and its geometrical descriptors.

Seven deterministic variables $b_1 = t_p$, $b_2 = h_w$, $b_3 = t_w$, $b_4 = b_f$, $b_5 = t_f$, $b_6 = \sigma_y$, $b_7 = E$, and ten random variables $x_1 = M_{w,BL,h}$, $x_2 = P_{w,BL,h}$, $x_3 = M_{sw,BL,h}$, $x_4 = P_{sw,BL,h}$, $x_5 = \sigma_u$, $x_6 = x_u$, $x_7 = x_{p,sw}$, $x_8 = x_{m,sw}$, $x_9 = x_{p,w}$, $x_{10} = x_{m,w}$, are considered here.

The ultimate stress capacity, $\sigma_u(\mathbf{b}, \mathbf{x})$ is assumed to be estimated with a model uncertainty x_u, which is described by the Normal probability density function, $x_u \sim N_{x,u}(1.05, 0.1)$.

The model uncertainty factor $x_{m,w}$ accounts for the uncertainties in the wave-induced vertical bending moment calculation. Resulting in $x_{m,w} \sim N_{x,m,w}(1, 0.1)$ and the model uncertainty factor concerning the still water load is $x_{m,sw} \sim N_{x,m,sw}(1, 0.1)$ and concerning the local pressure load are modelled by $x_{p,sw} \sim N_{p,sw}(1, 0.1)$ and $x_{p,w} \sim N_{p,w}(0.95, 0.095)$.

The 5% confidence level value of the ultimate bending moment $M_u^{5\%} = M_u^c$ is calculated by MARS2000 [17] software and it is assumed that COV is 0.08 and it is fitted to the Lognormal probability density function:

$$f_{Mu} = \frac{1}{M_u \sigma_{Mu} \sqrt{2\pi}} e^{-\frac{(\ln(M_u) - \mu_{Mu})}{2\sigma_{Mu}^2}} \quad (20)$$

$$\sigma_{Mu} = \sqrt{\ln(COV^2 + 1)} \quad (21)$$

$$F^{-1}_{M_u}(0.05, \mu_{M_u}, \sigma_{M_u}) = M_u^{5\%} \quad (22)$$

The Gumbel distribution, for the extreme values of the vertical wave-induced bending moment, over the reference period T_r is derived based on the shape, h and scale, q factors of the Weibull distribution function as [18]:

$$\alpha_m = q(\ln(n))^h \quad (23)$$

$$\beta_m = \frac{q}{h}(\ln(n))^{(1-h)/h} \quad (24)$$

where α_m and β_m are the parameters of the Gumbel distribution, n is the mean load cycles expected over the reference period T_r for a given mean value wave period T_W.

where p is part-time in which the ship is in seagoing conditions.

The Gumbel distribution function is described as:

$$F_{Mw} = \exp\left\{-\exp\left(-\frac{M_{w,e}-\alpha_m}{\beta_m}\right)\right\} \quad (25)$$

where $M_{W,e}$ is a random variable that represents the extreme value of the vertical wave-induced bending moment over the reference period, T_r.

The still water bending moment is fitted to a Normal distribution, where regression relationships define the statistical descriptors of the still water bending moment as a function of the ship length, L and deadweight ratio, W= (DWT/Full load) [19, 20]:

$$E(M_{SW}) = \frac{E(M_{SW,max})M_{SW,CS}}{100} \quad (26)$$

$$StDev(M_{SW}) = \frac{StDev(M_{SW,max})M_{SW,CS}}{100} \quad (27)$$

5.1.2 Fatigue strength

The limit state function related to the fatigue damage assessment is defined as:

$$g_2(\mathbf{b},\mathbf{x})=\ln(D)+\ln(A)-m\ln(B)-\ln(\Omega)-\ln(T_D) \quad (28)$$

where D is fatigue damage, T_D is the fatigue design life, A represents the uncertainties related to fatigue strength, B is the uncertainties due to the idealized assumptions in the fatigue load calculation and Ω is stress parameter.

The random variable follows the Log-normal distribution with mean values as $E[\ln(D)]=\ln(\tilde{D})$, $E[\ln(A)]=\ln(\tilde{A})$, $E[\ln(B)]=\ln(\tilde{B})$ and the standard deviations are defined as $\sigma_{\ln(D)}=\sqrt{\ln(1+COV(D)^2)}$, $\sigma_{\ln(A)}=\sqrt{\ln(1+COV(A)^2)}$ and $\sigma_{\ln(B)}=\sqrt{\ln(1+COV(B)^2)}$.

For the analysis performed here $\tilde{D}=$ 1.0, $\tilde{A}=1.45\times10^{12}$, $\tilde{B}$ =0.7, COV(D)=0.3, COV(A) =0.512 and COV(B) =0.50.

5.2 Target reliability

The risk is defined here as a product of the probability of failure and the impact during a period, which in general may be assumed as the service life of the ship, which may be expressed in monetary value [8]:

$$Risk(t)=\Sigma_j P_{f,j}(P[g(\mathbf{x}_{1,j}|t)\leq 0])\, C_{f,j}(\mathbf{x}_{2,j}|t) \quad (29)$$

where $P_{f,j}(P[g(\mathbf{x}_{1,j}|t)\leq 0])$ is the probability of failure, $C_{f,j}(\mathbf{x}_2|t)$ is the impact, the consequence cost of failure, $\mathbf{x}_1$ and $\mathbf{x}_2$ are the vectors of parameters involved in the probability of failure and consequence analyses and $t\in[0, \tau_S]$.

The total expected risk should cover the risk associated with the structural failure, $Risk_{Pf}$ (t^n|DM, β) and the one with the structural safety measure, $Risk_{me}$ (DM, β), which are as a function of the time, t^n, reliability index, β and design modifications, DM:

$$Risk_{total}(t^n|DM,\beta)=Risk_{Pf}(t^n|DM,\beta)+Risk_{me}(DM,\beta) \quad (30)$$

The risk related to the ship structural collapse over the service life, t^n accounts for the probability of failure, P_f (t_j|DM, β), the cost of the ship in the year t_j, C_s (t_j|DM, β), the cost associated with the loss of cargo, C_c, the cost of the accidental spill, C_d and the cost associated with the loss of human life C_v:

$$C_{Pf}(t^n|DM,\ \beta)=\Sigma_j^n\{P_f(t_j|DM,\beta)[f_1C_s(t_j|DM,\beta)+f_2C_c+f_3C_d+f_4C_v]e^{-\gamma tj}\} \quad (31)$$

A detailed description of the parameters involved in Eqn (31) is given in [8] and the sensitivity analysis concerning the risk estimates in [7].

The target risk or reliability levels are used for performing RBDO for ship structures to minimize the total consequence cost over the service life of the structure, where the failure results in economic losses and consequences.

Input variables related to the present analysis are: cost of steel 950 USD/t, labor cost, 45 man-hours/USD, discount rate, 5 %, initial cost of the ship, 6.3E+07 USD, cost of scrap, 270 USD/t, fuel & oil, 1402 t, cost of fuel & oil/ton to be cleaned, 600 USD/t, cargo, 71,000 t, cost of cargo, 1,200 USD/t, member of crew, 21, service life, 25 years, initial weight of ship hull steel, 19,600 t [7, 21].

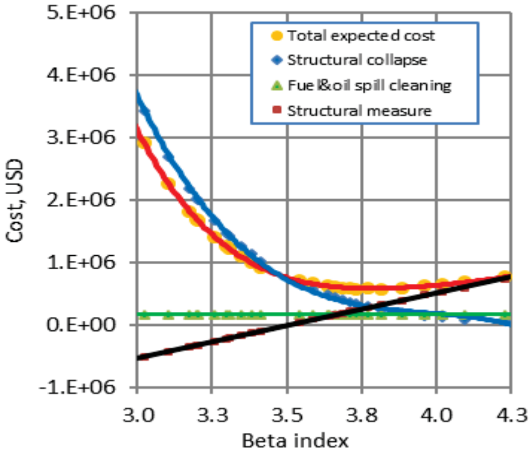

Figure 3 Expected costs

The corrosion degradation is modelled by a mean value, $E[d^{cd}(t)]$ and standard deviation, $StDev[d^{cd}(t)]$ of the corrosion depth as a function of time as defined in [22, 23]:

$$E[d^{cd}(t)]=d_{\infty}[1-\exp(-(t-\tau_C)/\tau_t], t>\tau_C \quad (32)$$

$$StDev[d^{cd}(t)]= a \, Ln(t -\tau_C- b) - c], t>\tau_C \quad (33)$$

where a, b and c are coefficients, the coating life is τ_C=5 years, and the transition life is τ_t = 7 years, and the long-term corrosion thickness of any individual structural component are defined based on the corrosion margins as defined in [24, 25].

The expected cost related to total cost, structural collapse, fuel&oil spill cleaning, structural measure as a function of beta reliability index are shown in Figure 3. The target risk or reliability level is defined as the beta reliability index associated with the minimum total expected cost.

6 ANALYSIS

6.1 Multi-objective optimization

The Pareto frontier is employed here allowing for the optimization of the three criteria, as they are defined in the present study, minimizing the net sectional area, deflection and the fatigue damage, verifying all trade-offs among the optimal design solutions of the three criteria.

Figure 4 shows the minimization of the three objective functions, F_1 (net sectional area), F_2 (deflection) and F_3 (fatigue damage) simultaneously.

Each design solution, allocated at that frontier represents unique design solution parameters. The Pareto optimal solution collects here 32 optimal design solutions that are going to be verified concerning the target reliability in the next section, leading to an additional constraint in the optimization process.

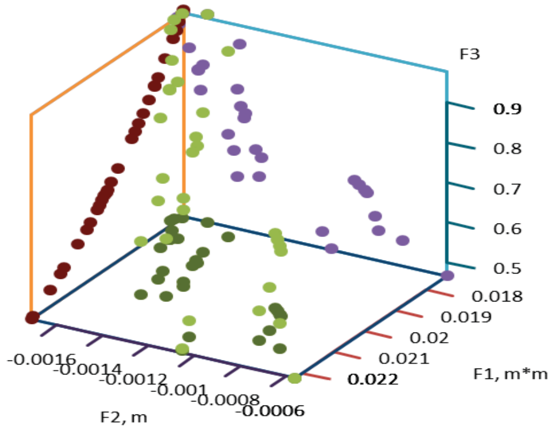

Figure 4 Pareto frontier solution: F1-net section area vs F3-fatigue damage vs F2-deflection.

6.2 Reliability-based design

The reliability analysis is incorporated into the optimization procedure, which is referred here as reliability-based design optimization, RBDO. The statistical nature of the constraints and design problems are defined in the objective function including the probabilistic constraints. The reliability target level can specify probabilistic constraints.

The reliability is performed based on the FORM, and all random variables are considered as non-correlated ones. Applying FORM as a decision tool, the estimated probability of failure needs to be compared to an accepted target level. The target levels depend on different factors as reported in [26]. The target level in a redundant structure may vary between $P_f = 10^{-3}$ ($\beta = 3.09$) for less serious and $P_f = 10^{-4}$ ($\beta = 3.71$) for severe consequences of failure values of the acceptable annual probability of failure [27].

During the RBDO analysis, the local fatigue (tensile load) and ultimate global strength (compressive load) probability of failure were accounted for where the two events are considered as non-correlated and presented as a series system with a weighting factor of 0.5.

The final beta index β, as a function of design optimisation at the Pareto frontier, is shown in Figure 6. The range of the Beta index of all design solutions at the Pareto frontier is from 2.9 to 4.3.

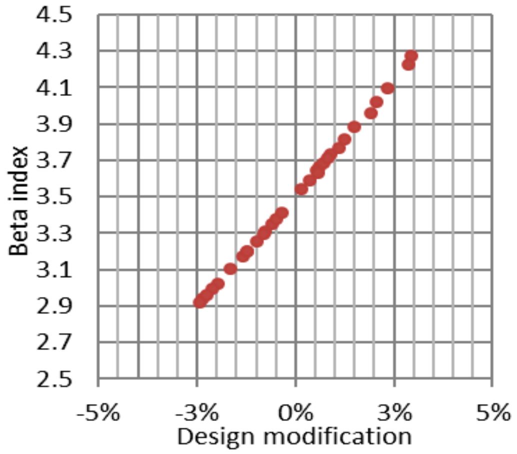

Figure 5 Beta index as a function of design modifications

The minimum risk (5.76E+05 USD) of structural collapse and associated cost identify the target beta reliability index for analyzed structures as $\beta = 3.8$, as can be seen from Figure 6.

The RBDO result leads to a design solution 23, which is represented by t_p= 0.016 m, h_w=0.409 m, t_w=0.013 m, b_f = 0.104 m t_f= 0.015 m, the section area is 0.0205 m^2.

Comparison with the original design section area of 0.0225 m^2, the optimized section area is reduced by 9%.

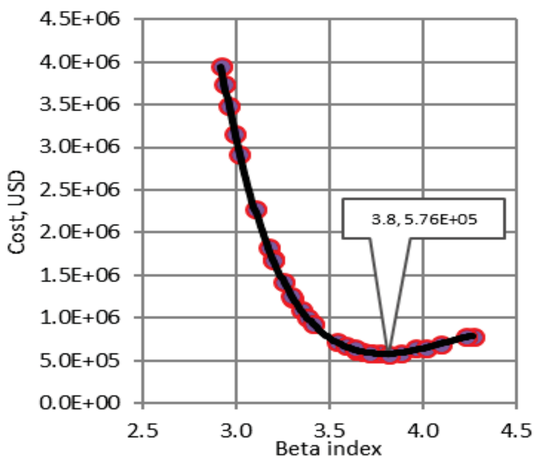

Figure 6 Target beta reliability index

7 CONCLUSIONS

This objective of this work was to develop an advanced approach to perform a reliability-based design optimization of ship structures subjected to stochastic loads and accounting for the local fatigue damage and ultimate global strength. The optimum design solution accounts for three objective functions in minimizing the weight, structural deflection and fatigue damage. The Pareto frontier was used to define the feasible surface solution of the design variables. The target risk or reliability level was used for performing a reliability design optimization in defining the most acceptable solution in minimizing the total consequence cost over the service life of the structure. Comparing with the original section area, the optimized stiffened plate section area is reduced by 9 %. The presented approach is flexible and demonstrated an excellent capacity to be used in the structural design of complex systems.

8 ACKNOWLEDGEMENT

This paper reports a work partly developed in the project ”Ship Lifecycle Software Solutions”, (SHIPLYS), which was financed by the European Union through the Contract No 690770 - SHIPLYS - H2020-MG-2014-2015.

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