

Development of Reliability-Based Damage-Tolerant Optimal Design of Ship Structures

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Abstract: While in service, ship structures are continuously subjected to environmental loading and deterioration, which could lead to increased inspection and maintenance costs during a vessel's lifecycle. The design strategy presented in this study considers structural damage, such as corrosion and fatigue, and makes some provision for their impact on structural integrity. If adopted during the conception and design stage, such a strategy could lead to a reduction in lifecycle costs. The approach synergistically combines advanced computational methods, damage models, probabilistic tools, and optimization techniques to enhance the robustness and overall structural reliability of ship structures. The study first presents a formulation of system reliability-based damage-tolerant optimal design models. The design strategy is illustrated through an example problem involving the redesign of a tanker structure for optimal performance and reliability. The sensitivity of the optimal design to uncertain design parameters, such as material properties and loads, is also investigated. DOI: 10.1061/AJRU66.0000836. © 2015 American Society of Civil Engineers.

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Introduction

The lifecycle management of a ship structure can be divided into four stages: (1) conception and design; (2) fabrication and production; (3) operation and maintenance; and (4) disposal. Decisions made during conception, design, and fabrication have the greatest impact on the durability, maintainability, inspectability, and cost of a vessel's operation and maintenance. Advances in structural computation methods, reliability tools, and optimization techniques should be combined and incorporated into an optimal decision-making process, thereby minimizing both initial and future costs while maximizing structural safety.

Optimal design of a ship structure involves the selection of materials for structural components, sizing of component dimensions, and choice of topological arrangement of structural components (configuration, geometric layout, etc.) that best enhances the robustness and overall safety of the structure. The rising cost of design materials, coupled with the high costs associated with operating a vessel, will require that its weight be optimized in order to maximize the benefits of cost-effective usage of available resources. However, uncertainties arising from randomness in applied loads and material properties as well as errors in behavioral models

are inevitable and must be considered during the design stage to assure structural safety and reliability. Previous research efforts (Ayyub et al. 2000; Atua 1998, for example) have been devoted to the presentation of models used for characterizing the high level of uncertainty arising from load parameters. These load-based models must be applied in conjunction with strength-based models to effectively assess the vessel's reliability during the initial design stage.

A commonly-used probabilistic method for ship structural design involves a load-resistance design philosophy. This strategy combines the uncertainty in both material properties and applied loads to achieve optimal selection of structural components. However, the approach is based on an assessment of individual component reliability, and, as such, does not account for the interaction between the physical and failure models of various components in assessing the reliability of the entire system. The overall system reliability of a ship structure can be vastly different from individual component reliabilities, depending on the vessel layout, its topology, material, configuration, member sizing, connection types, and applied loading used in design. An optimization approach that considers the overall structural system reliability in addition to component reliabilities should be used to assess the adequacy and relative merits of alternative system designs with respect to established objectives. Thus, system-reliability-based optimization is required to properly account for the large number of potential failure modes and their complex interaction in terms of common loading, strength correlation, and relative occurrence of risks. In this regard, Pu (1997) has made an attempt at such optimization for a small waterplane area twin hull (SWATH) ship structure.

During the expected life of a vessel, deterioration or damage may occur in a variety of forms as a result of corrosion, fatigue, buckling, and accidental damage. An optimal structural design must therefore envision the possible occurrence of such damage modes. Moreover, provision for their impact on structural integrity must be made during the design stage in order to reduce maintenance and failure costs. A probabilistic-based damage-tolerant optimal system design approach, which accounts for the possibility of structural damage during the lifetime of the vessel, is formulated in this study. An optimization tool with the capability of implementing

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the aforementioned strategy is discussed. An example problem involving the optimal redesign of the midship section of an existing tanker structure is used for demonstration.

The extreme lifecycle loads used during the design phase of a ship structure are also subject to uncertainties. To minimize the cost of design, it is important to numerically investigate the sensitivities of the optimal structural design to changes in the probabilistic characteristics (e.g., mean value, standard deviation, probability distribution, etc.) of the load-based design parameters. Such information could be compiled in a database and subsequently used as a guide during the design stage.

Formulation of a System-Reliability-Based Damage-Tolerant Optimization Strategy

Two optimal damage-tolerant design problems applicable to the design of ship structures, wherein the system reliability appears either as a constraint or as an objective function, can be stated as follows:

1. Minimize the initial cost of design (i.e., weight), subject to constraints on both initial (i.e., undamaged) and damaged system and component reliabilities. Mathematically this is expressed as Minimize, $w(X)$, subject to the following constraints:

$$\beta_0(X) > \beta_{0,th}$$

$$\beta_{dam}(X, D) > \beta_{dam,th}$$

$$\beta_{sys}(X) > \beta_{sys,th}$$

$$X_L < X < X_u$$

where $w(X)$ = weight of the ship section; $\beta_{sys}(X)$ = system reliability index of the ship section; w or β = weight or reliability index.

2. Maximize the damage-tolerant system reliability subject to constraints on both the initial cost of design (i.e., weight) and component/system reliabilities of initial and damaged systems. Mathematically this is expressed by

Maximize, $\beta_{sys}(X)$, subject to the following constraints:

$$\beta_0(X) > \beta_{0,th}$$

$$\beta_{dam}(X, D) > \beta_{dam,th}$$

$$w(X) < w_{th}$$

$$X_L < X < X_u$$

where w = the weight; X = the design variables, namely structural scantling; the subscript th = some prescribed threshold value for the associated parameter (β or w); and X_L and X_u = the lower and upper bounds, respectively, on the collection of design parameters denoted by X .

The first problem outlined in the preceding discussion seeks to find the optimal values of the design variables (X) that lead to a reduction in weight and the associated costs (material, fabrication, operational costs including fuel consumption, speed limitations, etc.), while maintaining the original and damaged reliability indices above specified threshold values. This approach combines a deterministic objective function with probabilistic constraints and deterministic side constraints (bounds on design variables).

The second problem endeavors to find the optimal values of the design variables (X) that maximize the system reliability index

(i.e., safety), while ensuring that original and damaged reliability indices remain above specified threshold values, and the structural weight lies below a selected threshold. The maximum threshold value for weight, for example, may be defined in terms of a specified percentage reduction below that of an initial design based on engineering judgment, experience, and load resistance factor design (LRFD) suggestions. This approach implies the amalgamation of a probabilistic objective function with both probabilistic and deterministic main constraints, and deterministic side constraints (bounds on design variables).

An alternative formulation of Problem 1 could involve the definition of structural reliability constraints in terms of failure probability (POF). That is, the problem may be redefined as

1. Minimize the objective function, $w(X)$, subject to the following POF-based constraints:

$$P_{f0}(X) < P_{f0,th}$$

$$P_{fdam}(X, D) < P_{fdam,th}$$

$$P_{fsys}(X) < P_{fsys,th}$$

$$X_L < X < X_u$$

whereas the second problem can be redefined as

2. Minimize the objective function, $P_{fsys}(X)$, subject to the following constraints:

$$P_{f0}(X) < P_{f0,th}$$

$$P_{fdam}(X, D) < P_{fdam,th}$$

$$w(X) < w_{th}$$

$$X_L < X < X_u$$

where $P_{f0,th}$, $P_{fdam,th}$, and $P_{fsys,th}$ = prescribed threshold values for the probability of failure of the original intact design, the damaged design, and the overall system, respectively.

Selection of Design Parameters

The design variables that should be considered in the optimal design of a ship structure include

1. Sizing variables (e.g., cross-section dimensions of structural members);
2. Shape variables (e.g., configuration and geometric layout);
3. Material variables (mechanical and/or physical properties of the materials to be used);
4. Topological variables (general arrangement, e.g., location of major bulkheads); and
5. Structural system types (for example, stiffened panels or longitudinals).

Initial values, as well as their bounds, should be selected based on experience, engineering judgment, and LRFD.

Selection of Constraints

During the initial design stage, it may be desirable to place constraints on maximum allowable weight, which is affected not only by material selection, but also by member sizing. In the event that structural damage has occurred to some extent, constraints may be placed instead on maximum damage weights. Constraints could also include the minimum allowable margin of safety for

Table 1. Principal Dimensions of a Tanker Vessel

Parameter	Dimension (m)
Length (L)	220
Breadth (B)	38.1
Depth (D)	17.4
Draft (T)	13.5
Block coefficient	0.75

the structure, which could be defined in terms of either probability of failure or a reliability index for dominant system components. The minimum allowable value of postdamage safety margins can also be specified as a constraint. The structural safety of an optimal design, defined in terms of limit state functions, is affected by a number of factors, including sizing (component dimensions), material selection, geometric and topological layout of components, and quality of fabrication. Initial values and minimum/maximum bounds on component sizes, also known as side constraints, should be based on experience, engineering judgement, and LFRD estimates.

Computational Tools for Reliability Analysis and Structural Design Optimization

Many reliability-based computation tools that can be applied to ship structural design have been developed over the years. A review of the capabilities and limitation of such tools have been presented in Mansour et al. (1997) and Liu et al. (1993). Examples of these tools are summarized in Cronvall (2011), including *PROBAN*, *CALREL*, *NEUSSUS*, *ISPUD*, *STRUREL*, *RASOS*, *RELAN*, *PRAISE*, *PROF*, which feature capabilities ranging from crude Monte Carlo Simulation (MCS) to advanced methods such as first-order and second-order reliability methods (*FORM*, *SORM*). The tools also allow for computation of both time-invariant and time-dependent component/system reliabilities and failure probabilities. Some of the algorithms implemented in these tools can be found in standard studies such as Ang and Tang (2007) and Ayyub (2014). The theory of structural optimization is well documented in standard texts, including those by Adeli (1994) and Kamat (1993). Algorithms for both integer and continuous variable or mixed optimization problems are also discussed in these works. Software tools for structural

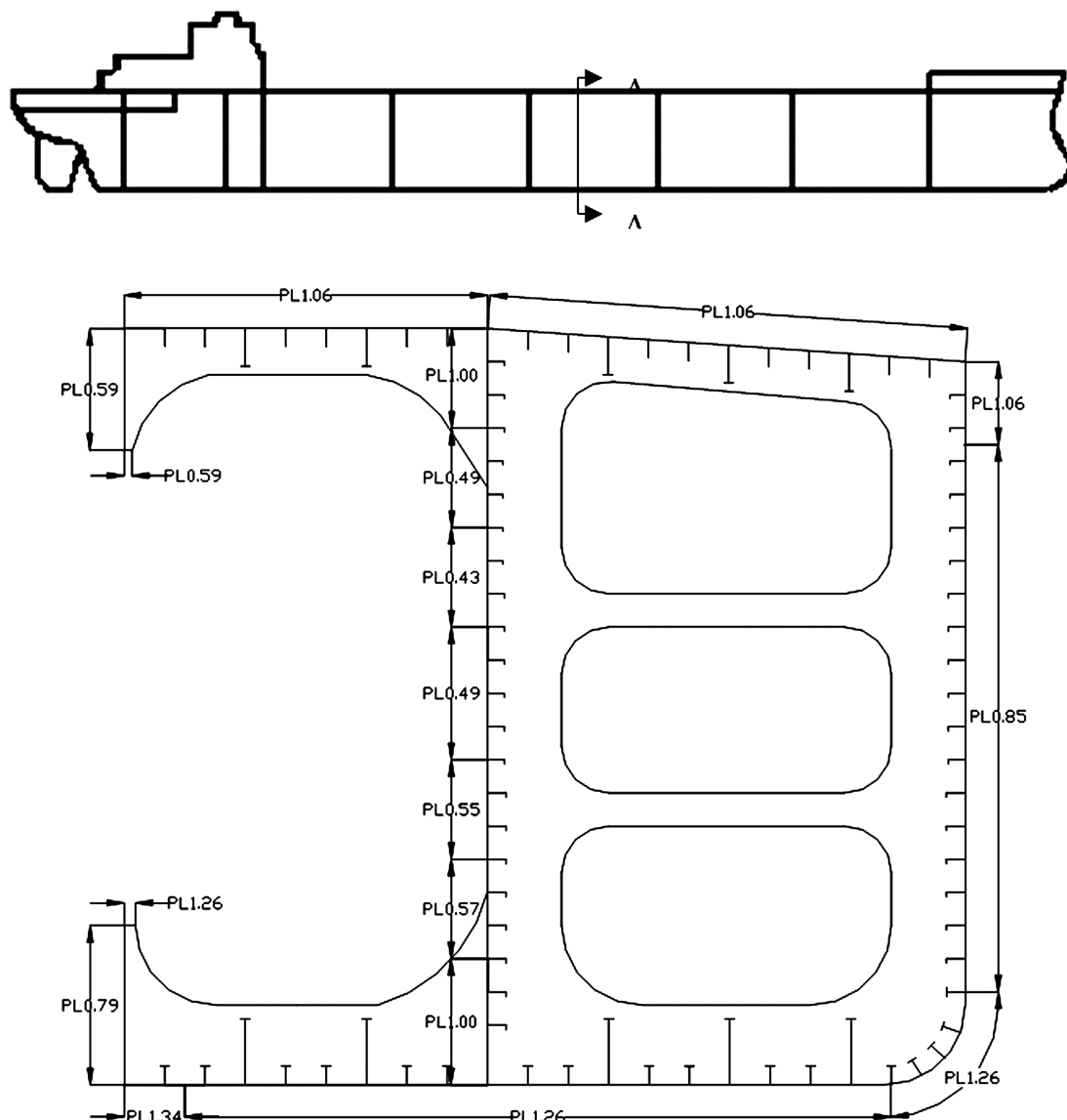


Fig. 1. Schematic diagram of tanker vessel (Section A-A), showing hull and bulkhead plating thickness (1.00 in. = 2.54 cm)

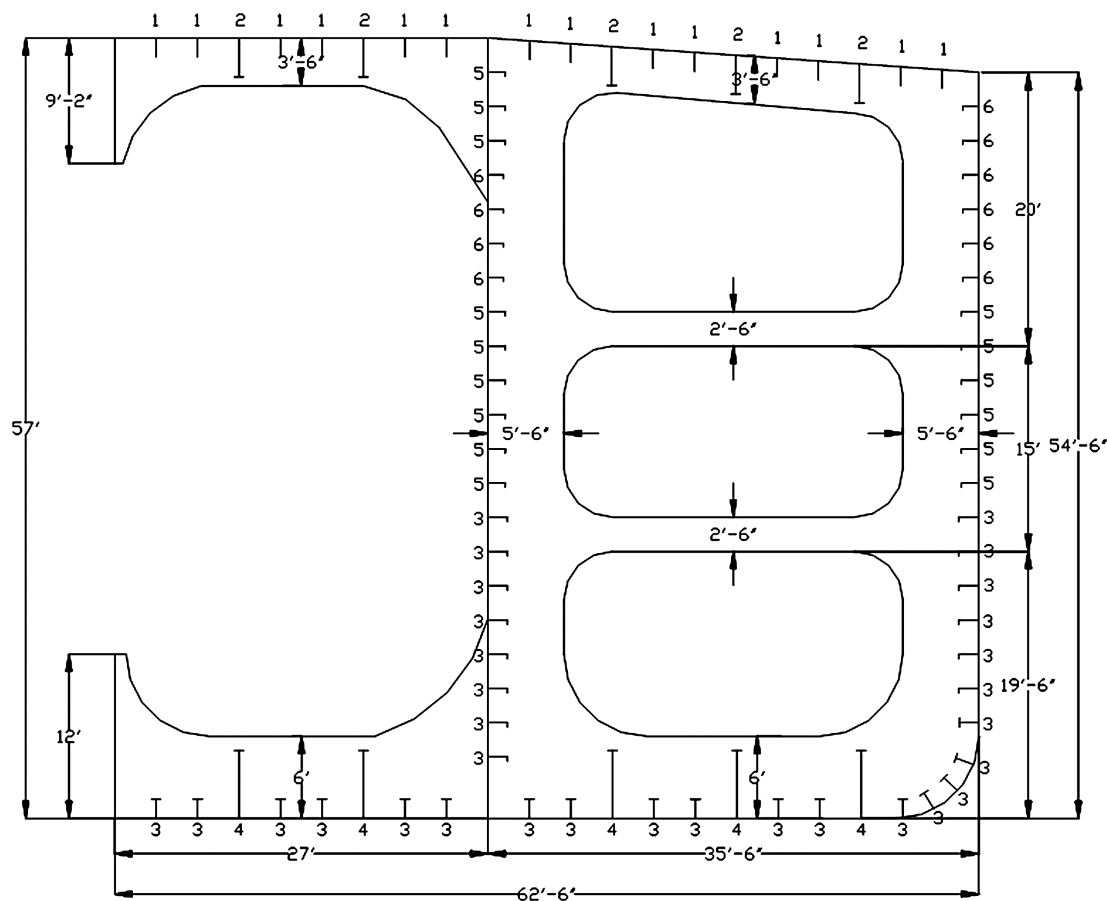


Fig. 2. Schematic diagram of tanker vessel showing cross-sectional dimensions (ft and in.) and stiffeners type codes (1.00 ft = 0.31 m)

optimization, such as *TSO*, *FASTOP*, *ASTROS*, *GENESIS*, and *COSMOS*, are summarized in Kamat (1993).

Reliability estimation and optimization capabilities have been seamlessly integrated into the computational tool *SMARTOPT*, which has been developed by Martec (Akpan et al. 2000) and will be employed in the current study. *SMARTOPT* features two efficient optimization algorithms, namely modified feasible direction (MFD) and sequential linear programming (SLP).

Demonstration of Reliability-Based Damage-Tolerant Design

Description of Example Ship

The reliability-based damage-tolerant design optimization strategy is applied to a tanker structure to determine the optimal scantling for the midship section. The overall dimensions of the vessel are

provided in Table 1. Schematic diagrams of the vessel and its cross-sectional profile, along with typical stiffener dimensions, are illustrated in Figs. 1 and 2, and Table 2, respectively.

Description of Limit State Equations

The integrity of the system is evaluated using the ultimate capacity limit state function for the structure. This limit state function is defined in terms of the ultimate moment capacity of the hull girder, and the load-induced moment resulting from a combination of the still-water bending moment, wave-induced bending moment, and dynamic bending moment. The following relation defines the overall load-induced bending moment, M_L :

$$M_L = M_{SW} + k_W(M_W + k_D M_{Dyn}) \quad (1)$$

where M_{SW} = the still-water bending moment; M_W = the wave-induced bending moment; M_{Dyn} = the dynamic bending moment; and k_{Dyn} = the correlation factor between wave-induced and dynamic bending moments. The correlation factor k_{Dyn} depends on whether the bending is of the hogging or sagging type (Mansour et al. 1994; Atua 1998). The ultimate moment capacity of a hull girder, denoted by M_U , can be computed using a variety of methods, ranging from analytical to nonlinear elasto-plastic finite-element-based methods (Ayyub et al. 2000; Akpan et al. 2001). For demonstration purposes, an analytical representation of M_U is employed in this study. For an initial design, the ultimate moment capacity of a hull girder can be defined as follows:

$$M_{u,0} = \phi \sigma_{u,0} Z_0(X) \quad (2)$$

Table 2. Dimensions of Typical Longitudinal Stiffeners

Stiffener number	Stiffener dimensions (mm)	
	Web	Flange
1	450 × 35.5	N/A
2	1,000 × 16.0	400.0 × 16.0
3	465 × 18.0	190.5 × 25.4
4	1,220 × 16.0	350.5 × 25.4
5	371 × 16.0	100.0 × 16.0
6	297 × 11.5	100.0 × 16.0

where ϕ = a nondimensional factor known as the buckling knock-down factor; $\sigma_{u,0}$ = the original (i.e., undamaged) ultimate strength of the hull material; and $Z_0(X)$ = the midship section modulus, which may be calculated using any standard monograph on ship structures, such as that found in Hughes (1988). The midship section modulus is a function of both structural topology and member sizing, denoted here by X . A limit state function representing the initial, undamaged design is given by

$$g_0 = M_{u,0} - M_L \quad (3)$$

The presence of structural damage such as corrosion, fatigue cracking, and/or accidental damage lead to reduction in the ultimate moment capacity of the ship structure. The damaged ship ultimate moment capacity is given by

$$M_{u,dam} = \phi \sigma_{u,dam} Z_{dam}(X) \quad (4)$$

where $Z_{dam}(X)$ = the damaged midship section modulus; and $\sigma_{u,dam}$ = the damaged ultimate strength of the hull at midship. This parameter is a random variable for which a value is often difficult to estimate with certainty. Ayyub et al. (2000) and Akpan et al. (2002) have presented methodologies for computing midship section moduli under the influence of corrosion and fatigue damage. A second limit state function, which acknowledges the occurrence of structural damage, may be defined using

$$g_{dam} = M_{u,dam} - M_L \quad (5)$$

Based on the choice of design variables, member sizing, and structural topology, the failure probabilities for the original and damaged structures can be computed as $P_{f,0}(X)$ and $P_{f,dam}(X, D)$, respectively, where D describes the nature of the damage. Alternatively, the reliability indices for the intact and damaged designs, $\beta_0(X)$ and $\beta_{dam}(X, D)$, respectively, can be used to represent the safety inherent in each case. Assuming a series system, the two limit state functions above can be combined to obtain the overall system reliability index $\beta_{sys}(X)$ or system failure probability $P_{sys}(X)$, both of which are functions of the aforementioned design parameters denoted by X . Furthermore, algorithms available for computing failure probabilities and reliability indices, both at the component and system levels, are well defined and have been successfully incorporated into the *COMPASS* reliability software tool (Lui et al. 1993). Such algorithms include FORM, SORM, Monte Carlo simulation (with and without importance sampling), and PNET algorithms, as well as unimodal and bimodal bound methods for system reliability.

Results of Optimal Designs

For the current problem, a single material is assumed for the structural design parameters. Therefore, the weight of the entire vessel can be effectively represented by an extrapolation of the cross-sectional area of the midship. The design parameters are listed in Table 3. The thickness dimensions of these parameters constitute the design variables. The vessel represents an existing ship structure, the nominal or initial design of which is given in Ayyub et al. (2000) and Akpan et al. (2001). The optimization formulation that follows assumes that the upper and lower bounds of the design variables lie within $\pm 40\%$ of those used in the initial design. Formulas used to compute the ship loads for this vessel can also be found in Ayyub et al. (2000). Probabilistic descriptions of the load and other random variables are given in Tables 4 and 5.

Optimization in terms of weight reduction will be the focus of discussion in this section. The threshold values for the constraints

Table 3. Design Variables Input and Optimization Output

Design variable number	Name	Initial design thickness	Optimal design thickness	
			Nondamage tolerant	Damage tolerant
1	Deck 1	26.9	16.1	16.1
2	Deck 2	26.9	16.1	16.1
3	Deck stiffener 1	35.6	21.4	21.4
4	Deck stiffener 2	16.0	9.60	9.60
5	Deck stiffener 3	15.0	9.19	17.5
6	Deck stiffener 4	7.49	4.49	8.97
7	Starboard 1	26.9	16.1	16.1
8	Starboard 2	21.6	13.0	13.0
9	Starboard 3	32.0	19.2	44.7
10	Starboard stiffener 1	11.4	6.84	6.84
11	Starboard stiffener 2	16.0	9.60	9.60
12	Starboard stiffener 3	18.0	10.8	10.8
13	Bottom	34.0	47.6	47.6
14	Bottom 2	32.0	43.1	44.8
15	Bottom stiffener 1	18.0	21.9	25.2
16	Bottom stiffener 2	16.0	11.3	22.4
17	Bottom stiffener 3	10.0	6.00	11.4
18	Bottom stiffener 4	32.0	19.2	29.8
19	Bulkhead 1	25.4	15.2	15.2
20	Bulkhead 2	12.5	7.50	7.50
21	Bulkhead 3	10.9	6.54	6.54
22	Bulkhead 4	12.5	7.50	7.50
23	Bulkhead 5	14.0	8.40	8.40
24	Bulkhead 6	14.5	8.70	8.70
25	Bulkhead 7	25.4	15.2	35.5
26	Bulkhead stiffener 1	18.0	10.8	10.8
27	Bulkhead stiffener 2	11.4	6.84	6.84
28	Bulkhead stiffener 3	16.0	9.60	9.60
29	Bulkhead stiffener 4	18.0	10.8	10.8

Table 4. Probabilistic Characteristics of Principal Random Variables

Random variable	Mean value	Coefficient of variation	Distribution type
Ultimate stress, σ_u	281.4 MPa	0.10	Lognormal
Knockdown factor, ϕ	0.95	—	Fixed
Stillwater moment, M_{sw}	2.058×10^6 kN-m	0.40	Normal
Wave-induced moment, M_w	3.213×10^6 kN-m	0.10	Extreme
Dynamic bending moment, M_d	2.058×10^6 kN-m	0.40	Normal

Table 5. Probabilistic Characterization of Model Uncertainty Random Variables (Reprinted from Mansour and Hoven 1994)

Random variable	Distribution type	Mean	Coefficient of variation
x_u	Normal	1.00	0.15
x_{sw}	Normal	1.00	0.05
x_w	Normal	0.90	0.15
x_s	Normal	1.15	0.03

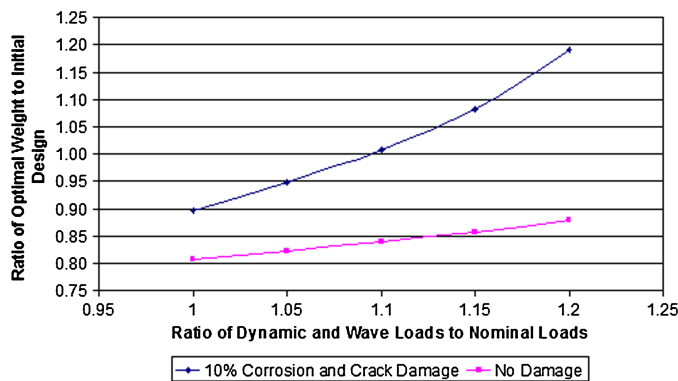
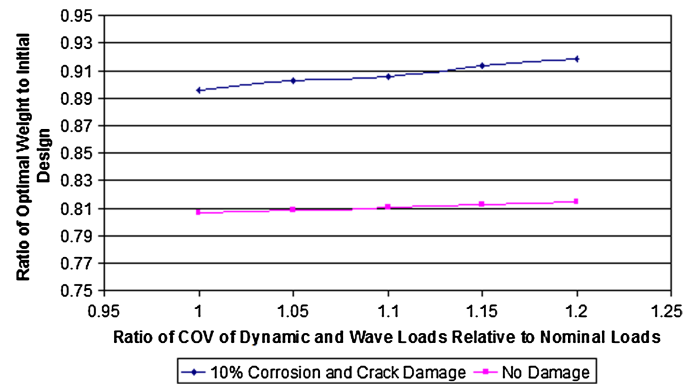
are summarized in Table 6. Since optimization routines can get locked in local minimum or maximums, a global optimal design can be ensured by randomly selecting the initial points from which to launch the optimization process, and also by making use of both optimization algorithms available in *SMARTOPT*.

Table 6. Optimization Output and Threshold Values on Main Constraints

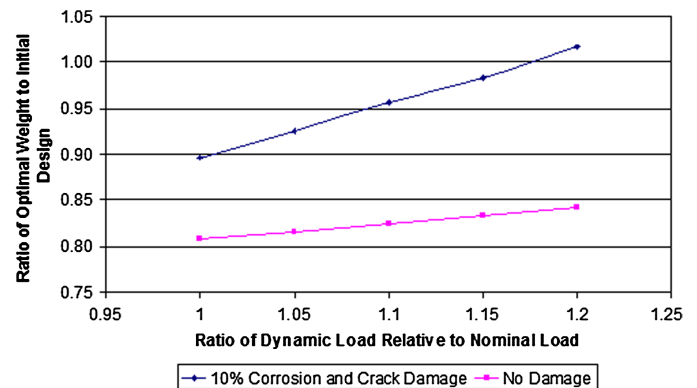
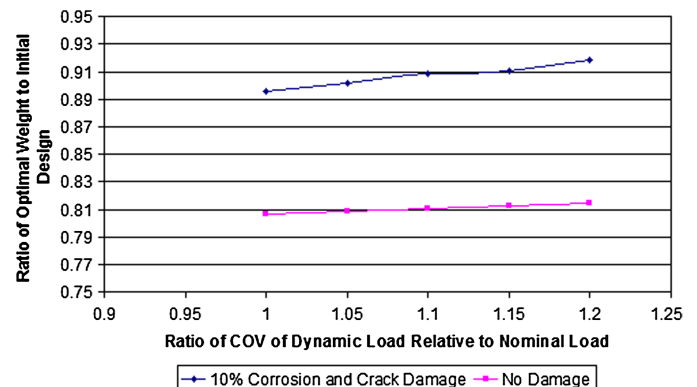
Parameter	Intact design (undamaged)	Damage-tolerant design
Initial design weight (kg)	2,040	2,040
Final (optimal) design (kg)	1,646	1,827
% reduction in weight	19.5	11
Threshold values for (main) constraints	110% of initial design reliability	100% of initial intact design reliability
Number of active design variables (side constraints)	25	21
Number of active (main) constraints	3	2

It is assumed that the vessel will experience both corrosion-based and fatigue-based structural damage during its lifetime. The envisioned worst-case scenarios for these two damage modes are employed in the optimal design process. More specifically, it is assumed that all major structural components listed in Table 5 will undergo a 10% reduction in size due to corrosion, and that cracks will occur at the joints. In terms of fatigue damage, it is assumed that a crack at a joint in a hull girder can be modeled by considering two different cracks: one in the stiffener itself and one in the plate to which it is welded. It is assumed that a crack can initiate at the weld between the plate and the stiffener, and that crack propagation may occur in either of the two. The crack in the plate is modeled as a through-thickness crack that propagates away from the stiffener in the transverse direction, decreasing the contribution of the plate to the net section modulus resisting the longitudinal loads. The crack in the stiffener is assumed to initiate on the edge connected to the weld and then propagate across the stiffener, decreasing its net effective area available to resist longitudinal loads. A net reduction of 10% of the plate and stiffener dimensions due to fatigue cracking is assumed in the optimization. Formulas used for computing these reductions can be found in Akpan et al. (2002).

A summary of the optimal design results from damage-tolerant and undamaged design is presented in Table 6. Both approaches lead to weight-reduced optimal designs. More specifically, the undamaged design approach leads to a 19.5% reduction in structural weight, while the damage-tolerant optimal design results in only an 11% reduction. Thus, as one might expect, the damage-tolerant design approach yields a much heavier vessel than that predicted under the assumption of negligible structural damage. Furthermore, both designs are more robust in terms of reliability than the initial design (based on experience, judgment, and LRFD)

**Fig. 3.** Sensitivity of probabilistic optimal design to mean values of dynamic and wave loads**Fig. 4.** Sensitivity of probabilistic optimal design to COV of dynamic and wave loads

since the threshold values assigned to the constraint-reliability indices, which are not violated during the optimization process, are 10% larger than those used in the nonoptimized initial existing design. In addition, there are a total of 21 and 25 active side constraints for the damage-tolerant and intact designs, respectively. In the current example, these active constraints assumed the lower-bound values of the design variables denoted by X . The implication of this observation is that if the lower-bound values of these active

**Fig. 5.** Sensitivity of probabilistic optimal design to mean value of dynamic load**Fig. 6.** Sensitivity of probabilistic optimal design to COV of dynamic load

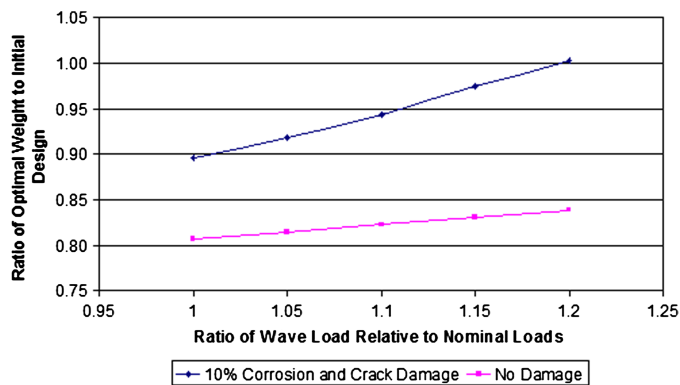


Fig. 7. Sensitivity of probabilistic optimal designs to mean value of wave load

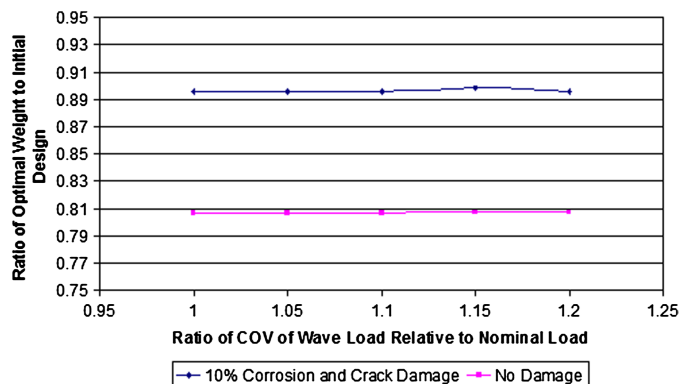


Fig. 8. Sensitivity of probabilistic optimal design to COV of wave load

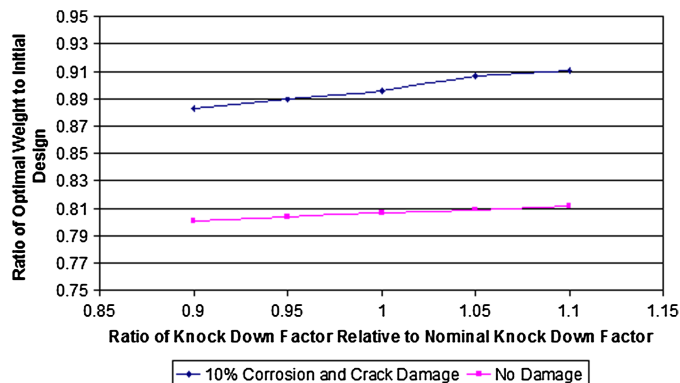


Fig. 9. Sensitivity of probabilistic optimal design to mean value of buckling knockdown factor

side constraints (design variables) may be reduced, it could be possible to obtain an improved design with an even lower total weight.

The extreme values of the load variables used during the design process are usually based upon the results of either sea trials or motion analyses, which cannot be executed on a vessel that is still at the conception stage. It is therefore of utmost importance to investigate the sensitivities of the predicted optimal designs, especially with regards to the degree of weight reduction, to changes in the probabilistic description of the load random variables considered in the optimization process. For each design

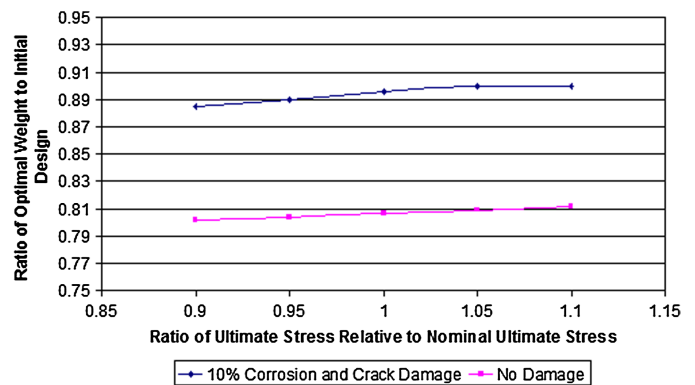


Fig. 10. Sensitivity of probabilistic optimal design to mean value of ultimate strength

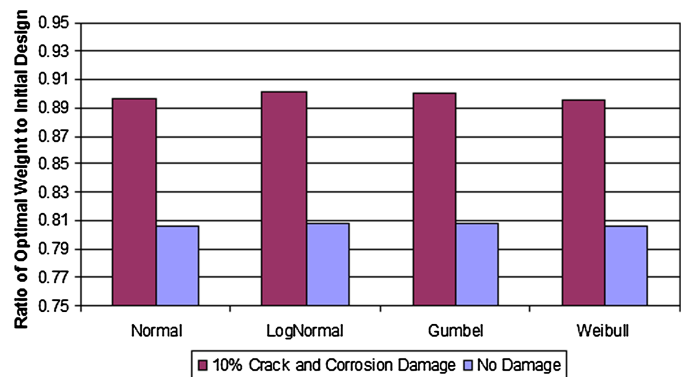


Fig. 11. Sensitivity of optimal design to probabilistic distribution of load parameters

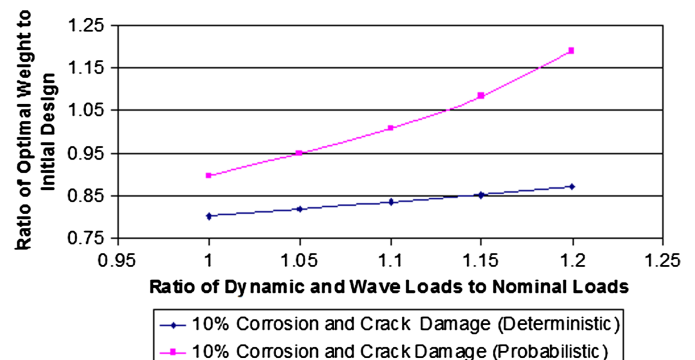


Fig. 12. Sensitivity of optimal design to mean value dynamic and wave loads

approach (i.e., damage-intolerant and damage-tolerant), the sensitivity to change in a number of load variables was considered, including mean value, coefficient of variation and probability distributions of the dynamic load, wave bending moment, and combined loads. The results of the sensitivity study are presented in Figs. 3–12.

For the current example problem, the reliability-based optimal structural weight tends to increase with increases in the mean value of both dynamic and wave loads. The optimal weight predicted using the damage-tolerant design approach is always higher than that

predicted assuming the design remains intact. Moreover, it is seen that this increase in structural weight does not necessarily follow a linear relationship, as is the case when the effects of structural damage are included. Although the optimal structural weight increases with changes in the coefficient of variation (COV) of the dynamic load, a similar change in the COV of the wave load has either minimal or no effect. Furthermore, the choice of probabilistic distribution for the dynamic load does not significantly impact the optimal design predictions in both the absence and presence of structural damage. Similarly, the ultimate-stress and knockdown factor parameters exhibit little impact on the optimization results. It can therefore be concluded that for the example problem under consideration, resources should be focused on obtaining an accurate description of the mean values of the dynamic and wave design loads, since the optimal design is much more sensitive to these parameters.

Conclusions

Ship structural design optimization not only enhances the robustness and overall reliability of a ship structure, but also helps to recognize the benefits of cost-effective usage of available resources. Design optimization is best accomplished using a probabilistic-based system reliability approach, which accounts for not only the uncertainties associated with the probabilistic characterization of the design parameters, but also the numerous potential failure mechanisms, their potential interaction, and their impact on structural integrity.

The present investigation has advanced the formulation of a probabilistic-based damage-tolerant optimal design strategy for ship structural systems. Design optimization has been formulated in terms of two main objective functions for ship structures: (1) minimization of design weight (and hence, cost), subject to constraints on undamaged and damaged component/system reliabilities; and (2) maximization of damage-tolerant system reliabilities, subject to constraints on design cost (or weight) and undamaged/damaged component reliabilities. Alternatively, these objective functions and constraints may be cast in terms of probability of failure. The optimization strategy has been implemented in the computational tool *SMARTOPT*, which includes FORM/SORM/MCS techniques, time-invariant and time-dependent reliabilities/failure probabilities, and also features two efficient design optimization algorithms.

The proposed formulation is demonstrated by means of an example problem, in which an existing tanker is redesigned for optimal performance, and reliability using limit state functions based on ultimate capacity in both the absence and presence of structural damage. For the example problem and structural damage specified herein, results show that design optimization in both the presence and absence of structural damage yields significant improvements in the overall robustness of the original (undamaged) design. In terms of cost savings, a damage-tolerant design approach forecasts nearly a 10% increase in weight compared to that predicted in the absence of structural damage. A sensitivity analysis suggests that for best results, available resources should be focused on the accurate description of mean dynamic and wave loading.

It should be reiterated that the formulation presented herein is very general, and may be applied to the optimization of virtually any facet (individual or combination thereof) of ship structural design. However, in terms of the results presented herein, some minor

limitations should be pointed out. First, the fidelity of the reliability results depends on the integrity of the structural model used to predict ultimate strength capacity. Although a simplified model for ultimate strength was used here, any suitable model [analytical, numerical (e.g., idealized structural unit method, Paik 2004), LRFD-suggested (Ayyub et al. 2002), finite element-based, etc.] could have been used instead to potentially improve the quality of the results. Additional models available for use may be found in Akpan et al. (2002). Secondly, the results presented in this study did not address optimization in terms of topological rearrangement. Lastly, in the case of the damage-tolerant design optimization, coating damage was not considered. Such limitations will be the subject of future investigations.

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